A Hybrid Manufacturing/Remanufacturing System With Random Remanufacturing Yield and Market-Driven Product Acquisition

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***Abstract*—Remanufacturing has created considerable benefits to both industry and community. This paper generates insights into the acquisition management and production planning of a hybrid manufacturing/remanufacturing system. The acquisition quantity of the used products is stochastic and sensitive to the acquisition price, and the uncertain quality of the acquired used products leads to a random yield in the remanufacturing process. With such a market-driven acquisition channel and a random remanufacturing yield, it is shown how the acquisition pricing, remanufacturing, and manufacturing decisions can be coordinated in order to maximize the total expected profit. Sequential and parallel remanufacturing/manufacturing processes are considered in different cases. In each case, we use a stochastic dynamic programming to formulate and analyze the model, showing that the optimal policy is characterized by several critical values and functions. We derive conditions under which the firm should open/close the acquisition channel and utilize/discard the remanufacturing option. By comparing the two cases, we show that expediting the remanufacturing process will help the firm to better utilize the acquisition channel and the remanufacturing option, as the optimal acquisition price and remanufacturing quantity are both higher in the case of sequential processes.**

***Index Terms*—Product acquisition, random yield, remanufacturing, stochastic dynamic program.**

I. Introduction

REMANUFACTURING is an environmentally and economically sound way to deal with products after customer usage, representing great opportunities for improving productivity, saving resources, and reducing manufacturing costs. Therefore, many firms implement collection channels for used product return and integrate corresponding remanufacturing strategies with their regular production system. For instance, Xerox, which is renowned for its green manufacturing and sustainable services, earned over $80 million by implementing a remanufacturing program in 1997 [1]. Similar examples of the benefits obtained from remanufacturing are easily found in different industries with an estimation of 120 trillion BTUs/year of energy savings worldwide, which accounts for 16 million barrels of crude oil and $500 million in energy costs [2].

To achieve such environmental and economical advantages, the acquisition of used products is regarded as a first step in the remanufacturing process. One way to gather the used products is to utilize a market-driven channel by paying an acquisition price to the end users or the core dealers, which is an effective incentive mechanism to collect an appropriate number of used products for remanufacturing. Since the acquisition quantity of the used products could be larger when a higher acquisition price is offered, this approach grants the firm a partial control on used product returns and, thus, has been widely adopted in the remanufacturing industry (see, e.g., [3] and [4]). However, due to the high fluctuation in times, as well as the quantities and qualities of the return items, such a market-driven acquisition channel should be carefully designed, with the corresponding remanufacturing and manufacturing strategies effectively coordinated.

The objective of this research is to investigate the acquisition pricing decision and the integrated production planning in a hybrid remanufacturing/manufacturing system with a market-driven channel for used product returns, which is partly motivated by our collaboration with a local manufacturing firm of printer ink and toner cartridges in Shandong Province, China. The firm is producing a new version of its self-owned brand toner cartridge, which can be either manufactured from raw materials bought from an outside supplier, or refurbished from the used cartridge. As manufacturing a new one is more costly than refurbishing, the firm exerts substantial efforts to build a collection channel to acquire the used cartridges by offering a refund to the end users who return them. Such a hybrid system is also adopted in the fields that lease office equipment such as photocopiers and printers [5], and in those that manufacture automotive parts [6]–[8], single-use cameras [9], cans, paper, or glasses [10], where a remanufactured unit is treated the same as a newly manufactured one. In these cases, a common problem faced by the manufacturing firms is how to properly set the acquisition price in the collection market, and to harmoniously produce through the two channels of manufacturing and remanufacturing. The problem is complicated in nature due to

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the inherent uncertainties in the product acquisition channel and the subsequent remanufacturing process.

In this paper, we consider a hybrid remanufacturing/manufacturing system, which satisfies demand by either manufacturing new products or remanufacturing the used products acquired from a market-driven channel. In this channel, the quantity of used product supply is uncertain and sensitive to the acquisition price. Moreover, there is a random yield in the remanufacturing process due to the uncertain quality of the returned items; not all items from the used product inventory can be remanufactured to the required standard quality. Hence, once the acquisition of used product is finished, two scenarios can occur depending on the relative length of processing times between manufacturing and remanufacturing. In the case of prompt remanufacturing, the manufacturing process can be started after the remanufacturing process, and thus, the manufacturing quantity can be decided after the remanufacturing random yield is realized. In contrast, in the case of slow remanufacturing, the manufacturing and remanufacturing quantities have to be decided in parallel as both operations need to be started around the same time. Both cases are addressed in this paper, and the optimal acquisition price as well as the manufacturing/remanufacturing planning policies is explored under given initial inventories of used and finished products.

We also seek to answer the following questions and thereby provide tactical and managerial insights for firms that benefit from both manufacturing and remanufacturing operations.

1) What is the effect of *expediting* the remanufacturing process on the decisions of remanufacturing quantity and acquisition price?
2) When should the firm implement a single sourcing policy in this hybrid system, i.e., when should the firm rely only on manufacturing, or only on remanufacturing to satisfy demand? Also, when should the firm open or close the market-driven acquisition channel?

To gain clear insights into these questions, and similar to [11], we focus on a single-period problem, which can also serve as a basis for a multiperiod setting. The rest of the paper is organized as follows. In Section II, we provide a brief literature review. In Section III, we describe the model, assumptions, and the sequence of events. Sections IV and V investigate the scenarios of sequential and parallel remanufacturing/manufacturing processes, respectively, and derive the optimal acquisition pricing strategy as well as the optimal manufacturing/remanufacturing policies. Section VI applies our generalized results to two special cases, and Section VII concludes this paper.

II. Literature Review

There has been substantial research into the production planning and inventory management in remanufacturing systems. For a comprehensive review, we refer the reader to [12]–[14]. Our study is particularly related to those considering the hybrid systems of joint manufacturing and remanufacturing, with the common feature that market demand can be satisfied from both manufacturing new products and remanufacturing returned ones. Simpson [15] first studies a periodic review inventory system with stochastic, and mutually dependent demands and returns, and provides the optimality of a three-parameter inventory policy. Kelle and Silver [16] consider a different model with independent demand and return processes, where all returned products should be remanufactured. Inderfurth [17] shows that the optimal policy derived in [15] is still optimal in the case of fixed cost when the lead times for remanufacturing and manufacturing are identical. Van der Laan *et al.* [18] analyze a push control strategy and a pull control strategy in a hybrid system, and compare them with the traditional systems without remanufacturing. Teunter *et al.* [19] explore the superior inventory strategies for hybrid manufacturing/remanufacturing systems with a long lead time for manufacturing and a short lead time for remanufacturing. Wang *et al.* [20] analyze the impacts of the amount of products manufactured and the proportion of the remanufactured part to the returned products on the total cost of the hybrid system, showing that the cost can be reduced significantly if these two critical values are optimally set. Other related works include [5], [21]–[23], etc. Unlike our paper, all the aforementioned studies assume that the quantity of returned products is exogenous and uncontrolled. In reality, however, the quantity of such products can be related to the incentives (e.g., a purchasing price) provided by the firm.

In addition to considering the quantity of the returned items, our paper incorporates the quality uncertainty of the acquired used product, which is modeled by a random remanufacturing yield. Inderfurth [24] shows that the uncertainties in returns and demand can be a considerable obstacle to a consequently environmentally benign recovery strategy within a reverse logistics system. Inderfurth and Langella [25] develop heuristics for the problem of obtaining parts for remanufacturing by disassembling used products or procuring new ones, under the consideration of random disassembly yields. Corbaciolu and Van der Laan [26] analyze a two-product system with an end-product stock containing both manufactured and remanufactured products, and the remanufacturable stock containing used products of different quality. Zikopoulos and Tagaras [27] investigate the production problem in a reverse supply chain consisting of two collection sites and a refurbishing site, and examine how the profitability of reuse activities is affected by the uncertainty regarding the quality of returned products. Denizel *et al.* [28] propose a stochastic programming formulation to solve the remanufacturing production planning problem when inputs of the remanufacturing system have different, and uncertain quality levels and capacity constraints.

As the quality uncertainty is usually modeled as a remanufacturing yield, there has been growing research on the effect of yield information on reverse logistics systems. For example, Ferrer [29] considers the value of remanufacturing yield information and compares it to the value of reducing lead times. Ferrer and Ketzenberg [30] extend the model of [29] into the case of multiple parts per product and infinite time horizons. Ketzenberg *et al.* [31] also address the value of yield information in determining the optimal configuration of a mixed assembly–disassembly line. Galbreth and Blackburn [32] explore acquisition and sorting/remanufacturing policies in the case of a continuum of quality levels for cores with a fixed quality distribution. The main premise is that remanufacturing costs will go down if only the returned products with better quality are remanufactured. Ketzenberg *et al.* [33] explore the value of information in the context of a firm that faces uncertainty with respect to demand, product return, and product remanufacturing yield, by first analyzing a simple single-period model and then proving that the results carry over a multiperiod setting. Unlike our work, none of these studies consider a market-driven acquisition channel.

Although the research on remanufacturing systems is vast, only a few papers consider a market-driven acquisition channel for used products. Guide and Van Wassenhove [3] and Guide and Jayaraman [34] are the first to investigate this field, pointing out the importance of used product acquisition management to deal with the uncertainty in timing, quantity, and quality of the returned products. Guide *et al.* [35] develop a quantitative model to determine the optimal acquisition prices of used products and the selling price of remanufactured products, assuming that the quantity of return items can be fully controlled by the acquisition price. Bakal and Akcali [36] extend the model of [35] into the case of random remanufacturing yield and analyze the impact of yield on the remanufacturing profitability. Karakayali *et al.* [37] study the problem of determining the optimal acquisition price of the end-of-life products and the selling price of the remanufactured parts under centralized as well as decentralized remanufacturer-driven and collector-driven decentralized channels. However, all the papers mentioned previously consider the acquisition pricing problem under a pure remanufacturing setting and in isolation from manufacturing, whereas our paper integrates the decisions related to used product acquisition, remanufacturing, and manufacturing.

Kaya [10] and Mukhopadhyay and Ma [38] are the studies most closely related to our work. Mukhopadhyay and Ma [38] address a hybrid system where both used and new parts can serve as an input in the production process to satisfy demand. Their paper models the quality variation of returned product parts through a random yield and considers the cases of short and long delivery lead time of new parts, which are similar to our setting. Kaya [10] also studies the joint decisions of the acquisition price with the remanufacturing and manufacturing quantities under both perfect and partial demand substitution. Our paper differs from the aforementioned studies in the following ways.

1) We address the decision problems of manufacturing, remanufacturing, and acquisition price in a market-driven channel, and examine a more complex (and realistic) setting where both remanufacturing yield and used product acquisition are random. For example, Mukhopadhyay and Ma [38] do not incorporate the market-driven acquisition channel and its underlying uncertainty, while Kaya [10] neglects the issue of random remanufacturing yield due to the uncertainty in used product quality.
2) By allowing for initial inventories in the system, we derive optimal policies for the product acquisition, remanufacturing, and manufacturing that better fit the system. More specifically, we provide explicit conditions on when to open or close the used product acquisition channel, and when to rely only on the remanufacturing or manufacturing to satisfy demand. Furthermore, we provide comparative results on the acquisition prices and remanufacturing quantities between the cases of sequential and parallel remanufacturing/manufacturing processes. Although there have been some studies on the production policy and the value of information in remanufacturing systems, our results are new to the literature.
3) We consider very generalized settings for both the supply and demand sides, as we do not limit our model to any specific acquisition function or revenue function. This renders our results applicable to a wider range of applications, including the most commonly used deterministic and random demand functions as special cases.

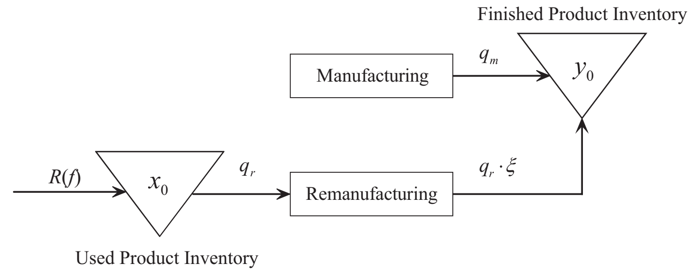

Fig. 1. Hybrid remanufacturing/manufacturing system.

III. Model Description

A. Problem and Assumptions

In this paper, we consider a hybrid manufacturing/remanufacturing system with a used product inventory and a finished product inventory that have initial stocks x_0 and y_0, respectively (see Fig. 1). Demand is satisfied by the units in the finished product inventory consisting of 1) the initial stock of finished products, 2) the newly manufactured products, and 3) the items recovered from the used product inventory. To provide enough used products for remanufacturing, a market-driven acquisition channel can be utilized. We denote the supply of used products by a random variable $R(f)$, which depends on the acquisition price $f \in [\underline{f}, \overline{f}]$. The acquired used products are transported to the used product inventory to be remanufactured. However, there is a random yield $\xi \in [0,1]$ in the remanufacturing process due to the uncertainty in the quality of used products. The cumulative distribution function (CDF) and probability density function (PDF) of ξ are known as G_ξ and g_ξ, respectively, with its mean denoted by $\mu \leq 1$. On the other hand, the manufacturing process is assumed to be under a perfect yield with a sufficient supply of raw material. Both the remanufactured products and the newly manufactured ones are stored in the finished product inventory.

Besides the acquisition price, the firm also pays for a variable unit cost c_t per used product, which represents the related transportation and handling costs. The remanufacturing and manufacturing costs are denoted by c_r and c_m, respectively. There is a holding cost h_1 for each unit of used product not remanufactured, which can be negative when the leftover used product incurs a salvage value instead of a holding cost. We

TABLE I
LIST OF NOTATION

Notation	*Representation*
x_0/y_0	initial stock in the used/finished product inventory
x_1/y_1	stock in the used/finished product inventory after acquisition/remanufacturing
c_m/c_r	unit manufacturing/remanufacturing cost
c_t/h_1	unit handling/holding cost of used product
f	acquisition price, decision variable
q_r/q_m	remanufacturing/manufacturing quantity, decision variable
$\Pi(y)$	revenue function with finished product quantity y
$R(f)/r(f)$	acquisition quantity with acquisition price f/ expectation of $R(f)$
ε	random disturbance in the acquisition quantity
ξ/μ	random remanufacturing yield/expectation of ξ
$g_i(\cdot)/G_i(\cdot)$	density/distribution function of random variable i, $i = \varepsilon, \xi$
$\pi_i(\cdot)$	objective function for Model 1, *i.e.*, the sequential manufacturing/remanufacturing case, with $i = 1, 2, 3, 4$ representing the various decision stages
$\widehat{\pi}_i(\cdot)$	objective function for Model 2, *i.e.*, the parallel manufacturing/remanufacturing case, with $i = 2, 3, 4$ representing the various decision stages
$f_i^*, q_{ri}^*, q_{mi}^*$	optimal decision variables for Model i, $i = 1, 2$

assume $-c_t < h_1 < c_r$, which rules out the following two trivial cases: 1) $-h_1 > c_t$, where the acquisition will be initiated for obtaining the salvage value rather than for remanufacturing, and 2) $h_1 \geq c_r$, where the remanufacturing will be initiated for avoiding the holding cost rather than for obtaining revenue.

The firm faces the problem of jointly determining the acquisition price f, remanufacturing quantity q_r, and the manufacturing quantity q_m. The objective is to maximize the expected profit, which is equal to the expected revenue minus the expected costs on acquisition, remanufacturing, and manufacturing. We denote a generalized function $\Pi(y)$ as the expected revenue of having y units of finished products available for sale in the market. For example, it can be that $\Pi(y) = pE\min[D, y]$ when D is a random demand and p is an exogenous selling price. Specific cases of $\Pi(\cdot)$ will be discussed in Section VI.

We make the following assumptions for the acquisition quantity of used products and the obtained revenue from selling finished products.

Assumption 1: $R(f) = r(f) \cdot \varepsilon$ or $R(f) = r(f) + \varepsilon$, where $r(f)$ is a deterministic function satisfying $r'(f) > 0$ and $r''(f) \leq 0$, while ε is a random variable representing the stochastic disturbance in the used product acquisition process, which is assumed to be independent of the acquisition price f and the remanufacturing yield ξ.

Assumption 1 indicates that the acquisition quantity of used products is modeled in an additive or a multiplicative form, in which the acquisition noise can be isolated as a price-independent factor. Without loss of generality, we normalize $E[\varepsilon] = 0$ in the additive form, and $E[\varepsilon] = 1$ in the multiplicative form. Hence, $r(f)$ becomes the expected acquisition quantity with acquisition price f. Denote the PDF and CDF of ε by g_ε and G_ε, respectively. Assumption 1 also indicates that the amount of increase in the expected acquisition quantity diminishes as the acquisition price increases. This concavity property is satisfied by various acquisition functions such as: 1) affine: $r(f) = \alpha + \beta f$, where $\alpha \geq 0, \beta > 0$; 2) exponential: $r(f) = \alpha f^\beta$, where $\alpha > 0, 1 \geq \beta > 0$; 3) fractional: $r(f) = \frac{\alpha f}{f+\beta}$, where $\alpha > 0, \beta \geq 0$; and 4) logarithmic: $r(f) = \alpha \ln(f)$, where $\alpha > 0$. Note that the majority of existing literature on acquisition management assume that the acquisition quantity is a deterministic (and usually a linear) function of acquisition price (see, e.g., [35]–[37]). However, our model is a more generalized one and includes the forms assumed in such studies as special cases.

Assumption 2: $\Pi(\cdot)$ is twice differentiable and $\Pi''(\cdot) \leq 0$; $\Pi'(+\infty) < \min[c_m, (c_r - h_1)/\mu] < \max[c_m, c_r + c_t] < \Pi'(0)$.

Assumption 2 implies that the expected revenue from selling finished products is concave with respect to the finish product quantity,[1] which coincides with the common assumptions of utility theory in economics. Assumption 2 also indicates that the marginal revenue is neither too high nor too low, which rules out the trivial case of zero production or infinite production. Our general revenue function includes most demand forms commonly used in the literature. An example is the standard newsvendor setting considered in [38]. Section VI will provide more discussions on this aspect.

We summarize the notations used throughout the paper in Table I.

[1]Except for specific declaration, all properties on monotonicity and concavity in this paper are in the weak sense.

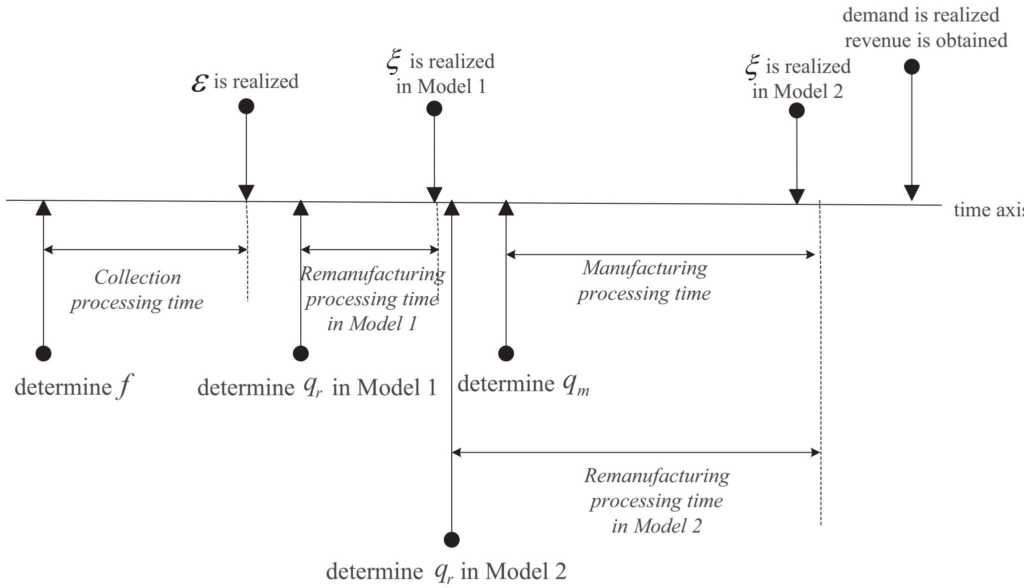

Fig. 2. Sequence of events in two models.

B. Sequence of Events

The sequence of events depends on the remanufacturing/manufacturing processing time. When the remanufacturing process is prompt,[2] manufacturing can be started after the remanufacturing and finished in time to satisfy demand. In such a situation, the manufacturing quantity can be determined after observing the realization of remanufacturing yield. That is, the firm can wait to observe the output of the remanufacturing process and start the production process afterward to prepare for satisfying demand. In contrast, when the remanufacturing process is slow, the manufacturing and remanufacturing need to be started almost at the same time, and hence, the remanufacturing yield cannot be observed prior to manufacturing.

In practice, it is often observed that the processing time of remanufacturing a used product is fast and the remanufacturing/manufacturing decisions can be made sequentially. Examples include the production of automobile parts, engines, household appliances, and photocopiers, among others. Fast remanufacturing is especially notable when the remanufactured parts are used as service parts if the product itself is no longer manufactured, that is, in the final phase of the service period [19]. However, sometimes the case of parallel manufacturing/remanufacturing processes can also occur. For instance, returned truck tyres can be devulcanized and reconverted into rubber first, and then, it is mixed with virgin material to produce new tyres. The additional devulcanizing process slows down the remanufacturing. Another example is the case of recycling used pizza boxes in the Wall-Mart closed-loop supply chain, where recycling is rather time consuming compared to producing new boxes. In all, both settings with sequential or parallel remanufacturing/manufacturing have wide practical applications. Consequently, although we consider a single-period problem, the decision sequences can be different depending on the relative length between the processing times of manufacturing and remanufacturing operations.

[2]The prompt remanufacturing scenario is equivalent to a prompt manufacturing setting in our framework: in either scenario, there is enough time in the period to process them sequentially. However, when both manufacturing and remanufacturing are slow, they need to be performed in parallel, and hence, the realization of the random yield cannot be effectively utilized.

In our setting, both the manufacturing and remanufacturing operations are initialized after the acquisition price for used product is set. Noting that the acquisition price f is chosen from the feasible interval $[\underline{f}, \overline{f}]$, we say that the acquisition channel is activated if and only if $f > \underline{f}$. Here, $\underline{f}$ can be 0, positive, or negative, depending on the practice. For example, Extended Producer Responsibility can prescribe the manufacturer to take back the produced products after usage so $\underline{f}$ can be set positive to maintain some collection rate; $\underline{f}$ can also be negative if the returned product contains toxic material or has been altered beyond acceptable limits, so the final user may make a payment to the collector or the manufacturer who takes it back (see [37] and [39]).

We also use notations R and ξ to denote the realizations of random variables R and ξ, respectively, as it is easy for readers to tell when they are random variables and when they are realizations. The sequence of events is depicted in Fig. 2 and stated as follows.

1) The firm determines the acquisition price f, based on the initial inventories x_0, y_0, the distributions of random noise in the acquisition process, ε, and the remanufacturing yield, ξ.

2) The random noise in the acquisition process, ε, is realized. The used products with realized quantity $R(f)$ are transported to the used product inventory. The used product inventory has $x_1 = x_0 + R(f)$ units.

3) In the case of sequential remanufacturing/manufacturing, the remanufacturing quantity q_r is first decided, and then, the manufacturing quantity q_m is determined after the remanufacturing yield ξ is realized. That is, q_m is determined after

remanufacturing according to $y_0 + q_r \cdot \xi = y_1$ units in the finished product inventory. In the case of parallel remanufacturing/manufacturing, the remanufacturing quantity q_r and the manufacturing quantity q_m are decided simultaneously.

4) After the manufacturing and remanufacturing are completed, the finished products with quantity $q_r \cdot \xi + q_m$ are transported to the finished product inventory. Thus, a total quantity of $y = y_0 + q_r \cdot \xi + q_m$ units will be ready to serve the demand and the revenue $\Pi(y)$ will be expected.

IV. Model 1: Sequential Remanufacturing/Manufacturing

This section discusses the case of sequential remanufacturing/manufacturing, in which the acquisition price, remanufacturing quantity, and the manufacturing quantity are determined in sequence. We formulate this problem as a three-stage stochastic dynamic program, and adopt a backward approach to solve it: we first explore the optimal manufacturing policy, then turn to the remanufacturing policy, and, finally, explore the acquisition pricing problem.

A. Optimal Manufacturing Policy

Suppose that after remanufacturing, we already have $y_0 + q_r \cdot \xi = y_1$ units in the finished product inventory. We first solve the problem of choosing the manufacturing quantity q_m to maximize the expected profit, which can be formulated as

$$\max_{q_m \geq 0} \{\Pi(q_m + y_1) - c_m q_m\}. \tag{1}$$

This problem is equivalent to choosing the target level y for the final finished product inventory, which is formulated as

$$\max_{y \geq y_1} \{\Pi(y) - c_m y\} + c_m y_1. \tag{2}$$

Proposition 1: Given the on-hand finished product inventory level y_1, the optimal manufacturing quantity q^*_{m1} is

$$q^*_{m1} = \begin{cases} s^*_1 - y_1, & \text{if } y_1 < s^*_1 \\ 0, & \text{if } y_1 \geq s^*_1 \end{cases} \tag{3}$$

where s^*_1 is characterized by

$$\Pi'(y)|_{y=s^*_1} = c_m. \tag{4}$$

Proposition 1 shows that the optimal manufacturing policy is a policy of ordering up to level s^*_1, at which the marginal revenue that can be gained is equal to the manufacturing cost.

B. Optimal Remanufacturing Policy

Let $\pi_1(y_1) = \max_{y \geq y_1} \{\Pi(y) - c_m y\} + c_m y_1$ be the maximized expected profit after manufacturing new products, given that y_1 units have been in the finished product inventory. Now, we turn to determining the optimal remanufacturing policy. Given that the on-hand used product inventory level is $x_0 + r(f) \cdot \varepsilon = x_1$ after acquisition, and the initial finished product inventory level is y_0, the problem is to determine the remanufacturing quantity to maximize the expected profit, which can be formulated as

$$\max_{0 \leq q_r \leq x_1} \pi_2(q_r | x_1, y_0) = \{E_\xi[\pi_1(q_r \cdot \xi + y_0)] - c_r q_r - h_1(x_1 - q_r)^+\} \tag{5}$$

where notation $(a)^+ = \max[a, 0]$. We present the following lemma before providing the optimal remanufacturing policy.

Lemma 1: 1) $\pi_1(y_1)$ is concave in y_1 and $\pi'_1(y_1) \leq \max[\Pi'(y_1), c_m]$ for all y_1; 2) For any given $y_0, \pi_2(q_r | x_1, y_0)$ is jointly concave in q_r and x_1 on $[0, x_1] \times [0, +\infty)$.

Lemma 1 shows that the concavities of the profit functions are preserved after the remanufacturing stage with respect to the finished product quantity, and before the remanufacturing stage with respect to the remanufacturing quantity and the existing used product quantity. These properties serve as a basis for deriving the optimal remanufacturing policy.

Define function $S_{\xi 1}(y)$ in an implicit way such that

$$\int_0^1 \pi'_1(S_{\xi 1} t + y) t g_\xi(t) dt = c_r - h_1. \tag{6}$$

That is, first consider a real-valued variable $S_{\xi 1}$ characterized by (6), whose value obviously depends on variable y. This dependence can be regarded as a function, which is also denoted as $S_{\xi 1}(y)$ for the ease of notation. Clearly, $S_{\xi 1}(y)$ is a decreasing function of y. Using notation $S_{\xi 1}(y)$, we can obtain the following result.

Proposition 2: 1) If $c_m < (c_r - h_1)/\mu$, the optimal remanufacturing quantity $q^*_{r1} = 0$; 2) If $c_m \geq (c_r - h_1)/\mu$, the optimal remanufacturing quantity q^*_{r1} is

$$q^*_{r1} = \begin{cases} x_1, & \text{if } y_0 \leq S^{-1}_{\xi 1}(x_1) \\ S_{\xi 1}(y_0) > 0, & \text{if } S^{-1}_{\xi 1}(x_1) < y_0 < s^*_2 \\ 0, & \text{if } y_0 \geq s^*_2 \end{cases} \tag{7}$$

where s^*_2 is characterized by

$$\Pi'(y)|_{y=s^*_2} = \frac{c_r - h_1}{\mu}. \tag{8}$$

Proposition 2 characterizes the optimal remanufacturing quantity, given the on-hand inventory levels of finished and used products. It states that the firm will remanufacture if, and only if, two conditions are satisfied. The first condition is that the manufacturing cost is greater than the difference of the remanufacturing cost and the inventory holding cost divided by the mean of the remanufacturing yield, which can be regarded as an *effective remanufacturing cost*. If this condition holds, then implementing remanufacturing is advantageous to manufacturing. This cost advantage can be seen, for instance, in the automobile market. It is reported that a remanufactured automobile part normally costs 50% to 75% of the cost of a comparable new one, and a remanufactured engine saves 50% of the energy and 33% of the labor compared to producing a new one.[3] Another famous example of remanufacturing cost advantage is Kodak's disposable cameras. The design of Kodak's single-use camera makes the product easy to disassemble and up to 90% of the parts are

[3]Automotive Parts Remanufacturers Association, http://apra.org/About/Reman.asp

remanufacturable. This enables Kodak to save a considerable amount of money by collecting and refurbishing the product while reloading them with films and selling them again [40]. Proposition 2 can also be used to partially explain the reason why remanufacturing in the laptop market is not as prevalent as in other electronic product industries. The core problem is that the design of disassembling and remanufacturing processes in the laptop market is far less mature. As a result, the relatively high effective remanufacturing cost discourages the firm from collecting and remanufacturing.

The second condition for the firm to initiate the remanufacturing process is that the initial finished inventory level is less than a threshold which depends on the revenue function, the effective remanufacturing cost, and the mean of the random yield. In this case, the optimal remanufacturing policy is defined in Proposition 2 by an *order-up-to* level $S_{\xi 1}(y_0)$, which is more complex than the traditional order-up-to level policy. This is a direct effect of random remanufacturing yield. However, the distribution of this yield matters only when the two aforementioned conditions are satisfied.

Corollary 1: 1) When $c_m \geq (c_r - h_1)/\mu, s_2^* = S_{\xi 1}^{-1}(0) \geq s_1^*$; 2) q_{r1}^* is increasing in x_1, and decreasing in y_0.

Corollary 1 indicates that when remanufacturing has a cost advantage to manufacturing, the no-remanufacturing threshold of the finished product inventory (i.e., the threshold above which the remanufacturing will not be activated) is no less than the nonmanufacturing threshold of the finished product inventory (i.e., the threshold above which the manufacturing will not be activated later). Moreover, the optimal remanufacturing quantity is decreasing in the initial inventory of finished products and increasing in the on-hand inventory of used products. This is intuitive because an increase in the finished product inventory will depress the need for remanufacturing, whereas a higher used product inventory will provide more used products for use in the remanufacturing process.

C. Optimal Acquisition Pricing Policy

Let $\pi_3(x_1|y_0) = \max_{0 \leq q_r \leq x_1} \pi_2(q_r|x_1, y_0)$. We now explore the decision problem of the acquisition price f, given the initial inventories x_0 and y_0:

$$\max_{f \in [\underline{f}, \overline{f}]} \pi_4(f|x_0, y_0) = \{E_\varepsilon[\pi_3(R(f) + x_0|y_0) - (f + c_t) \cdot R(f)]\}. \quad (9)$$

Lemma 2: $\pi_3(x_1|y_0)$ is a concave function of x_1, for any given y_0.

Lemma 2 shows that the concavity property is preserved for the optimized expected profit after acquisition, which enables us to provide the following results regarding the acquisition pricing decision.

Proposition 3: The optimal acquisition price, f_1^*, is unique and is characterized as follows:

1) If $c_m < (c_t + c_r)/\mu$ or $-S_{\xi 1}(y_0) + x_0 \geq 0$, then $f_1^* = \underline{f}$;

2) If $c_m \geq (c_t + c_r)/\mu$ and $-S_{\xi 1}(y_0) + x_0 < 0$, then f_1^* is the solution to

$$\int_0^{+\infty} \pi_3'(r(f)t + x_0|y_0) t g_\varepsilon(t) dt = \frac{r(f)}{r'(f)} + c_t + f \quad (10)$$

in the case of $R(f) = r(f) \cdot \varepsilon$ and is the solution to

$$\int_{-\infty}^{+\infty} \pi_3'(r(f) + t + x_0|y_0) g_\varepsilon(t) dt = \frac{r(f)}{r'(f)} + c_t + f \quad (11)$$

in the case of $R(f) = r(f) + \varepsilon$.

Proposition 3 characterizes the optimal acquisition price, given the initial inventory levels of the finished and used products. Define $l_1(x_0, y_0) = x_0 - S_{\xi 1}(y_0)$. Note that $S_{\xi 1}(\cdot)$ is a decreasing function, so $l_1(x_0, y_0)$ is an increasing function of x_0 and y_0 (and linearly increasing in x_0). Proposition 3 indicates that the firm should activate the acquisition channel only if two conditions are satisfied. The first condition guarantees the cost advantage of acquisition/remanufacturing over manufacturing: $(c_r + c_t)/\mu \leq c_m$. The second condition requires the initial inventory levels to be low enough: $l_1(x_0, y_0) < 0$, or equivalently, $\int_0^1 \pi_1'(x_0 t + y_0) t g_\xi(t) dt > c_r - h_1$. That is, the second condition (of inventory) could be dependent on the system state dynamics, but the first condition (of cost) is the basic premise for collecting and remanufacturing the used products. This result can explain the motivation of the subsidy scheme offered by the Chinese government. In June 2009, the government announced a 2 billion RMB subsidy scheme for the electronic appliance manufacturers adopting trade-in rebates to their customers. As an allowance was given to the manufacturers for each product replacement, this scheme virtually lowered the unit handling/transportation cost of acquired used items, which boosted the incentive for the manufacturers to open their acquisition channels.

Corollary 2: f_1^* is decreasing in x_0 and y_0.

Corollary 2 indicates that the optimal acquisition price is decreasing in the initial inventory levels of used and finished products. In other words, a higher incentive for returning used items should be provided, when the firm is facing low inventory levels. This is intuitive because an increase in either inventory level will depress the need for collecting used products.

We summarize the optimal policy for the case of sequential remanufacturing/manufacturing as follows.

Optimal Policy of Model 1: In the sequential remanufacturing/manufacturing case, the optimal acquisition pricing, remanufacturing, and manufacturing decisions are determined by two critical values s_1^*, s_2^* defined in (4) and (8), respectively, and a critical function $S_{\xi 1}(\cdot)$ defined in (6). If acquisition/remanufacturing has a cost advantage $(c_r + c_t)/\mu \leq c_m$ and the initial inventories satisfy $l_1(x_0, y_0) = x_0 - S_{\xi 1}(y_0) < 0$, the firm should activate the acquisition channel with an acquisition price characterized by (10) or (11); otherwise, the firm should never collect used products. If remanufacturing has a cost advantage $(c_r - h_1)/\mu \leq c_m$ and the initial finished product inventory y_0 is lower than s_2^*, the firm should follow an order-up-to remanufacturing policy defined by the function $S_{\xi 1}(y_0)$; otherwise, the firm should never remanufacture, and the manufacturing policy is an order-up-to level s_1^* policy.

V. Model 2: Parallel Remanufacturing/Manufacturing

When the remanufacturing process is slow, the manufacturing and remanufacturing decisions need to be made simultaneously after the used product acquisition. We formulate this problem as a two-stage stochastic dynamic program and adopt a backward approach to solve it. We first derive the optimal joint manufacturing/remanufacturing policy and then explore the optimal acquisition pricing problem.

A. *Optimal Policy of Joint Remanufacturing and Manufacturing*

Supposing that the used and finished product inventories are x_1 and y_0, respectively, then the joint manufacturing and remanufacturing problem is

$$\max_{0\le q_r\le x_1, 0\le q_m} \widehat{\pi_2}(q_r, q_m|x_1, y_0) = E_\xi\{\Pi(y_0 + q_r\xi + q_m) - c_m q_m - c_r q_r - h_1(x_1 - q_r)\}. \quad (12)$$

The following lemma states the concavity of the above objective function, which directly follows from the concavity of the revenue function $\Pi(\cdot)$.

Lemma 3: 1) $\widehat{\pi_2}(q_r, q_m|x_1, y_0)$ is jointly concave in q_r and q_m in $[0, +\infty) \times [0, +\infty)$, for any given x_1, y_0. 2) $\widehat{\pi_2}(q_r, q_m|x_1, y_0)$ is jointly concave in q_r, q_m, and x_1 in $[0, x_1] \times [0, +\infty) \times [0, +\infty)$, for any given y_0.

Lemma 3 shows the joint concavity of the objective function $\widehat{\pi_2}(q_r, q_m|x_1, y_0)$ with respect to the decision variables, i.e., the remanufacturing and manufacturing quantities. In addition, the joint concavity can be preserved if the used product inventory level after acquisition is included as a third variable, in the space where the remanufacturing quantity is constrained.

Let (q_r^*, q_m^*) be the optimizer of

$$\max_{0\le q_r, 0\le q_m} \widehat{\pi_2}(q_r, q_m|x_1, y_0) \quad (13)$$

where the constraint $q_r \le x_1$ is relaxed. Since (q_r^*, q_m^*) depends only on y_0, we use notation $(q_r^*(y_0), q_m^*(y_0))$ to represent this dependence and explore these solutions in detail. Moreover, consider the bidimensional space with q_m-axis as the horizontal axis and q_r-axis as the vertical axis. Let $(q_m^{(i)}, 0)$ and $(0, q_r^{(i)})$ denote the points of intersection of line $\frac{\partial\widehat{\pi_2}}{\partial q_i} = 0$ with the q_m-axis and q_r-axis, respectively, for $i = m, r$. These quantities are depicted in Fig. 3. It is clear that $q_m^{(m)}$ $(q_r^{(r)})$ is the optimal manufacturing (remanufacturing) quantity if only the manufacturing (remanufacturing) option is available, and $q_m^{(r)}$ $(q_r^{(m)})$ is the suboptimal manufacturing(remanufacturing) quantity for which the marginal profit of remanufacturing(manufacturing) equals zero. For convenience, we summarize the notations used in this section in Table II. Noting that s_1^* and s_2^* have been defined in the previous section, we obtain the following lemma using a similar analysis and argument as in [27].

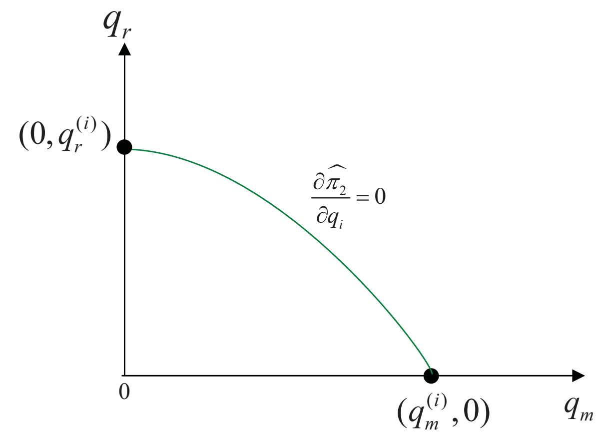

Fig. 3. Points of intersection of line $\frac{\partial\widehat{\pi_2}}{\partial q_i} = 0$ with the q_m-axis and q_r-axis.

TABLE II
Notations Used in Section V-A

Notation	*Representation*
q_i, $i \in \{r, m\}$	remanufacturing/manufacturing quantity (decision variable)
q_{i2}^*, $i \in \{r, m\}$	optimal solution of problem (12)
q_i^*, $i \in \{r, m\}$	optimal solution of problem (13)
$(q_m^{(i)}, 0)$, $i \in \{r, m\}$	intersection of curve $\frac{\partial\widehat{\pi_2}}{\partial q_i} = 0$ and q_m-axis
$(0, q_r^{(i)})$, $i \in \{r, m\}$	intersection of curve $\frac{\partial\widehat{\pi_2}}{\partial q_i} = 0$ and q_r-axis

Lemma 4: 1) If $c_m < (c_r - h_1)/\mu$, then

$$(q_m^*, q_r^*) = \begin{cases} (s_1^* - y_0, 0), & \text{if } y_0 \le s_1^* \\ (0, 0), & \text{if } y_0 > s_1^* \end{cases} \quad (14)$$

2) If $c_m \ge (c_r - h_1)/\mu$ and $y_0 \ge s_2^*$, then

$$(q_m^*, q_r^*) = (0, 0) \quad (15)$$

if $c_m \ge (c_r - h_1)/\mu$, and either (a) $s_1^* \le y_0 < s_2^*$ or (b) $y_0 < s_1^*$, and $q_r^{(r)} \ge q_r^{(m)}$,[4]
then

$$(q_m^*, q_r^*) = (0, q_r^{(r)}) \quad (16)$$

if $c_m \ge (c_r - h_1)/\mu, y_0 \le s_1^*$, and $q_r^{(r)} < q_r^{(m)}$, then (q_m^*, q_r^*) is the intersection of the two curves: $\frac{\partial\widehat{\pi_2}}{\partial q_m} = 0$ and $\frac{\partial\widehat{\pi_2}}{\partial q_r} = 0$.

Lemma 4 provides the optimal solution for problem (13) in which the constraint on the remanufacturing quantity is relaxed. The optimal remanufacturing quantity q_r^* is always zero if it does not have a cost advantage over manufacturing. On the other hand, (q_m^*, q_r^*) fully satisfies the first-order conditions only when $c_m \ge (c_r - h_1)/\mu, y_0 \le s_1^*$, and $q_r^{(r)} < q_r^{(m)}$. In all other cases, the optimal manufacturing quantity q_m^* is zero.

[4]Here, "If A, and either a or b, and C" means $A \cap (a \cup b) \cap C$, for conditions A, a, b, C.

Proposition 4: 1) If $c_m < (c_r - h_1)/\mu$, the optimal manufacturing and remanufacturing quantities are

$$(q^*_{m2}, q^*_{r2}) = \begin{cases} (s^*_1 - y_0, 0), & \text{if } y_0 \le s^*_1 \\ (0, 0), & \text{if } y_0 > s^*_1 \end{cases} \quad (17)$$

2) If $c_m \ge (c_r - h_1)/\mu$, the optimal manufacturing and remanufacturing quantities are

$$(q^*_{m2}, q^*_{r2}) = \begin{cases} (0,0), & \text{if } y_0 > s^*_2 \\ (0, \min\{q_r^{(r)}, x_1\}), & \text{if } s^*_1 < y_0 \le s^*_2 \\ (0, \min\{q_r^{(r)}, x_1\}), & \text{if } y_0 \le s^*_1 \text{ and } q_r^{(m)} \le \min\{q_r^{(r)}, x_1\} \\ (Q_m(q^*_{r2}), \min\{x_1, q^*_r\}), & \text{if } y_0 \le s^*_1 \text{ and } q_r^{(m)} > \min\{q_r^{(r)}, x_1\} \end{cases} \quad (18)$$

where $Q_m(x)$ is the solution q_m of the equation $\frac{\partial \widehat{\pi_2}(q_m, q_r)}{\partial q_m}|_{q_r = x} = 0$.

Proposition 4 characterizes the optimal joint manufacturing and remanufacturing decision, given the on-hand inventories of finished and used products. The conditions under which the remanufacturing is activated are exactly the same as what we observed in the sequential remanufacturing/manufacturing case: the remanufacturing should have a cost advantage over the manufacturing, $(c_r - h_1)/\mu \le c_m$, and the initial finished product inventory should be low enough, $y_0 < s^*_2$. When remanufacturing has the cost advantage, the remanufacturing policy is an order-up-to level $q^*_r(y_0)$ policy. Proposition 4 also shows that the optimal manufacturing policy is an order-up-to level s^*_1 when remanufacturing has no cost advantage over manufacturing. When the remanufacturing has a cost advantage, the manufacturing quantity is positive only if two conditions simultaneously hold: $y_0 \le s^*_1$ and $q_r^{(m)} > \min\{q_r^{(r)}, x_1\}$.

Define function $S_{\xi 2}(y)$ in an implicit way such that

$$\int_0^1 \Pi'(S_{\xi 2} t + y) t g_\xi(t) dt = c_r - h_1. \quad (19)$$

It is obvious that $S_{\xi 2}(y)$ is a decreasing function of y, and $q_r^{(r)} = S_{\xi 2}(0)$. Recall that $S_{\xi 1}(y)$ and $S_{\xi 2}(y)$ represent the optimal remanufacturing quantities when the inventory level of finished products is y in the sequential and parallel remanufacturing/manufacturing case, respectively. We have the following results.

Corollary 3: 1) q^*_{r2} is increasing in x_1 and decreasing in y_0; q^*_{m2} is decreasing in x_1 and y_0. 2) $S_{\xi 2}(y) \le S_{\xi 1}(y)$. 3) For any given x_1 and y_0, $q^*_{r2} \le q^*_{r1}$.

Corollary 3 indicates that the optimal remanufacturing quantity is decreasing in the initial inventory level of finished products and increasing in the on-hand inventory level of used products after acquisition, which is similar to the result in the sequential remanufacturing/manufacturing case. Furthermore, the manufacturing quantity is decreasing in both inventory levels. An interesting result is that for any given inventory levels x_1 and y_0, the remanufacturing quantity in the parallel remanufacturing/manufacturing case is no more than that in the sequential remanufacturing/manufacturing case, which illuminates the effect of expediting the remanufacturing process. That is, the earlier release of yield realization helps the firm to more effectively benefit from the remanufacturing option, which is a cheaper way to satisfy the demand compared to manufacturing.

B. Optimal Acquisition Pricing Policy

Let $\widehat{\pi_3}(x_1|y_0) = \max_{0 \le q_r \le x_1, 0 \le q_m} \widehat{\pi_2}(q_r, q_m | x_1, y_0)$. Given the initial inventory levels x_0 and y_0, the problem is to choose the optimal acquisition price to maximize the following profit function:

$$\max_{f \in [\underline{f}, \overline{f}]} \widehat{\pi_4}(f | x_0, y_0) = \{E_\varepsilon[\widehat{\pi_3}(R(f) + x_0 | y_0) - (f + c_t) \cdot R(f)]\}. \quad (20)$$

Lemma 5: $\widehat{\pi_3}(x_1|y_0)$ is a concave function of x_1, for any given y_0.

Lemma 5 shows that the concavity property is preserved for the expected profit function after acquisition, which enables us to provide the following results on the used product acquisition decision.

Proposition 5: The optimal acquisition price, f^*_2, is unique and is characterized as follows:

1) If $c_m \le (c_t + c_r)/\mu$, or $-S_{\xi 2}(y_0 + q^*_m(y_0)) + x_0 \ge 0$, then $f^*_2 = \underline{f}$;

2) If $c_m > (c_r - h_1)/\mu$ and $-S_{\xi 2}(y_0 + q^*_m(y_0)) + x_0 < 0$, then f^*_2 is the solution to

$$\int_0^{+\infty} \widehat{\pi_3}'(r(f)t + x_0 | y_0) t g_\varepsilon(t) dt = \frac{r(f)}{r'(f)} + c_t + f \quad (21)$$

in the case of $R(f) = r(f) \cdot \varepsilon$, and is the solution to

$$\int_{-\infty}^{+\infty} \widehat{\pi_3}'(r(f) + t + x_0 | y_0) g_\varepsilon(t) dt = \frac{r(f)}{r'(f)} + c_t + f \quad (22)$$

in the case of $R(f) = r(f) + \varepsilon$.

Proposition 5 characterizes the optimal acquisition price decision, given the initial inventory levels of finished and used products. Define $l_2(x_0, y_0) = x_0 - S_{\xi 2}(y_0 + q^*_m(y_0))$. According to Corollary 3, $y_0 + q^*_m(y_0)$ is increasing in y_0, although $q^*_m(y_0)$ is decreasing in y_0. Thus, $l_2(x_0, y_0)$ is an increasing function of x_0 and y_0 (and linearly increasing in x_0). Proposition 5 indicates that the firm should activate the acquisition only if two conditions are satisfied. The first condition guarantees the cost advantage of acquisition/remanufacturing over manufacturing: $(c_r + c_t)/\mu \le c_m$, which is the same as the sequential remanufacturing/manufacturing case. The second condition requires that the initial inventory levels should be low enough: $l_2(x_0, y_0) < 0$, or equivalently, $\int_0^1 \Pi'(x_0 t + y_0 + q^*_m(y_0)) t g_\xi(t) dt > c_r - h_1$.

Corollary 4: 1) f^*_2 is decreasing in x_0 and y_0; 2) $f^*_2 \le f^*_1$.

Corollary 4 indicates that the optimal acquisition price is decreasing in the initial inventory levels of used and finished products. It is intuitive because an increase in either inventory level will depress the need for collecting used products. Moreover, for the same initial inventory levels, the acquisition price in the parallel remanufacturing/manufacturing case is less than or equal to that in the sequential remanufacturing/manufacturing case. Note that when the acquisition/remanufacturing does not have a cost advantage over the manufacturing, the acquisition channel is not activated in either sequential or parallel process case. Thus, the difference between the two cases occurs if and only if the acquisition/remanufacturing is economically advantageous. Furthermore, since $S_{\xi 1}(y_0) \geq S_{\xi 2}(y_0) \geq S_{\xi 2}(y_0 + q_m^*(y_0))$, we obtain $l_1(x_0, y_0) \leq l_2(x_0, y_0) < 0$. This shows that on the initial inventory map of used product and finished product, the nonacquisition region of Model 2 contains the nonacquisition region of Model 1, which implies that the acquisition channel is more frequently used when the remanufacturing/manufacturing decisions are made sequentially. Combined with Corollary 4, we draw the conclusion that prompt remanufacturing economically helps the firm through a better use of the used product acquisition as well as the remanufacturing option, but only when it has a cost advantage over the manufacturing option.

We summarize the optimal policy for the case of slow manufacturing as follows.

Optimal Policy of Model 2: In the parallel remanufacturing/manufacturing case, the optimal acquisition, remanufacturing, and manufacturing decisions are determined by two critical values s_1^*, s_2^* defined in (4) and (8), respectively, the critical functions $q_m^*(y), q_r^*(y)$ defined in Lemma 4, and $S_{\xi 2}(\cdot)$ defined in (19). If the acquisition/remanufacturing has a cost advantage $(c_r + c_t)/\mu \leq c_m$ and the initial inventories satisfy $l_2(x_0, y_0) = x_0 - S_{\xi 2}(y_0 + q_m^*(y_0)) < 0$, the firm should activate the acquisition channel with an acquisition price characterized by (21) or (22); otherwise, the firm should never collect used products. If remanufacturing has a cost advantage $(c_r - h_1)/\mu \leq c_m$ and the initial finished product inventory y_0 is lower than s_2^*, the firm should follow an order-up-to remanufacturing policy defined by the function $q_r^*(y_0)$; otherwise, the firm should never remanufacture. The firm should never manufacture if the initial finished product inventory y_0 is more than s_2^*, and should adopt an order-up-to level s_1^* policy as the manufacturing policy if remanufacturing does not have a cost advantage (i.e., $(c_r - h_1)/\mu > c_m$) and y_0 is lower than s_2^*; in other cases, the optimal manufacturing quantity has no simple analytic expression (the solution is prescribed in Proposition 4 and can be numerically solved).

VI. Special Cases and Applications

A. Special Case 1: Deterministic Yield

Consider a special case when the remanufacturing yield is deterministic, i.e., $Pr(\xi = \mu) = 1$. This is an important case since in practice the remanufacturing yield can be regarded as fixed under some scenarios. For instance, when a sorting procedure is implemented at the collection site, the firm can ensure a steady input quality into its remanufacturing process. As the remanufacturing uncertainty is eliminated in this case, Model 1 and Model 2 coincide. We have the following results for this special case.

Corollary 5: 1) If $c_m < (c_r - h_1)/\mu$ and $Pr(\xi = \mu) = 1$, then the optimal manufacturing and remanufacturing quantities are

$$(q_m^*, q_r^*) = \begin{cases} (s_1^* - y_0, 0), & \text{if } y_0 \leq s_1^* \\ (0, 0), & \text{if } y_0 > s_1^* \end{cases} \tag{23}$$

2) If $c_m \geq (c_r - h_1)/\mu$ and $Pr(\xi = \mu) = 1$, then the optimal manufacturing and remanufacturing quantities are

$$(q_m^*, q_r^*) = \begin{cases} (0, 0), & \text{if } y_0 \geq s_2^* \\ \left(0, \dfrac{s_2^* - y_0}{\mu}\right), & \text{if } y_0 + x_1\mu \geq s_2^* > y_0 \\ (0, x_1), & \text{if } s_2^* > y_0 + x_1\mu \geq s_1^* \\ (s_1^* - y_o - x_1\mu, x_1), & \text{if } s_1^* > y_0 + x_1\mu \end{cases} \tag{24}$$

where s_1^* and s_2^* are defined in (4) and (8), respectively. That is, the optimal policy is to first remanufacture up to level s_2^* and then to manufacture up to level s_1^*.

Corollary 5 characterizes the optimal remanufacturing and manufacturing quantities for given on-hand inventory levels of used and finished products. Compared to the case of random remanufacturing yield, the remanufacturing/manufacturing policy is considerably simplified in the case of deterministic yield. When the remanufacturing has a cost advantage, the optimal policy is to first remanufacture up to level s_2^* and then to manufacture up to level s_1^*. Note that $s_2^* \geq s_1^*$, and hence, the manufacturing is in fact never activated unless the quantity of used products is not sufficient. When the remanufacturing does not have a cost advantage, the firm should never remanufacture and the optimal manufacturing policy is to produce up to level s_1^*.

Corollary 6: 1) If $c_m < (c_r + c_t)/\mu$ and $Pr(\xi = \mu) = 1$, then the optimal acquisition price is $f^* = \underline{f}$.

2) If $c_m \geq (c_r + c_t)/\mu$ and $Pr(\xi = \mu) = 1$, then the optimal acquisition price is

$$f^* = \begin{cases} \underline{f}, & \text{if } x_0\mu + y_0 \geq s_2^* \\ f_a^*, & \text{if } s_2^* > x_0\mu + y_0 > s_1^* \\ f_b^*, & \text{if } s_1^* \geq y_0 + x_0\mu \end{cases} \tag{25}$$

in which f_a^* is characterized in the case of $R(f) = r(f) \cdot \varepsilon$ by

$$\int_0^{\frac{s_2^* - y_0 - \mu x_0}{\mu r(f)}} [\Pi'(r(f)t\mu + x_0\mu + y_0) \cdot \mu - c_r] t g_\varepsilon(t) dt = \frac{r(f)}{r'(f)} + c_t + f \tag{26}$$

and in the case of $R(f) = r(f) + \varepsilon$ by

$$\int_{-\infty}^{\frac{s_2^* - y_0 - \mu x_0}{\mu} - r(f)} [\Pi'((r(f) + t + x_0)\mu + y_0) \cdot \mu - c_r] g_\varepsilon(t) dt = \frac{r(f)}{r'(f)} + c_t + f \tag{27}$$

while f_b^* is characterized in the case of $R(f) = r(f) \cdot \varepsilon$ by

$$\int_{\frac{s_1^* - y_0 - \mu x_0}{\mu r(f)}}^{\frac{s_2^* - y_0 - \mu x_0}{\mu r(f)}} [\Pi'(r(f)t\mu + x_0\mu + y_0) \cdot \mu - c_r] t g_\varepsilon(t) dt + \int_0^{\frac{s_1^* - y_0 - \mu x_0}{\mu r(f)}} (c_m\mu - c_r) t g_\varepsilon(t) dt = \frac{r(f)}{r'(f)} + c_t + f \tag{28}$$

and in the case of $R(f) = r(f) + \varepsilon$ by

$$\int_{\frac{s_1^*-y_0-\mu x_0}{\mu}-r(f)}^{\frac{s_2^*-y_0-\mu x_0}{\mu}-r(f)} [\Pi'((r(f)+t+x_0)\mu + y_0)\cdot \mu - c_r] g_\varepsilon(t)dt + \int_{-\infty}^{\frac{s_q^*-y_0-\mu x_0}{\mu}-r(f)} (c_m\mu - c_r) g_\varepsilon(t)dt = \frac{r(f)}{r'(f)} + c_t + f. \quad (29)$$

Corollary 6 indicates that both of the two critical trajectories indicating whether the acquisition channel should be activated, i.e., $l_1(x_0, y_0) = 0$ and $l_2(x_0, y_0) = 0$, degenerate to the same trajectory $x_0\mu + y_0 = s_2^*$, when the remanufacturing yield is deterministic. It is noteworthy that the left side of this equation is a simple, linear function of the initial inventories of used and finished products, and the weighting coefficient on the used product inventory is exactly the deterministic yield. The right side of this equation is a crucial value that has been defined in the previous section. It also implies that under the perfect yield scenario, i.e., $\mu = 1$, the initial inventories of used products and finished products have a symmetric status in determining whether the acquisition channel should be activated.

B. Special Case 2: Newsvendor Setting

When the firm faces a random demand D for the finished products in a newsvendor type setting, we have $\Pi(y) = pE\min(D, y) - h_2E(y - D)^+$, in which the selling price p and the leftover holding cost h_2 are exogenous parameters. This newsvendor-type scenario is common in both remanufacturing industry and research literature, e.g., [10], [27], [29], and [38]. Let g_D and G_D be the PDF and CDF of Demand D. In this case, Assumption 2 in Section III-A is equivalent to the following assumption.

Assumption 3: $p > \max[c_m, c_r + c_t] > \min[c_m, c_r - h_1] > -h_2$.

Therefore, under Assumption 3, all the previous results in Sections IV and V hold. In particular, the critical functions $(q_r^*(y_0), q_m^*(y_0))$ are characterized by

$$\begin{cases} E_\xi\{G_D(y_0 + q_r\xi + q_m)\} = \dfrac{p - c_m}{p + h_2} \\ E_\xi\{G_D(y_0 + q_r\xi + q_m)\varepsilon\} = \dfrac{p\mu - c_r + h_1}{p + h_2}. \end{cases} \quad (30)$$

In addition, $\{q_m^{(m)}, q_r^{(m)}, q_m^{(r)}, q_r^{(r)}\}$ are characterized by

$$\begin{cases} G_D(y_0 + q_m^{(m)})\} = \dfrac{p - c_m}{p + h_2} \\ E_\xi\{G_D(y_0 + q_r^{(m)}\xi)\} = \dfrac{p - c_m}{p + h_2} \\ G_D(y_0 + q_m^{(r)}) = \dfrac{p - (c_r - h_1)/\mu}{p + h_2} \\ E_\xi\{G_D(y_0 + q_r^{(r)}\xi)\xi\} = \dfrac{p\mu - c_r + h_1}{p + h_2}. \end{cases} \quad (31)$$

We can also express s_1^*, s_2^*, l_1, and l_2 as follows.

Corollary 7: For the newsvendor setting, we have $s_1^* = G_D^{-1}(\frac{p-c_m}{p+h_2})$, $s_2^* = G_D^{-1}(\frac{p-(c_r-h_1)/\mu}{p+h_2})$

$$l_1(x_0, y_0) = 0 \Leftrightarrow c_r - h_1 - \int_0^{\frac{s_1^*-y_0}{x_0}} c_m t g_\varepsilon(t)dt - \int_{\frac{s_1^*-y_0}{x_0}}^1 [p - (p + h_2)G_D(t)] t g_\xi(t)dt = 0 \quad (32)$$

$$l_2(x_0, y_0) = 0 \Leftrightarrow c_r - h_1 - p\mu + (p + h_2) \times \int_0^1 G_D(x_0t + y_0 + q_m^*(y_0)) t g_\xi(t)dt = 0. \quad (33)$$

Our model also fits in the situation where the firm is a price-setting newsvendor, i.e., the firm faces the problem of determining market price p to maximize the expected revenue

$$\Pi(y) = \max_{p\geq 0}\{pE\{\min[D(p), y]\} - h_2E[y - D(p)]^+\}. \quad (34)$$

Assumption 4: Demand D has a multiplicative form $D(p) = d(p)\cdot\rho$, where ρ is a positive random variable with an increasing generalized failure rate on its support, and $d(p)$ satisfies the following conditions for $p \in (0, P^u)$:

1) $d(p)$ is positive and strictly decreasing;
2) $\lim_{p\to P^u} pd(p) = 0$;
3) The elasticity $\eta(p) = -p\frac{d'(p)}{d(p)}$ is increasing;
4) $\frac{p}{\eta(p)}$ is monotone and convex; and
5) $p(1 - \frac{1}{\eta(p)})$ is strictly increasing.

It is suggested by Song *et al.* [41] that $\Pi(y)$ is a concave and increasing function if Assumption 4 is satisfied. Hence, Assumption 4 plus some appropriate boundary conditions will guarantee that our previous results can be applied.

VII. Numerical Experiments

We conducted numerical experiments to study the impact of system parameters, and to further compare the two cases of sequential and parallel remanufacturing/manufacturing processes. In the experiments, we supposed that all items in the finished product inventory are to satisfy a random demand D, with selling price p and leftover holding cost h_2. That is, we set the revenue function as a newsvendor type, $\Pi(y) = pE\min(D, y) - h_2E(y - D)^+$. In addition, we used the multiplicative acquisition form $R(f) = r(f)\cdot\varepsilon$ and set the acquisition quantity as $r(f) = \alpha + \beta f$ (the additive form could also be used with similar results obtained). The base parameters were set as $x_0 = 0, y_0 = 0, c_r = 3, c_m = 10, h_1 = 1, h_2 = 2, c_t = 0, p = 20, \alpha = 0, \beta = 5, \underline{f} = 0$, and $\overline{f} = 10$. We assumed that random variables D, ξ, and ε follow the uniform distributions U(0,100), U(0.3,0.7),[5] and U(0.7,1.3). The parameters were set to avoid cases such as $f^* = \underline{f}$ or $q_r^* = 0$, in which the two cases coincide and no insights can be provided for us. We also used $\Delta = (\pi_1^* - \pi_2^*)/\pi_2^*$ to denote the value of expediting the remanufacturing process.

[5]We fix the mean of random yield to 0.5 to observe the impact of the yield variance. However, it can be easily scaled to other values since we use the uniform distribution.

TABLE III
EFFECT OF THE REMANUFACTURING YIELD UNCERTAINTY VAR(ξ)

	Sequential Processes		Parallel Processes		
ξ	f_1^*	π_1^*	f_2^*	π_2^*	Δ
$U(0.4, 0.6)$	1.1	246.75	1.0	240.53	2.58%
$U(0.3, 0.7)$	1.1	243.46	1.0	236.21	3.07%
$U(0.2, 0.8)$	1.1	242.36	1.0	234.74	3.25%
$U(0.1, 0.9)$	1.0	241.81	0.9	233.97	3.35%
$U(0, 1)$	1.0	241.49	0.9	233.48	3.43%

TABLE IV
EFFECT OF THE ACQUISITION UNCERTAINTY VAR(ε)

	Sequential Processes		Parallel Processes		
ε	f_1^*	π_1^*	f_2^*	π_2^*	Δ
$U(0.9, 1.1)$	1.1	245.72	1.0	237.80	3.33%
$U(0.7, 1.3)$	1.1	243.45	1.0	236.08	3.07%
$U(0.5, 1.5)$	1.1	242.21	1.0	235.53	2.84%
$U(0.3, 1.7)$	1.0	241.69	0.9	235.20	2.76%
$U(0.1, 1.9)$	1.0	241.35	0.9	235.01	2.70%

TABLE V
EFFECT OF THE REMANUFACTURING COST c_r

	Sequential Processes		Parallel Processes		
c_r	f_1^*	π_1^*	f_2^*	π_2^*	Δ
1	2.1	259.81	1.9	250.62	3.67%
1.5	1.8	254.72	1.7	246.11	3.50%
2	1.6	250.30	1.5	242.20	3.35%
2.5	1.3	246.55	1.2	238.91	3.20%
3	1.1	243.46	1.0	236.21	3.07%

We varied the variance of ξ, the variance of ε, and the values of c_r and c_t, respectively, to observe the effects of these important parameters. The results are shown in Tables III– VI.

The numerical examples verify the main results from the analysis of the two cases of manufacturing/remanufacturing sequence, of which the sequential processes yield a higher acquisition price and a better system performance. The following managerial insights are also obtained.

First, Table III shows that as the variance of remanufacturing yield increases, the optimal acquisition prices decrease in both sequential and parallel manufacturing/remanufacturing cases. This implies that the firm tends to lower the acquisition price to mitigate the risk as the uncertainty in the remanufacturing process increases. On the other hand, the value of expediting the remanufacturing process is increasing in the variance of remanufacturing yield. This implies that the firm should be willing to exert additional effort to expedite the remanufacturing process when the quality of used product becomes more variant.

TABLE VI
EFFECT OF THE ACQUISITION COST c_t

	Sequential Processes		Parallel Processes		
c_t	f_1^*	π_1^*	f_2^*	π_2^*	Δ
0	1.1	243.46	1.0	236.21	3.07%
0.3	0.9	241.97	0.8	234.88	3.02%
0.6	0.8	240.71	0.7	233.77	2.97%
0.9	0.6	239.68	0.5	232.88	2.92%
1.2	0.5	238.86	0.4	232.21	2.86%

Second, Table IV shows that as the variance of acquisition quantity increases, the optimal acquisition prices decrease in both sequential and parallel manufacturing/remanufacturing cases. This implies that the firm tends to lower the acquisition price to mitigate the risk as the uncertainty in the acquisition process increases. Similarly, the value of expediting the remanufacturing process is decreasing with the variance of acquisition quantity. This implies that the firm should be willing to exert additional effort to expedite the remanufacturing process when the acquisition quantity of used product becomes less variant.

Finally, Tables V and VI show that the acquisition prices are decreasing with the remanufacturing cost and the acquisition cost, in both sequential and parallel manufacturing/remanufacturing cases. This implies that raising these costs will discourage the firm from acquiring and remanufacturing used products. On the other hand, the value of expediting the remanufacturing process is also decreasing in the remanufacturing and acquisition costs. This implies that the firm should be willing to exert additional effort to expedite the remanufacturing process when the acquisition and remanufacturing costs become lower, in which the advantage of acquisition and remanufacturing over manufacturing is more prominent.

VIII. CONCLUSION

As an environmentally friendly and cost-effective approach, remanufacturing requires used products to be acquired and reprocessed. This paper considers a hybrid remanufacturing/manufacturing system with a market-driven acquisition channel, in which the acquisition quantity of used products is stochastic and sensitive to the acquisition price. Our work also considers a random yield in the remanufacturing process, which represents the uncertainty in the quality of acquired used products. We show how the firm should carefully evaluate the initial inventories of used product and finished product, and effectively coordinate the decisions on the acquisition price, remanufacturing, and manufacturing quantities.

We investigate two particular cases: When the remanufacturing is prompt, the firm determines the acquisition price, remanufacturing quantity, and manufacturing quantity sequentially; when the remanufacturing is slow, the firm chooses the acquisition price first, and then determines the remanufacturing quantity and manufacturing quantity simultaneously. We formulate a stochastic dynamic program for each case, and develop the optimal policy for used product acquisition and remanufacturing/manufacturing. Through a thorough analysis of the optimal policies, we make the following observations.

1) The premise of activating the acquisition is its cost advantage over manufacturing, which is characterized by $c_r + c_t < \mu c_m$. Another condition to activate the acquisition is that both initial inventories of used product x_0 and finished product y_0 are adequately low, which is characterized by some critical values and functions derived in this paper. This condition is different for the cases of sequential and parallel remanufacturing/manufacturing, unless the remanufacturing yield is a constant μ, for which the condition becomes $x_0\mu + y_0 < s_2^*$.

2) The premise of activating the remanufacturing is its cost advantage over manufacturing, which is characterized by $c_r - h_1 < \mu c_m$. Another condition to activate the remanufacturing is that the finished product y_0 is lower than some critical value derived in our paper. This condition is the same for the cases of sequential and parallel remanufacturing/manufacturing.

3) Both the acquisition price and the remanufacturing quantity in the sequential manufacturing/remanufacturing case are no less than those in the parallel process case, which indicates that expediting the remanufacturing can effectively help the firm to make a better use of both acquisition and remanufacturing options.

4) The optimal acquisition prices are decreasing in the variances of acquisition quantity and remanufacturing yield, which implies that the firm tends to lower the acquisition price to mitigate the risk as the uncertainties in used product acquisition and remanufacturing increase. On the other hand, the value of expediting the remanufacturing process is increasing in the variance of remanufacturing yield while decreasing in that of acquisition quantity, which implies that the firm should be willing to exert more effort to expedite the remanufacturing process when the quality of used product becomes more variant and the quantity of used product becomes less variant.

Based on a survey we gave to several managers from different industries who are concerned with remanufacturing/manufacturing decisions, we find that the results and insights provided in this paper can be useful in practice. (The survey results can be found in the supplementary material of this paper.)

Our work is among the first efforts to provide insights into the structure of an optimally coordinated acquisition and production policy for a hybrid system under a stochastic acquisition and remanufacturing environment. Considering the problem complexity in our single-period setting, it is not difficult to surmise that in a multiperiod situation the optimal policy structure could be extremely complicated. In this regard, our results can be used as a heuristic policy for such dynamic settings. Nevertheless, developing a more appropriate and efficient heuristic policy for the multiperiod problem is still an important direction for future research and can also be useful in practice. One can also extend the model into a situation where a third party is responsible for collecting used items. In such a situation, the firm also needs to provide enough incentives for the third-party to operate the acquisition channel in a way that is beneficial to the firm. The design of such incentive schemes is another important direction for future research.

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