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Pricing End-of-Life Components

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ABSTRACT

The main objective of a product recovery facility (PRF) is to disassemble end-of-life (EOL) products and sell the reclaimed components for reuse and recovered materials in second-hand markets. Variability in the inflow of EOL products and fluctuation in demand for reusable components contribute to the volatility in inventory levels. To stay profitable the PRFs ought to manage their inventory by regulating the price appropriately to minimize holding costs. This work presents two deterministic pricing models for a PRF bounded by environmental regulations. In the first model, the demand is price dependent and in the second, the demand is both price and time dependent. The models are valid for single component with no inventory replenishment sale during the selling horizon. Numerical examples are presented to illustrate the models.

Keywords: Pricing models, Second-hand markets, EOL products, Product and material recovery

1. INTRODUCTION

In the past decade, growing concerns about the environmental impact of end-of-life (EOL) products, especially from the electronics industry, have prompted local governments to enforce regulations for appropriate handling of these products. For example, in Massachusetts the local legislation requires that the computer monitors and TVs, which contain lead, cannot be dumped in garbage or landfilled; instead they must be either returned to retailers or handed over to product recovery agencies.¹ The goal of such regulation is to promote recycling of materials and reuse of components obtained from EOL products.

A product recovery facility (PRF) is a firm dedicated to recovering reusable components and recyclable materials from EOL products and selling them in second-hand markets. A PRF can procure EOL products from collection centers or directly from customers by giving incentives. It can be a subsidiary of the original equipment manufacturer or an independent firm working autonomously. PRFs often struggle to make profits because of the following reasons:

- Product and material recovery from EOL products for reuse and recycling purposes is a labor intense and costly process.
- Customers discard their products with no fixed pattern, in most cases this makes it difficult for the PRFs to predict their arrival rate and quantity. The variability in the inflow of EOL products makes it hard to plan for their materials, equipment and human resource requirements.
- Variability in the inflow of EOL products and demand for reusable components can cause inventory fluctuations.² For example an unexpected arrival of a batch of EOL computers can flood the inventory level of hard-drives or a sudden demand for media drives can deplete their inventory quickly. Varying inventory levels affect the holding costs and subsequently the profits of PRFs.
- Incentives such as discounts, promotions, and markdowns on list prices to control inventory levels can result in low profits or losses.

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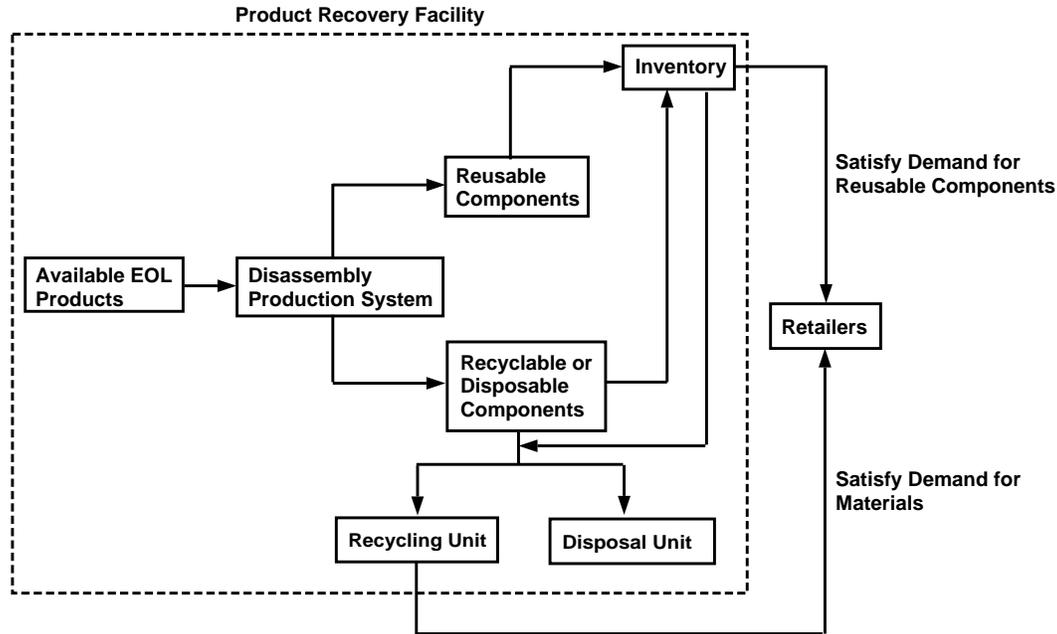


Figure 1. Product Recovery Facility

- Stockouts or volatile inventory levels can occur because of imbalances in the inflow of EOL products and demand for reusable components. The ensuing backorders can cause revenue loss or high inventory levels can beef up holding costs.

A PRF can either adopt a push or a pull production system to perform disassembly.³ In a push system, the EOL products are disassembled and stocked to satisfy the anticipated demand. Whereas in a pull system, EOL products are disassembled only when orders for reusable or recyclable components are received. A pull system, though effective in controlling inventory levels, is usually unrealistic because the availability of the desired quantity of EOL products can be neither guaranteed nor predicted in practice. A push system is more realistic because it can absorb the inevitable demand fluctuations through safety stocks. Therefore this work primarily focuses on the pricing issues of PRFs that implement a push system.

PRFs disassemble EOL products and segregate recovered components into reusable, recyclable, and disposable components (see Figure 1). The reusable components are tested for their usability potential before they are sent to inventory. Recyclable components are sent to the recycling unit for virgin material extraction, and the disposable components are sent to the disposal unit. PRFs sell reusable components and virgin materials directly to customers or retailers.

Unlike original equipment manufacturers (OEMs), who can plan for their raw material requirements, PRFs have to deal with uncertainties in the availability of EOL products. However, demand uncertainty exists for the output of OEMs as well as PRFs. To stay profitable, inventory control is extremely important for both the OEM and PRF. The adverse effects of inventory build up are more severe for the PRF because, (a) there is overhead of inventory holding costs, (b) items become obsolete and hence are difficult to sell, and (c) obsolete items have to be either recycled or disposed of; none of them are attractive options. Apart from the constraints mentioned above, PRFs have to work according to stringent environmental regulations imposed by local and federal governing bodies. An important regulation that is addressed in this work is an upper limit on the amount of waste PRFs can dispose of into landfills. Therefore PRFs should sell reusable components and recyclable material to periodically clear their inventories and to stay profitable. The current work presents analytical models to assist PRF managers to determine the price of reusable components under strict environmental regulations.

2. RELATED WORK

Products returned to OEMs can be classified as follows,^{4 5}:

- The newly purchased products are returned because they failed to meet customer expectations. They are usually returned within 30 days of their purchase.
- Products are returned at the end of an evaluation period. These are the products evaluated by select customers to test their features before they are introduced into markets. The evaluation period is normally 30 days.
- Products are returned due to manufacturing defects before the expiration of their warranty period.
- Products are returned at the end of their leasing period.
- Products are discarded by customers at their EOL.

The returned products are either refurbished or remanufactured and sold along with the OEM's new products. The remanufactured products are priced such that the demand for new products is not adversely affected.

Pricing of remanufactured products keeping the firms profits in perspective has been studied by Guide *et al.*⁶ They present an economic model for a remanufacturing firm that determines the optimal product acquisition price and selling price for a class of remanufactured products that are ranked according to their quality. Majumder and Groenevelt⁷ and Ferrer and Swaminathan⁸ model the competition between an OEM and a remanufacturer. Ferguson and Toktay⁹ study the effect of competition between new and remanufactured products manufactured by an OEM. Vorasayan and Ryan¹⁰ present analytical models to determine the optimal price and quantities of refurbished products. There is hardly any work that addresses the issues of firms involved in product recovery from EOL products. This work focuses on pricing models for firms engaged in product recovery from EOL products.

3. PRICING MODELS FOR EOL COMPONENTS

In this paper, two analytical models are developed to assist managers in determining the pricing of reusable components. In the first model the demand is price dependent whereas in the second it is both price and time dependent. Following assumptions are made in formulating both models.

- The PRF is operating in a market devoid of competition from other PRFs.
- The cost of acquiring EOL products from customers and collection centers is small and negligible.
- Customers buy items without any price reservations and do not exhibit strategic behavior.
- The demand is deterministic, which means that the PRF has an accurate forecast of the quantity of items required for the selling horizon.
- The PRF sells only one type of product/component which is a discrete item.
- The PRF's inventory is not replenished during the selling horizon.
- The demand function is continuous, differentiable, and strictly decreasing.

Let n be the inventory level of the PRF at the beginning of a selling horizon and T be the length of the selling horizon. The PRF has to sell n items before the end of the selling horizon. Let $(\lambda(p))$ be the demand intensity function which gives the number of items in demand per unit time and p be the price. At the end of the selling horizon the unsold inventory, assumed to have zero salvage value, is diverted to either recycle or disposal. Let α be the portion of unsold inventory sent for disposal and let $c > 0$ be the predetermined upper limit on the items that can be disposed of. The value of c is usually determined by the government regulations. The PRF should determine the optimal price, p^* , such that the revenue per unit time is maximized over T . The PRF can encounter one of the four situations over the selling horizon:

Case 1 : The PRF sold exactly n items by the end of the selling horizon.

Case 2 : The fraction of inventory that has to be disposed of is within the pre-specified limit c .

Case 3 : The fraction of inventory that has to be disposed of exceeds c . The surplus beyond c is disposed of at a penalty cost.

Case 4 : There is an inventory stockout. Inventory stockouts in regular manufacturing firms negatively impact the customer's future buying. However, inventory stockouts in PRFs may not influence customer's future buying. Instead such a situation is desirable for PRFs because it can save inventory holding costs, disposal costs, and fetch more revenue than raw materials obtained by their recycling.

Examples of items that can be sold using the proposed pricing models are monitors, hard-drives, media drives, cell phones, printers, and scanners. If PRFs sell items that do not contain hazardous material, then the regulations should not be considered while determining their selling prices. The pricing models reported in literature can be used by the PRFs in such cases.¹¹

3.1. Price dependent demand

In this model it is assumed that demand is only dependent on the price p of an item offered by the PRF.

For *Case 1* the optimal price p^* is obtained by solving $\lambda(p^*)T = n$. For *Case 2*, the optimal price is obtained from the optimization problem,

$$\max_p p\lambda(p)T$$

$$\alpha [n - \lambda(p)T] \leq c$$

For *Case 3*, the objective function is the same as in *Case 2* but $\alpha [n - \lambda(p)T] > c$ would be its constraint. For these two optimization problems, an optimal solution is guaranteed if $\lambda(p)$ is decreasing in T and the revenue function $p\lambda(p)$ is concave.¹² The two problems are standard non-linear optimization problems which can be solved using Karush-Kuhn-Tucker (KKT) conditions.¹³ For *Case 4*, the optimal price from either of the first three cases can be used. In all four cases the optimal price is independent of time so the price is set at the start of the selling horizon and kept unchanged during the selling horizon.

Let the demand function be $\lambda(p) = \frac{1}{e^p - 1}$. The optimal price in *Case 1* is $p^* = \ln\left(\frac{T}{n} + 1\right)$. For *Case 2* the optimization problem can be written as,

$$\max_p \frac{pT}{e^p - 1}$$

$$\alpha \left(n - \frac{T}{e^p - 1} \right) \leq c$$

Let $f(p) = \frac{pT}{e^p - 1}$ and $g(p) = \alpha \left(n - \frac{T}{e^p - 1} \right) - c$. Thus their partial derivatives with respect to p are,

$$\frac{\partial f}{\partial p} = \frac{Te^p(1-p) - T}{(e^p - 1)^2}$$

$$\frac{\partial g}{\partial p} = \frac{\alpha T e^p}{(e^p - 1)^2}$$

The following are KKT conditions in this case:

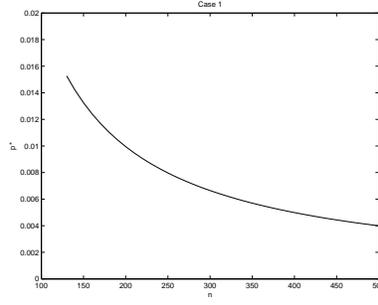


Figure 2. Price versus initial inventory for *Case 1*

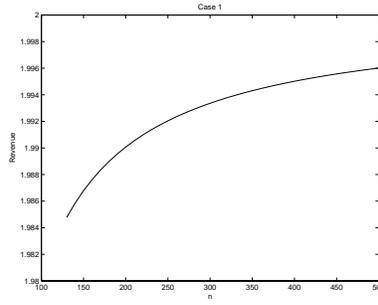


Figure 3. Revenue versus initial inventory for *Case 1*

1. $\frac{\partial f}{\partial p} - \beta \frac{\partial g}{\partial p} \leq 0$
2. $p \left(\frac{\partial f}{\partial p} - \beta \frac{\partial g}{\partial p} \right) = 0$
3. $n - \frac{T}{e^p - 1} - c' \leq 0$
4. $\beta \left(n - \frac{T}{e^p - 1} - c' \right) = 0$
5. $p \geq 0$
6. $\beta \geq 0$

Solving for p using the KKT conditions one gets, $p^* = \ln \left(\frac{T}{n-c'} + 1 \right)$, where $c' = \frac{c}{\alpha}$ and β is the Lagrange multiplier.

Following a similar approach, the optimal price for *Case 3* is obtained as, $p^* = \ln \left(\frac{T}{c-n} + 1 \right)$. One can perform sensitivity analysis to find the feasible selling horizon length, portion of disposable inventory, and initial inventory level that result in profits.

Numerical Illustration: Assuming that *Case 3* is not applicable for this illustration. Let $T = 2$ months, $c = 20$, and $\alpha = 20\%$. The variation in optimal price and expected revenue in *Case 1* and *Case 2* for a given initial inventory level is shown in Figures 2 and 3 and Figures 4 and 5 respectively.

From Figure 5 it can be observed that the revenue flattens out when initial inventory exceeds 300 items in *Case 2*. This trend is not observed in *Case 1*.

The variation in optimal price and expected revenue in *Case 2* for varying selling horizon lengths is shown in Figures 6 and 7 respectively. The price and revenue increase with T , which is expected because the longer the selling horizon the opportunity to sell products is higher.

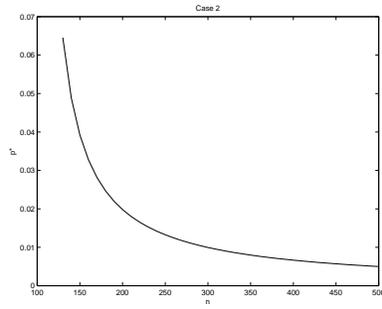


Figure 4. Price versus initial inventory for *Case 2*

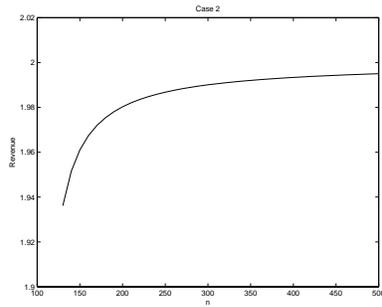


Figure 5. Revenue versus initial inventory for *Case 2*

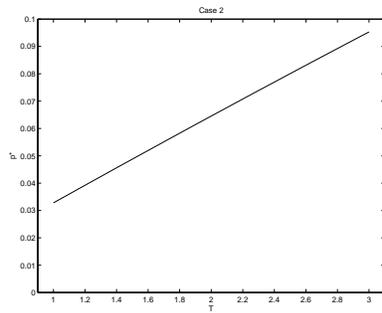


Figure 6. Price versus selling horizon for *Case 2*

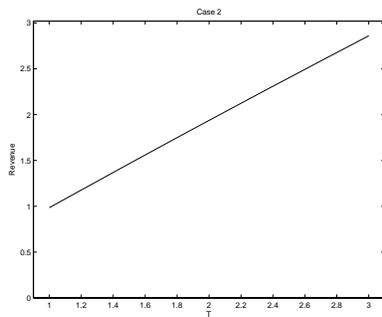


Figure 7. Revenue versus selling horizon for *Case 2*

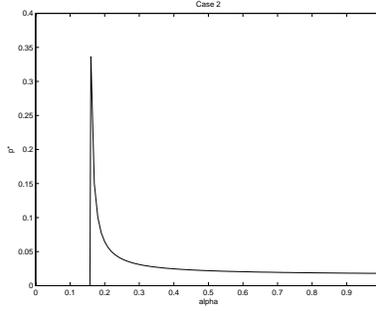


Figure 8. Price versus α for *Case 2*

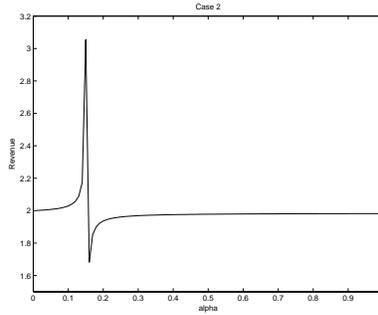


Figure 9. Revenue versus α for *Case 2*

The variation in optimal price and expected revenue in *Case 2* for various values of α is shown in Figures 8 and 9 respectively. The plots suggest that the revenue falls sharply if α increases beyond a certain value. The PRF should try to sell products such that they can keep α below the disastrous level.

3.2. Time and price dependent demand

In this model, demand varies with time, t , and price, p , of an item. The PRF still faces the four situations outlined in the previous section.

For *Case 1* the optimal price is obtained by solving $\int_0^T \lambda(p, t) dt = n$ for p .

For *Case 2* the optimization problem turns out to involve standard calculus of variations problem,

$$\max_p \int_0^T p \lambda(p, t) dt$$

subject to,

$$\alpha \left(n - \int_0^T \lambda(p, t) dt \right) \leq c$$

Following the procedure outlined in Kamien and Schwartz,¹⁴ the Lagrangian function is, $L = p\lambda(p, t) + \eta\lambda(p, t) = 0$, where η is the Lagrange multiplier. The Euler equation of L is

$$\frac{\partial L}{\partial p} = (p + \eta) \frac{\partial}{\partial p} \lambda(p, t) + \lambda(p, t) = 0$$

Solving for p one gets,

$$p^* = -\eta - \frac{\lambda(p, t)}{\frac{\partial}{\partial p}[\lambda(p, t)]} \quad (1)$$

In equation (1), if $\eta = 0$ then the optimal price is,

$$p^* = -\frac{\lambda(p^*, t)}{\lambda'_p(p^*, t)} \quad (2)$$

If $\eta > 0$ in equation (1) then only a lower bound exists,

$$p^* \leq -\frac{\lambda(p^*, t)}{\lambda'_p(p^*, t)} \quad (3)$$

where, $\lambda_p' = \frac{\partial}{\partial p}$.

For *Case 3*, following the same approach as in *Case 2*, the optimal price is obtained by,

$$p^* = \eta - \frac{\lambda(p, t)}{\lambda'_p(p, t)} \quad (4)$$

From equation (4), results similar to equations (2) and (3) can be obtained for $\eta = 0$ and $\eta > 0$. The sufficiency condition for p^* to be optimal in all three cases is that $p\lambda(p, t)$ be concave.

For *Case 4*, the optimal price from either of the first three cases can be used. It can be observed that the optimal price in all four cases is a function of time. It implies that the PRF has to change its prices at every moving time instant, which is not practically feasible. However the growth of Internet and e-commerce is facilitating the implementation of continuous pricing.¹¹ It can also be observed that c and n have no influence on optimal price in all four cases. This makes the model more convenient for the PRF to implement in practice.

Let $\lambda(p, t) = \frac{e^{-bt}}{p^r}$, where $b > 0$ is the demand elasticity and $r > 0$ is a constant.

In *Case 1*, $p^* = -\left(\frac{1-e^{-bT}}{nb}\right)^{\frac{1}{r}}$.

In *Case 2*, the optimal price is obtained by substituting, $\lambda_p = -\frac{re^{-bt}}{p^{r+1}}$, in equation (2), $p^* = -\frac{\eta}{(1-\frac{1}{r})}$.

In *Case 3*, the optimal price is, $p^* = \frac{\eta}{(1-\frac{1}{r})}$.

In the above, η is interpreted as the opportunity cost of selling an item from the inventory and it can be found from boundary conditions of the price.

Numerical Illustration: Assuming that *Case 3* is not applicable for this illustration, let $b = 1$, $r = 2$, $n = 130$ items, $T = 2$ months, $c = 20$, $\alpha = 20\%$. For *Case 1*, the optimal price and expected revenue are \$0.0816 and \$10.6022 respectively.

For *Case 2*, $p^* = -2\eta$. If the initial price at the start of the selling horizon is $p(0) = \$1$, then $\eta = -0.5$. So for *Case 2*, $p^* = \$1$ for the selling horizon.

4. CONCLUSIONS

Recovering reused components and recyclable material from EOL products is not a financially lucrative option for PRFs because of their volatile inventory levels. Sustaining a balance between the inflow and demand of EOL products is key for PRFs to keep their inventory levels under control. A carefully planned pricing policy is an effective management strategy to achieve this balance. This research presented two simple pricing models when the demand is deterministic. In the first model the demand was price dependent whereas in the second it was both price and time dependent. In the price dependent demand model, numerical examples indicated that the revenue earned in a selling horizon tends to become constant after a certain initial inventory level. These models are simple and easy to implement. Managers can get quick insight into the prices and revenue resulting from different demand models, selling horizons, and initial inventory levels.

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