Effects of Random Yield in Remanufacturing with Price-Sensitive Supply and Demand

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In this study, we investigate the effects of recovery yield rate on pricing decisions in reverse supply chains. Motivated by the automotive parts remanufacturing industry, we consider an end-of-life product from which a particular part can be recovered and remanufactured for reuse, and the remainder of the product can be recycled for material recovery. Both the supply of end-of-life products and demand for remanufactured parts are price-sensitive. Yield of the recovery process is random and depends on the acquisition price offered for the end-of-life products. In this setting, we develop models to determine the optimal acquisition price for the end-of-life products and the selling price for remanufactured parts. We also analyze the effects of yield variation to the profitability of remanufacturing, benefits of delaying pricing decisions until after yield realization, and value of perfect yield rate information.

Key words: remanufacturing; pricing; random yield; value of information

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1. Introduction
The automotive industry is one of the largest sectors of the United States economy, and each year thousands of vehicles are retired. Some vehicles are towed to salvage yards by their owners when they reach the end of their useful lives. Other vehicles are impounded and discarded by law enforcement agencies. The vehicles that are damaged in car accidents may be claimed to be beyond repair and wrecked by insurance agencies. As automobiles are durable products that are designed and manufactured for durability, majority of these end-of-life vehicles (particularly those impounded by the law enforcement agencies and those wrecked by the insurance industries) may still have some recoverable economic value associated with them. Therefore, automotive parts remanufacturing is a popular practice that has evolved into a major industry sector in the United States.

A closer examination of the automotive parts remanufacturing industry reveals that in addition to the original equipment manufacturer (OEM) and its (new/remanufacturing) part suppliers, there are several major players independent of the OEM, including salvage yards (end-of-life vehicle dismantlers), remanufacturable part brokers, and independent automotive part remanufacturers (Ferrer and Whybark 2001). We use the term independent automotive part remanufacturer in the broadest sense to include large firms that specialize in the remanufacturing of a particular automotive part and small engine repair shops that remanufacture a variety of parts for their customers. Typically, the salvage yards dismantle the end-of-life vehicles (ELVs) to harvest the reusable parts and sell them to automotive parts remanufacturers directly or via part brokers. The remanufacturers restore these parts into operating condition by cleaning, replacing, and refabricating some or all components of the part, and sell them as replacement service parts for vehicles that are still in use.

Recognizing the lucrative business potential associated with ELV dismantling and automotive parts remanufacturing, Ford decided to enter the business of automotive recycling. To this end, Ford purchased several automotive salvage yards and parts recycling companies, and unified them under the name Green-Leaf LLC (McCann 2003, Recycling Today Online...
2002). Ford also acquired Kwik-Fit, a European automotive maintenance and light repair business, in 1999, as well as Collision Team of America, a chain of collision repair centers in North America, between 1998 and 2001 (Autoparts 2002, BBC News 1999). Several industry observers' predictions that “Ford’s inexperience in the specialized world of automotive salvage would be a hindrance” were validated when Ford admitted that entering automotive recycling “was a poor business decision” (Recycling Today Online 2002). Industry observers said that “Experienced salvage and dismantling facility operators are careful not to overpay for ELVs purchased at auctions and from insurance companies. This may have been a problem for GreenLeaf (Recycling Today Online 2002).” In support of this argument, James L. Richardson, Heritage 2000 Manager at Ford, said that “The value of materials we were buying just was not there” (Recycling Today Online 2002).” In a major restructuring effort, Ford sold all three businesses between 2002 and 2003, and abandoned the recycling and remanufacturing business (Autoparts 2002; BBC News 2002; McCann 2003). Ford’s experience in the automotive recycling and parts remanufacturing highlights the importance of pricing decisions in the remanufacturing business.

This paper investigates pricing decisions made by an integrated automotive dismantling and parts remanufacturing firm (similar to GreenLeaf LLC) that has the pricing power in both the ELV supply and remanufactured parts demand markets. However, an automotive parts dismantling firm who buys ELVs and sells remanufacturable parts faces the same supply and demand pricing decisions. Similarly, an automotive parts remanufacturing firm who buys remanufacturable parts from salvage yards and/or parts brokers (rather than purchasing ELVs for dismantling) and sells remanufactured parts, as well as an automotive parts broker who buys remanufacturable parts from salvage yards and sells them to automotive parts remanufacturing firms, encounters the same pricing decisions. Therefore, our investigation applies to a number of different agents that operate under different settings in the automotive recycling and parts remanufacturing industry. In some settings, however, the firm may not have the power to set prices in both the supply and demand markets, i.e., either the ELV purchasing or the remanufactured part selling price may be exogenous. We consider such settings in our investigation as well. We also note that the setting we consider pertains to the processing of older generation vehicles. That is, the ELVs to be processed are around eight to fifteen years old, of which there is still a considerably sized population of vehicles in use that may need service parts for repair, and for which the OEM has already moved out of the service parts market, i.e., does not provide new or remanufactured supplier parts at reasonable prices.

In our work, we refer to the integrated automotive dismantling and parts remanufacturing firm as the remanufacturer. The remanufacturer specifies both the acquisition price for the ELVs and the selling price for the remanufactured parts. The supply of ELVs available to the firm is price-sensitive, i.e., it can be increased by offering a higher acquisition price. Moreover, the demand for the remanufactured part is also price-sensitive, i.e., it can be increased by offering a lower selling price. An important parameter that further complicates these decisions is the recovery yield. Fraction of parts that are remanufacturable is typically random, and may be dependent on the acquisition price in some cases.

In our study, we develop models to support the acquisition and sales pricing decisions we have discussed above and investigate the effects of random recovery yield on these decisions. We consider three different models. In the first model, the yield is deterministic, i.e., the remanufacturer knows the percentage of the ELVs with remanufacturable parts in advance. This model serves as a benchmark for the cases where the yield is random. In the second model, yield is random, and the remanufacturer has the opportunity to set the price of the remanufactured part after the realization of random yield. In the last model, however, both the acquisition price of the ELVs and the price of the remanufactured parts are to be determined simultaneously prior to the realization of random yield. We investigate the differences between these models and assess the value of postponed sales pricing opportunity to the remanufacturer.

These cases we consider are motivated from real-life applications in automotive parts remanufacturing. Some remanufacturers purchase ELVs at auctions. Once the parts are recovered and yield is realized, the remanufacturer sets the price for the remanufactured parts and sells them. This application is captured in our second model. In some cases, however, a part buyer contacts a remanufacturer requesting a particular part and the remanufacturer and buyer agree on the selling price. Then, the remanufacturer may have to purchase ELVs to satisfy the demand. If the yield is not enough to satisfy the demand, then the remanufacturer is still bound by the price decision made a priori, and may have to incur a penalty cost for the unsatisfied demand. This case corresponds to the third model in our analysis.

Although our work is primarily motivated by automotive parts remanufacturing, product cannibalization to recover the inherent value of some parts in end-of-life products is encountered in other industries, including computers and cellular phones. Therefore, we believe that our results can provide insights to a
number of sectors in remanufacturing. The rest of the paper is organized as follows. In the next section, we discuss the literature and contribution of this work. We introduce our assumptions and models in Section 3. Section 4 is devoted to the comparative analysis of the models and effects of random yield on pricing decisions. In Section 5, we analyze the value of perfect yield information and effects of various parameters on the value of information. We summarize our findings and suggest further research directions in Section 6.

2. Related Literature

Due to the increasing popularity of product recovery, there is a considerable body of literature on closed-loop (or reverse) supply chains. We refer the reader to several comprehensive reviews for a broad overview of the field. Fleischmann et al. (1997, 2000) provide a thorough review of quantitative models for reverse logistics. Gungor and Gupta (1999) provide an extensive review on environmentally conscious manufacturing and product recovery. Guide (2000) provides an insightful review by identifying major complicating characteristics in remanufacturing systems and proposes research directions. For the most recent developments in the field, we refer the reader to Guide and Van Wassenhove (2003) and Dekker et al. (2004).

This paper mainly focuses on the effects of random yield on pricing decisions and assesses the value of yield information in a remanufacturing environment. Hence, it is closely related to product acquisition management and models that evaluate the value of information in the context of reverse logistics. Yano and Lee (1995) provide an illustrative review of lot-sizing models with random yields. Examples of more recent studies are Hsu and Bassok (1999), Bollapragada and Morton (1999), Gurnani et al. (2000), and Kazaz (2004). The reader may also refer to Grosfeld-Nir and Gerchack (1999), Gurnani et al. (2000), and Kazaz (2004). The reader may also refer to Grosfeld-Nir and Gerchack (2002) for a review on multiple lot-sizing in production to order systems.

3. Model Description and Analysis

In our analysis, we consider a remanufacturer that acquires ELVs from final owners, and sells remanufactured parts that are recovered from the ELVs in the secondary parts market.

The supply of ELVs is a deterministic, linear function of the acquisition price, \( f \), paid to the final user of the product and can be modelled as \( S(f) = \alpha + \beta f \), where \( \alpha, \beta > 0 \). Note that \( f \) may be negative or positive depending on the final properties of the product. An ELV may have several remanufacturable parts, but, in this paper, we will focus on a single part. This is due to the fact that automotive part manufacturers typically specialize in the remanufacturing of a particular part, such as the transmission or the engine. After
ELVs are purchased, they are inspected to check whether the part satisfies quality limits, i.e., it is remanufacturable. Inspection and testing operations up to this point cost the firm $c$ per unit.

The percentage of the parts that conforms to the quality specifications is a random variable which is also dependent on the acquisition price. Parts that are not remanufacturable or not remanufactured as well as the body of the vehicle without the part (which we refer to as the hulk) are salvaged by selling them to a material recycler, who recovers the valuable, recyclable material in the part and the hulk. A part can be salvaged at a unit price of $s$ per part. Similarly, a hulk can be salvaged at a unit price of $h$ per hulk. We note that the salvage value of the part is the same regardless of its quality (i.e., whether it is remanufacturable or not) since the salvage value is proportional to the recyclable material content. We assume that the parts that satisfy the requirements are homogeneous, i.e., they can be remanufactured to the same quality level incurring the same unit cost, $c'$. As we have discussed in the introduction, the remanufacturer can set the price that maximizes his own profit as some kind of monopolist, i.e., the vehicle owner does not have an alternative source for the remanufactured part. Therefore, we assume that the demand for remanufactured parts in the secondary market can be modelled using a deterministic linear function of the selling price, denoted by $D(p) = a - bp$, where $a, b > 0$. The material flow in the problem environment we consider is depicted in Figure 1.

Table 1 summarizes the parameters used throughout the study. The condition of the ELVs in the final owner market is captured by the random variable $R$ with a probability distribution function (p.d.f.) $g(r)$, and cumulative distribution function (c.d.f.) $G(r)$. As the remanufacturer increases the acquisition price, ELVs in better condition will be available to the firm, which in turn may be interpreted as higher probability of obtaining a remanufacturable part from the ELV. This argument is handled by the function $t(f)$ in our model. Yield rate is modelled as the product of $R$ and $t(f)$. $t(f)$ is a concave, nondecreasing function of $f$ and converges to 1 as $f$ increases. In other words, random variable $R$ denotes the maximum attainable yield rate.

This modeling framework remains valid for an automotive parts remanufacturing firm who buys parts from salvage yards and/or parts brokers, and remanufactures the parts. In this case, we have $h = 0$, which has no impact on model analysis. Similarly, the modeling framework can represent the operating environment of a parts broker, who purchases parts from salvage yards and sells them to automotive parts remanufacturing firms. In this case, we have $c' = 0$, which also has no impact on model analysis. We briefly discuss the implications of both cases, that is $h = 0$ and $c' = 0$ at the end of Section 4.

3.1. Deterministic Pricing Model (DPM)

We first introduce the model where the percentage of ELVs with remanufacturable parts is deterministic, i.e., $R$ is no longer a random variable. The profit function of the firm for this case is

$$
\Pi(f, p) = (a - bp)(p - c') + (\alpha + \beta f)(h - f - c) + (1 - rt(f))(\alpha + \beta f)s + [rt(f)(\alpha + \beta f) - (a - bp)]^+s.
$$

Noting that the available supply of ELVs should be sufficient to cover the demand, and rearranging the terms, the pricing problem faced by the remanufacturer can be formulated as follows:

$$
\begin{align*}
\max_{f, p} \quad & (a - bp)(p - s - c') + (\alpha + \beta f)(h + s - f - c) \\
\text{subject to} \quad & (a - bp) \leq Rt(f)(\alpha + \beta f)
\end{align*}
$$

![Figure 1](image-url)
Objective function (1) maximizes the profit of the remanufacturer from the remanufactured part sales in the secondary parts market and hulk sales to the recycling market. Constraint (2) ensures that available supply of ELVs is enough to cover the demand for the remanufactured part. Optimal solution to this problem is characterized in Proposition 1.

**Proposition 1.** Optimal pricing decisions for DPM are as follows:

\[
(f^*, p^*) = \begin{cases} 
\left( \frac{K}{2 - \alpha/2\beta}, \frac{a - b(s + c)}{2} \right) & R \geq \frac{a - b(s + c)}{t(K/2 - \alpha/2\beta)(\alpha + \beta K)} \\
\left( f^0, \frac{a - R(f^0)(\alpha + \beta f)}{b} \right) & \text{otherwise}
\end{cases}
\]

where \( K = h + s - c \) and \( f^0 \) maximizes

\[
\Pi(f, p) = Rt(f)(\alpha + \beta f) \left( \frac{a - R(t(f)(\alpha + \beta f))}{b} - s - c' \right) + (\alpha + \beta f)(h + s - f - c)
\]

Proof. Deterministic pricing model is a concave maximization problem over a convex set in decision variables \( f \) and \( p \). Hence, either the solution that satisfies first order conditions is optimal or the constraint is binding. When \( R \geq (a - b(s + c'))/(t(K/2 - \alpha/2\beta)(\alpha + \beta K)) \), the optimal solution of the unconstrained problem satisfies the constraint. Otherwise, one of the variables can be expressed in terms of the other and the problem reduces to the maximization of a single variable function. The rest is straightforward algebra.

**Corollary 1.** Let \( r_0 = (a - b(s + cr))/[t(K/2 - \alpha/2\beta)(\alpha + \beta K)] \). If \( r_0 \leq 1 \), the profit of the remanufacturer is increasing in \( R \) until \( R = r_0 \) and remains constant thereafter. Otherwise, profit is strictly increasing in \( R \).

Proof. From Proposition 1, we can deduce that optimal remanufacturable supply exceeds optimal demand when \( R > r_0 \), i.e., the constraint is not binding. In this case, optimal decisions are independent of \( R \). Therefore, profit does not change in \( R \). On the other hand, when \( R < r_0 \), the constraint is binding. Increasing yield rate will result in an increase in the right hand side of the constraint and profit will increase.

**3.2. Postponed Pricing Model (PPM)**

In PPM, the remanufacturer has the opportunity to delay the determination of the selling price for the remanufactured parts until after the realization of the yield. In other words, the decision process consists of two stages. In the first stage, the acquisition price to be paid for ELVs is set and corresponding supply is collected. After the disassembly and inspection processes, i.e., the realization of the yield, selling price for the remanufactured parts is set and demand is observed. Note that the remanufacturer never faces lost sales since demand can always be adjusted through selling price to match with the number of remanufactured parts.

We begin the analysis with the second stage. Given the acquisition price, \( f \), and the realization of the maximum attainable yield rate, \( r \), second stage problem for the remanufacturer is to set the selling price to maximize his profits. In other words, she faces the following problem:

\[
\max_{r} (a - bp)(p - s - c') + (\alpha + \beta f)(h + s - f - c)
\]

subject to

\[
(a - bp) \leq rt(f)(\alpha + \beta f)
\]

Optimal solution to remanufacturer’s second stage problem is characterized in Proposition 2.

**Proposition 2.** Given the acquisition price and the realization of maximum attainable yield rate, the optimal selling price is

\[
p^* = \begin{cases} 
\frac{a + s + c'}{2b} \quad & r \geq \frac{k}{t(f)(\alpha + \beta f)} \\
\frac{a - rt(f)(\alpha + \beta f)}{b} \quad & r < \frac{k}{t(f)(\alpha + \beta f)}
\end{cases}
\]

where \( k = (a - b(s + cr))/2 \).

Proof. Second stage problem of the PPM is a concave maximization problem with a linear constraint. Hence, either the solution that satisfies first order conditions is optimal or the constraint is binding. When \( r \geq k/(t(f)(\alpha + \beta f)) \), the optimal solution of the unconstrained problem satisfies the constraint. Otherwise, sales pricing decision directly follows from the constraint.

We are now ready to analyze the first stage. Given the optimal selling price obtained from the second stage and the realization of the random yield, profit function becomes

\[
\Pi(f|R = r)
\]

\[
= \begin{cases} 
\frac{k^2}{b} + (\alpha + \beta f)(h + s - f - c) \quad & r \geq \frac{k}{t(f)(\alpha + \beta f)} \\
\frac{2k - t(f)r(\alpha + \beta f)}{b} \quad & r < \frac{k}{t(f)(\alpha + \beta f)}
\end{cases}
\]

\[
= \frac{t(f)r(\alpha + \beta f)}{b} + (\alpha + \beta f)(h + s - f - c)
\]

\[
+ (\alpha + \beta f)(h + s - f - c)
\]

\[
r \leq \frac{k}{t(f)(\alpha + \beta f)}
\]
Taking expectation with respect to $R$ yields

$$
E[\Pi(f)] = \int_{-\infty}^{\frac{k/(1-f(\alpha+bf))}{b}} \left[ (t(f)r(\alpha + bf) - 2k - t(f)r(\alpha + bf) + \frac{k^2}{b}g(r)dr + \frac{k^2}{b}g(r)dr + (\alpha + bf)(h + s - f - c) \right]
$$

As a result, the remanufacturer first sets the acquisition price for the ELVs optimizing her expected profit function (5) and collects the resulting supply of ELVs. After the realization of the random yield, selling price of remanufactured parts is set according to Proposition 2 and corresponding demand is realized.

Whether the expected profit (5) is concave or not depends on the characteristics of $t(f)$. If we assume $t(f) = (f + m)/(f + n)$ for $f \geq -m$ and 0 otherwise, and $n \geq m$, the resulting profit function is concave if $\alpha \geq n\beta$. For the cases where $\alpha < n\beta$, it is observed through a comprehensive numerical analysis that unimodality is preserved, although the function may no longer be concave.

### 3.3. Simultaneous Pricing Model (SPM)

In SPM, the remanufacturer has to determine the acquisition price for the ELVs and the selling price for the remanufactured parts simultaneously. Note that in such a case, the firm may incur penalty costs since the resulting yield may not cover the demand entirely.

Given any realization of the random yield, $R = r$, profit function of the remanufacturer is,

$$
\Pi(f, p|r) = \begin{cases} 
(a - bp)(p - s - c') + (\alpha + bf)(h + s - f - c) & r \geq \frac{a - bp}{t(f)(\alpha + bf)} \\
(t(f)r(\alpha + bf)(p - s - c') - v(a - bp - t(f)r(\alpha + bf)) + (\alpha + bf)(h + s - f - c) & r < \frac{a - bp}{t(f)(\alpha + bf)}
\end{cases}
$$

Taking expectation with respect to $R$ and rearranging the terms, we get

$$
E[\Pi(f, p)] = \int_{-\infty}^{\frac{a - bp}{t(f)(\alpha + bf)}} [rt(f)(\alpha + bf)(p + v - s - c') - v(a - bp)]g(r)dr + \int_{\frac{a - bp}{t(f)(\alpha + bf)}}^{\infty} [(a - bp) \quad (p - s - c')g(r)dr + (\alpha + bf)(h + s - f - c) \quad (6)
$$

As a result, the remanufacturer maximizes her expected profit function (6) over $f$ and $p$ simultaneously to solve the pricing problem.

In order to be able to use first derivatives to determine optimal prices, we need to show that the expected profit (6) is concave at the points where first derivatives are simultaneously zero. That is, to have pseudo-concavity of the expected profit, we should have (1) $\frac{\partial^2 E[\Pi(f, p)]}{\partial pf} < 0$; (2) $\frac{\partial^2 E[\Pi(f, p)]}{\partial f^2} \leq 0$; and (3) $H > 0$ at the points $(f, p)$ satisfying first order conditions, where $H$ denotes the Hessian matrix. For $t(f) = (f + m)/(f + n)$, it is trivial to show that condition (1) holds and condition (2) is satisfied when $\alpha \geq n\beta$, i.e., expected profit is pseudo-concave in its arguments separately. However, it is not that straightforward to claim the third condition. According to extensive computations utilizing different distribution functions and parameters, we conjecture that the profit function is pseudo-concave.

### 3.4. Special Cases: Exogenous Supply or Demand

Recall that the remanufacturer has the power to set both the acquisition price and the selling price. This also enables to control the supply and demand quantities. However, the remanufacturer may lack this power in certain settings. Hence, before analyzing the effects of random yield on the pricing decisions and the expected profit, we briefly discuss the cases where either the acquisition price or the selling price is exogenous.

#### 3.4.1. Exogenous Acquisition Price

When the remanufacturer is a price-taker in the supply market, i.e., $f$ is exogenous, she has no control on the quantity and the quality of the items supplied. Hence, without loss of generality we may assume that $t(f) = 1$, and the supply is not limited.

In PPM, following a similar analysis to Section 3.2, after observing the yield, the firm sets the selling price to

$$
p^* = \begin{cases} 
\frac{a + s + c'}{2b + \frac{2}{k/Q}} & r \geq \frac{k}{Q} \\
\frac{a - rQ}{b} & r < \frac{k}{Q}
\end{cases}
$$

where $k = (a - b(s + c'))/2$ and $Q$ is the quantity of used products acquired. After substituting the optimal selling price in the first stage problem, we obtain the expected profit function as follows:

$$
E[\Pi(Q)] = \int_{-\infty}^{\frac{k}{Q}} \left[ rQ\left(2k - rQ\right)g(r)dr + \int_{\frac{k}{Q}}^{\frac{k^2}{b}} g(r)dr + Q(h + s - f - c) \quad (7)
$$
Note that the only difference between Equation (5) and Equation (7) is that the term \( t(f)(\alpha + \beta f) \) in Equation (5) is replaced by \( Q \) in Equation (7). The firm now decides on the optimal supply quantity, \( Q \), by maximizing \( E[\Pi(Q)] \). Since \( E[\Pi(Q)] \) is concave, incorporating capacitated supply is straightforward. If the optimal quantity for the unconstrained problem is greater than the supply capacity, the firm sets the optimal quantity for the unconstrained problem is given by the market conditions, our models still apply.

In SPM, the firm has to decide on the order quantity and the selling price simultaneously, before the realization of yield rate. Similar to the analysis in Section 3.3, the expected profit in this case is

\[
E[\Pi(Q, p)] = \int_{-\infty}^{\infty} [rQ(p + v - s - c')] e^{-rt} dr + \int_{a-bp}^{\infty} [(a-bp)(v-d)] g(r) dr + \int_{a-bp}^{\infty} [(a-bp)(v-d)] g(r) dr + Q(h + s - f - c) \tag{8}
\]

The only difference between Equation (8) and Equation (6) is that the term \( t(f)(\alpha + \beta f) \) in Equation (6) is replaced by \( Q \) in Equation (8), as in the PPM case. As a result, we can conclude that both the PPM and the SPM are still valid when the acquisition price is determined by the market conditions, not the remanufacturer.

### 3.4.2. Exogenous Selling Price

We now consider the setting where selling price, \( p \), of the remanufactured parts is fixed. In such cases, demand is constant and deterministic, which is denoted by \( d \). Since the firm no longer has control on the selling price, PPM and SPM reduce to the same model, where the firm only sets the acquisition price. In this case, the expected profit function is as follows:

\[
E[\Pi(f)] = \int_{-\infty}^{\infty} \left[ rt(f)(\alpha + \beta f)(p + v - s - c') \right] e^{-rt} dr + \int_{a-bp}^{\infty} \left[ d(p - s - c')g(r)dr \right] + (\alpha + \beta f)(h + s - f - c) \tag{9}
\]

which is the same as the original SPM given in Section 3.3 except that \( p \) is no longer a decision variable. As a result, we can conclude that when the selling price is determined by the market conditions, our models still apply.

### 4. Computational Analysis

In this section, we analyze the effects of random yield on the pricing decisions of the remanufacturer and observe the differences in the profit levels generated by the models described in Sections 3.1 through 3.3.

Since it is not possible to obtain closed form solutions for our models, we carry out numerical experiments for our comparisons. Table 2 presents the data sets used throughout this section. Note that the only difference between the data sets is the unit salvage revenues for the hulk, \( h \), and the part, \( s \).

Recall that \( r_0 \) denotes the threshold yield rate, which, if less than one (i.e., \( r_0 < 1 \)), indicates that the profit in DPM is an increasing function when the maximum attainable yield rate is below this threshold value (i.e., \( R < r_0 \)) and remains the same when it exceeds this value (i.e., \( r_0 < R < 1 \)). If this threshold yield rate is greater than one (i.e., \( r_0 = 1 \)), then the profit in DPM is an increasing function of the maximum attainable yield rate. The data sets are designed so that we cover both of these cases. Namely, \( r_0 = 0.75 \) for the first set and \( r_0 = 2.72 \) for the second set. In the remainder of this paper, data sets one and two are referred as ‘high margin’ case and ‘low margin’ case, respectively, since the profit margin from recycling (without remanufacturing the part), which is \( h + s - f \), is higher for the first data set than that of the second set, which leads to different \( r_0 \) values.

Although the data sets presented in Table 2 differ only in \( h \) and \( s \), it should be noted that \( r_0 \) depends on the other parameters also. However, our findings in the subsequent sections remain valid for data sets with different parameters. That is, the observations for high margin and low margin cases apply for different data sets with \( r_0 \leq 1 \) and \( r_0 \geq 1 \), respectively. A detailed computational analysis with different data sets is available upon request.

We assume that \( t(f) = (f + m)/(f + n) \), where \( m = n \). We have considered different values for \( m \) and \( n \) and our findings are almost the same for all. Hence, we only report our computations for \( t(f) = (f + 2)/(f + 3) \). Computational results for different values are available upon request.

#### 4.1. Benchmark: Deterministic Pricing Model

We first analyze the case where the percentage of ELVs with remanufacturable parts is deterministic, i.e., \( R \) is not a random variable. This model will be used as a benchmark in the following sections while comparing PPM and SPM, and evaluating the effects of yield rate variation.

We now present results from our computational analysis.
study for the DPM to illustrate the differences between high and low margin cases. The results are summarized in Table 3. In the high margin case, when \( R > r_0 = 0.75 \), the optimal solution to the unconstrained problem satisfies the constraint, and since we do not have \( R \) in the objective function, the pricing decisions do not exhibit any change as \( R \) increases. Hence, we may conclude that the firm is not willing to take action to increase the maximum attainable yield rate when it is above a certain level.

For the low margin case, where the profit margin from recycling is considerably lower, it would not be beneficial for the firm to set the acquisition price as high as the low margin case. The number of ELVs with remanufacturable parts is equal to the demand. \( r_0 \) turns out to be 2.72, indicating that increasing maximum attainable yield rate benefits the firm since it results in a greater number of remanufacturable parts with a lower acquisition price and the firm’s main profit option is remanufacturing. To be able to adjust the level of increase in ELVs with remanufacturable parts while \( R \) is increasing, the firm first increases the acquisition price. As \( R \) continues to increase, the firm starts to decrease the acquisition price to balance the increase in the supply. Note that number of ELVs with remanufacturable parts continues to increase even if acquisition price is decreasing.

### 4.2. Effects of Random Yield on PPM

For the rest of this section, we assume that maximum attainable yield rate, \( R \), is a normal random variable with mean \( \mu \) and standard deviation \( \sigma \). To analyze the effects of \( \mu \), expected value of maximum attainable yield rate, we assume \( \sigma = 0.05 \), and increment \( \mu \) by 0.05 from 0.50 up to 0.85. Within these ranges, normality assumption remains reasonable since probability of a realization out of the range \((0, 1)\) is negligible. Table 4 summarizes our computations regarding the effects of \( \mu \) for high margin and low margin cases.

In the high margin case, the pricing decisions of the firm are almost identical to the DPM when \( \mu \) is sufficient to generate enough number of remanufacturable parts to satisfy unconstrained optimal demand. Hence, we may conclude that randomness in yield does not matter for the firm when \( \mu \) is above a certain value and the standard deviation is not too high. The overall behavior of pricing decisions to increasing \( \mu \) is the same as in DPM. Similar observations are also valid for the low margin case. This is mainly due to the opportunity to delay the sales pricing decision until after the realization of the yield. The firm may adjust its selling price so that he does not suffer from random

### Table 3 Effects of Maximum Attainable Yield Rate in DPM

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<th>( p )</th>
<th>( \Pi )</th>
<th>( S(f) )</th>
<th>( D(p) )</th>
<th>( f )</th>
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<th>( \Pi )</th>
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### Table 4 Effects of \( \mu \) in PPM

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</table>
yield. The difference of profits from the DPM is negligible in all cases.

We now analyze the effects of yield variation on the pricing decisions and the profit of the remanufacturer. The computations for high and low margin cases are presented in Table 5. In the high margin case, acquisition price decreases in the standard deviation of the maximum attainable yield rate, whereas the expected selling price, $E[p]$, increases. Note that the increase in $f$ outweighs the increase in $E[p]$ in the sense that expected number of remanufacturable parts exceeds expected demand as $\sigma$ increases, i.e., the firm creates a buffer inventory. The difference between profits generated in PPM and DPM is not significant when $\sigma$ is not too high. However, the decrease in expected profit increases more rapidly as $\sigma$ gets larger. In the low margin case, almost all conclusions drawn for the high margin case apply, but one: the firm cannot have buffer ELVs to compensate variability since salvaging the part and the hulk does not generate enough profit when remanufacturing option is not utilized.

### 4.3. Effects of Random Yield on SPM

In SPM, recall that we include a unit penalty cost, $v$, in our model to account for indirect costs incurred by the firm as a result of unsatisfied remanufactured part demand. In our computations, however, $v$ is assumed to be zero so that we may correctly address the differences between PPM and SPM. Later in Section 4.5, we consider different values for the penalty cost and see how the pricing decisions and the profits are affected.

We first analyze the effects of $\mu$. Table 6 provides computations for high and low margin cases. In the high margin case, both acquisition and selling prices decrease in $\mu$. Level of buffer inventory created by the remanufacturer is low when $\mu$ is low. When compared to DPM, the difference in profits is not significant and it disappears as $\mu$ increases. Note that overall performance of the firm does not deviate from the DPM. In the low margin case, since the firm’s main opportunity to generate profit is remanufacturing, the firm is more vulnerable to the uncertainty in yield. As a result, the decrease in profits with respect to the DPM is higher than the high margin case. The difference also does not vanish as $\mu$ increases.

We now analyze effects of the standard deviation of the maximum attainable yield rate on the pricing decisions and the expected profit of the remanufacturer. We assume that $\mu$ is constant at 0.5. Table 7 provides the computational results regarding high and low margin cases. In the high margin case, increasing $\sigma$ results in a significant decrease in her expected profit. In the low margin case, the effects of $\sigma$ are even more remarkable. Both acquisition and selling prices decrease in $\sigma$ resulting in an expected supply shortage. This is mainly because the firm is not willing to decrease the demand, since she guarantees to use all

### Table 5 Effects of $\sigma$ in PPM

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<th>$\sigma$</th>
<th>$f$</th>
<th>$E[p]$</th>
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### Table 6 Effects of $\mu$ in SPM

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<table>
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remanufacturable parts by maintaining demand exceeding supply. Also recall that \( v \) is assumed to be 0, i.e., excessive demand does not cost the firm. The decrease in the profits is even more in the low margin case.

### 4.4. Comparison of the Models

Main results regarding the effects of random yield in both PPM and SPM compared to DPM are summarized in Table 8. Note that the second column in this table indicates that either \( \mu \) or \( \sigma \) is increasing. In the high margin case, expected supply always exceeds demand in both PPM and SPM. The amount of the buffer inventory is especially significant in SPM. This is reasonable since the firm does not have the opportunity to adjust the selling price in response to the realization of the yield and the buffer inventory helps the firm deal with the uncertainties more effectively. As a result, when the standard deviation of the maximum attainable yield rate is at moderate levels, both models (especially PPM) generate profits close to the DPM. In the low margin case, PPM again performs close to the deterministic case whereas SPM results in lower profits. The expected supply is no longer greater than the demand since remanufacturing is the main profit option. In SPM, it is less than the demand since the firm wants to make sure that all remanufacturable parts are used to satisfy demand.

We now compare PPM and SPM in order to see whether the firm values the opportunity to delay the sales pricing decision until after the realization of the yield. Profit figures of the high margin case are depicted in Figures 2a and 2b. When the profit margin from recycling is high (\( r_0 \leq 1 \)), there are not significant differences between the PPM and SPM. Pricing decisions are almost the same, resulting in almost equal number of expected supply and demand for both models. PPM enables the firm to collect more profit than SPM when \( \mu \) is 0.5. This advantage of PPM diminishes as \( \mu \) increases (see Figure 2a). Neither of the models responds to the increase in standard deviation, i.e., the changes in pricing decisions are negligible. Profits generated in both models decrease in \( \sigma \). PPM generates more profit than SPM and the benefits of PPM become significant as \( \sigma \) increases (see Figure 2b).

When the profit margin from recycling is low (Figures 3a and 3b), the benefits of PPM become obvious, and as opposed to the high margin case, do not vanish as \( \mu \) increases. This is mainly due to the lack of responsiveness of SPM to uncertainty. Neither of the

### Table 7 Effects of \( \sigma \) in SPM

<table>
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<tr>
<th>( \sigma )</th>
<th>( f )</th>
<th>( \rho )</th>
<th>( E[I])</th>
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### Table 8 Summary of Results—Effects of Maximum Attainable Yield Rate

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<th>Supply vs. demand</th>
<th>Expected profit vs. DPM</th>
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<td>Expected supply</td>
<td>Negligible decrease</td>
</tr>
<tr>
<td>P</td>
<td>( \mu )</td>
<td>&gt;</td>
</tr>
<tr>
<td>P</td>
<td>( \sigma )</td>
<td>&gt;</td>
</tr>
<tr>
<td>M</td>
<td>Expected demand</td>
<td>Decrease not significant</td>
</tr>
<tr>
<td>S</td>
<td>Expected supply</td>
<td>1.53% decrease (( \mu = 0.5 ))</td>
</tr>
<tr>
<td>P</td>
<td>( \mu )</td>
<td>&gt;</td>
</tr>
<tr>
<td>M</td>
<td>Expected demand</td>
<td>Significant decrease</td>
</tr>
<tr>
<td>S</td>
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<td>P</td>
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<tr>
<td>M</td>
<td>Expected demand</td>
<td>(4.97% when ( \sigma = 0.16 ))</td>
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<table>
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<th></th>
<th>Supply vs. demand</th>
<th>Expected profit vs. DPM</th>
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</thead>
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<td><strong>Low margin</strong></td>
<td>Expected supply</td>
<td>Negligible decrease</td>
</tr>
<tr>
<td>P</td>
<td>Expected demand</td>
<td>Decrease not significant</td>
</tr>
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<td>P</td>
<td>Expected supply</td>
<td>&lt;1% when ( \sigma &lt; 0.1 )</td>
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<td>2.21% when ( \sigma = 0.16 )</td>
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<tr>
<td>S</td>
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<td>1.53% decrease (( \mu = 0.5 ))</td>
</tr>
<tr>
<td>P</td>
<td>Expected demand</td>
<td>as ( \mu ) increases</td>
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<tr>
<td>M</td>
<td>Expected demand</td>
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<tr>
<td>S</td>
<td>Expected supply</td>
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<tr>
<td>P</td>
<td>( \sigma )</td>
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<td>M</td>
<td>Expected demand</td>
<td>(8.98% when ( \sigma = 0.16 ))</td>
</tr>
</tbody>
</table>
models generates buffer inventories as in the high margin case. Therefore, delaying the sales pricing becomes more crucial which is not allowed in SPM. As the uncertainty increases, the difference between models becomes more significant.

In summary, PPM always outperforms SPM, i.e., postponing sales pricing decision until observing the yield is always beneficial for the remanufacturer. Benefits become more significant with lower yield rates, higher variation, and lower profit margins.

4.5. Other Considerations
We now extend the results of the above computational study to different settings and examine whether our observations are still valid.

4.5.1. Penalty Cost. The computational results up to this point assume that the penalty cost for unsatisfied demand in SPM is zero, i.e., the firm does not incur any additional cost other than the lost profit when the demand exceeds the supply of the remanufacturable parts. To analyze the effect of penalty cost, \( v \), on SPM and hence the differences between the models, we replicate our numerical study for SPM with various values for \( v \). Expected profit figures for different values of the penalty cost are provided in Figure 4.

When compared to SPM with \( v = 0 \), the decrease in profits resulting from penalty cost is not significant in the high margin case when the standard deviation is not too high. The difference vanishes as \( \mu \) increases which is reasonable since the buffer inventory enables the firm to avoid lost sales. The difference in the low margin case is more significant because the firm cannot create buffer inventory. Recall that when \( v = 0 \), the expected supply is exceeded by demand, especially when standard deviation is high. On the other hand, when \( v = 20 \) for instance, the firm can no longer bear lost sales and expected supply is almost equal to demand. Larger penalty costs would create buffer inventories instead of supply shortage in such cases. As standard deviation increases, the decrease in profits gets more significant when compared to SPM with \( v = 0 \).

4.5.2. Part Purchasing Only. Up to this point, we have considered the centralized setting where the remanufacturer purchases and dismantles the ELV, and
after remanufacturing the part, sells it in the secondary market. However, our models are applicable to broader settings by setting certain parameters to specific values.

For instance, we can represent a remanufacturer that purchases parts from the dismantler instead of the ELVs by just setting \( h = 0 \). In this case, the threshold yield rate value decreases all other parameters remaining the same. This is reasonable since the main profit option of the firm is remanufacturing now since the hulk is salvaged by the dismantler. Since an increase in the yield rate would increase the number of remanufacturable parts, the profit of the firm would also increase. Hence, unless the salvage value, \( s \) is high enough, our finding under low margin case fits in.

**4.5.3. Vehicle Dismantling Only.** Another setting that can be represented by our models is a dismantler purchasing ELVs and selling remanufacturable parts to the remanufacturer after dismantling and inspection operations. In this case, it is sufficient to set \( e' = 0 \). All other parameters remaining the same \( r_0 \) decreases in this case too. Since the firm sells remanufacturable parts instead of remanufactured parts, the profit margin increases. Hence, remanufacturable parts sale constitutes the greater share of the total profit which implies that increasing yield rate increases the profits of the firm. For instance, \( r_0 = 1.34 \) for the previously high margin case when \( e' = 0 \), which should now be considered as low margin also. To sum up, different settings can be handled with our current model, and our findings in the computational study remain valid.

**5. Value of Perfect Yield Information**

We consider a slightly different case in this section. Maximum attainable yield rate is assumed to be deterministic and \( R = 0.5 \). However, the remanufacturer has partial or no information about \( R \). We incorporate no information case by modelling maximum attainable yield rate to be uniformly distributed with support \((0,1)\). Partial information means that the support of the distribution gets narrower. Note that, in both cases, mean estimation of the remanufacturer is equal to the actual value of \( R \). We assume that \( t(f) = (f + m)/(f + n) \) and \( m = 0 \), letting \( n \) capture the sensitivity of the recovery rate with respect to changes in the acquisition price. Since prior computations indicate that increasing uncertainty has more severe effects in SPM, we assume that the remanufacturer has

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**Figure 4 Profit Figures for Different Values of Penalty Cost.**

(a) Profit vs. \( \mu \): High Margin

(b) Profit vs. \( \mu \): Low Margin

(c) Profit vs. \( \sigma \): High Margin

(d) Profit vs. \( \sigma \): Low Margin
to make both pricing decisions simultaneously, before perfect information is revealed.

In Table 9, we summarize the data set used throughout this section. Note that parameters regarding supply and demand are constant. We change cost and revenue parameters and the sensitivity of the recovery rate, and consider all possible combinations of the presented parameter values; a total of 486 cases. Maximum attainable yield rate is uniformly distributed on \((t, u)\) and \((t, u) = (0.5, 0.5)\) corresponds to the deterministic case, i.e., the remanufacturer has perfect information.

According to our computations, if the remanufacturer has no information about the maximum attainable yield rate, perfect information provides considerable improvements in profits on the average. The improvements are quite low when the profit margin from recycling is the highest \((h = 30, s = 10)\) whereas the maximum improvement occurs when the same profit margin is at its minimum, \((h = 10, s = 5)\). One may argue that perfect information is never attainable, i.e., no matter how much effort is provided, the firm cannot acquire exact information about the yield rate. However, partial information \(((t, u) = (0.4, 0.6))\) has also substantial value to the firm when compared to no information case.

Recall that the parameter \(n\) in the function \(t(f)\) represents the sensitivity of the recovery rate to the acquisition price. The value of information increases with \(n\), and the impact of \(n\) becomes more obvious as remanufacturing becomes the dominant option in terms of profitability. This is reasonable since the revenue from ELVs that are not remanufactured is not influenced by the yield rate and quantity of returns is independent of \(n\).

Figures 5a and 5b depict the overall effects of hulk value and remanufacturing cost on the value of information. Note that the percentage increase in the profit resulting from perfect information decrease in both hulk value and remanufacturing cost. The intuitive reason behind this phenomenon may be explained as follows. As the salvage value of the hulk decreases, the firm’s profits become more dependent on the remanufacturing option. Since supply of ELVs with remanufacturable parts depends on the yield, the firm suffers from uncertainty more than the case with high hulk value. The same reasoning also applies for the remanufacturing cost. As remanufacturing cost decreases, the profit gained by the remanufacturing option increases. However, this part of the profit is more vulnerable to uncertainties in the yield, increasing the value of information.

In summary, yield information is crucial for the operations of the firm, especially when the profit margin from recycling is low.

### 6. Conclusion

Key aspects of successful product recovery and remanufacturing include matching supply of used products with the demand for remanufactured products under yield uncertainty. There are a few studies in the literature that address these issues. To the best of our knowledge, all these models assume exogenous return and demand processes and aim to minimize the expected cost, i.e., the firm has no tools to influence the returns or the demand under yield uncertainty.

In this study, motivated by an application in automotive parts remanufacturing industry, we have considered a remanufacturing system where the quantity of end-of-life products in the final owner market and

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**Table 9: Parameter Set**

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>(\beta)</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(n)</th>
<th>(d)</th>
<th>(v)</th>
<th>(h)</th>
<th>(s)</th>
<th>((t, u))</th>
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<tbody>
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<td>3</td>
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<td>2</td>
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<td>10</td>
<td>30</td>
<td>10</td>
<td>(0.5, 0.5)</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>5</td>
<td>20</td>
<td>5</td>
<td>(0.4, 0.6)</td>
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<tr>
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<td>10</td>
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demand in the remanufactured parts market are linearly dependent on acquisition and selling prices respectively. We incorporated the uncertainty in the recovery process in our model and analyzed the effects of random yield on the profitability of the remanufacturing option. We also developed two different pricing models regarding the timing of the selling price decision. Through extensive computational analysis, we identified cases where increasing the yield rate and/or decreasing variation is crucial for the firm. Furthermore, the benefits of postponing the sales pricing decision are evaluated and its significance under certain circumstances is established. Lastly, we have investigated the value of partial or perfect yield rate information and analyzed the effects of various system parameters.

Note that current study analyzes a single-period model. An immediate extension may be the multi-period analysis where inventory carrying, setups and capacity restrictions may come into picture. Another avenue for further research would be to relax the assumption that all end-of-life products are homogeneous in terms of operational costs and selling prices as well as considering multiple remanufacturable parts that can be recovered from end-of-life products.

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References


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