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Pricing Decisions for Product Recovery Facilities in a Multi-Criteria Setting using Genetic Algorithms

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ABSTRACT

Independent and small scale product recovery facilities (PRFs) often struggle to achieve profits when faced with inconsistent inflows of discarded products, varying demand patterns for recovered components, and stringent environmental regulations. Inconsistent inflows coupled with the varying demand cause undue fluctuations in inventory levels and frequently affect costs involved in product recovery operations. An effective pricing strategy can stabilize the fluctuations in demand and consequently can allow PRFs to control inventory levels. This research determines the prices of reusable and recyclable components and acquisition price of discarded products that allow PRFs to simultaneously maximize their financial returns and minimize the product recovery costs. Genetic algorithms and analytic hierarchy process are employed to solve this multi-criteria decision making problem.

Keywords: Economic models, Second-hand markets, Multi-criteria decision making, Product recovery, Genetic algorithms.

1. INTRODUCTION AND RELATED WORK

Rising consumer awareness of the environment and the enormously growing quantities of products discarded by customers have led to legislations that hold the original equipment manufacturers (OEM) responsible for their products.¹²³⁴ Products discarded by customers can broadly be classified as obsolete or naturally aged. Components in the former could be reused whereas those in the later could be recycled for their virgin materials. In spite of the economic and environmental benefits associated with reuse and recycle of discarded products many OEMs are apprehensive of the idea of integrating product take back programs in their business models. They fear that it could affect their new product sales.⁵ Encouraged by this stance from OEMs, third-party firms are entering the market to exploit the economic potential in discarded products, allowing them to compete against the OEMs new products. The third-party firms, referred as product recovery facilities (PRFs), collect discarded products, perform product recovery operations, and sell the recovered components in secondary markets. IBM's Global Asset Recovery Services,⁶ AER Worldwide,⁷ NuKote,⁸ and ReCellular⁹ are good examples of PRFs. Healthy competition between the OEMs and PRFs has an environmentally benign effect: it eases the burden on landfills, minimizes the consumption of virgin materials, mitigates the energy requirements, and increases number of product life cycles. Usually PRFs are plagued financially by the costly and labor intense nature of product recovery operations, competition from OEMs, meagre revenue from sales, and environmental regulations. Prominent challenges faced by PRFs are: (a) expensive and skilled labor required for product recovery operations; (b) uncertainty in the timing and quantity of discarded products arriving at the PRFs; (c) fleeting inventory levels of recovered components ensuing from the unpredictable disposal of products and stochastic demand; (d) holding costs of surplus inventory; (e) lost sales due to stockouts; (f) disposal cost of leftover and obsolete inventory; and (e) promotional sales, discounts, and markdowns to clear inventory.

An effective way to address these challenges is to appropriately price components in the inventory. This strategy has a twofold impact: it facilitates inventory control and enhances the profit margin. Very few studies

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in the literature address the issue of pricing for PRFs which are usually small scale firms. Most of the studies focus on OEMs which are usually medium to large scale firms capable of practicing green manufacturing strategies even at the cost of lower profit margins to abide by environmental regulations and to appear eco-friendly in the market. Past studies in the literature are listed here.

Guide *et al.*¹⁰ determined the acquisition price of discarded products and the prices of remanufactured products which are categorized according to their quality level. Pricing in a duopoly was addressed by Majumder and Groenevelt¹¹ and Ferrer and Swaminathan.¹² Savaskan *et al.*¹³ evaluated different product take back configurations in a closed-loop supply chain with the wholesale and retail prices of remanufactured products as their metric. Ferguson and Toktay⁵ determined the optimal prices for new and remanufactured products produced by an OEM where remanufactured products can cannibalize the demand for their counterpart new products. Vorasayan and Ryan^{14,15} for an OEM, determined the optimal prices of remanufactured products and the optimal portion of the returned products to be remanufactured when new product sales are affected by the remanufactured ones. Ray *et al.*,¹⁶ investigated the effect on the sales when trade-in rebates are offered to customers who are willing to replace their products with new ones. Debo *et al.*¹⁷ determined the optimal price of remanufactured products and the level of production technology to remanufacture products for a monopolist firm whose customers distinguish between the new and the remanufactured products. In another work, Debo *et al.*¹⁸ captured the progressive market penetration of new and remanufactured products of an OEM through a Bass diffusion model, where the prices of new and remanufactured products and the level of remanufacturability dictate the diffusion process. Mitra¹⁹ determined the prices of remanufactured and refurbished products where their demand is dependent on price, quality of products, and availability of discarded products. Bakal and Akcali²⁰ studied the effect of the component yield from product recovery on the selling and acquisition prices and profits. Mondal and Mukherjee,²¹ investigated the economic factors that impact the product acquisition decisions and developed an analytical model to determine the optimal time to take back the products in use to maximize the ensuing economic benefit from remanufacturing. Vadde *et al.* have developed pricing models for PRFs when their inventories are vulnerable to gradual and sudden obsolescence,²² under certain inventory constraints,²³ when prices are have to be chosen from a pre-selected set,²⁴ and when the PRFs either passively accept discarded products or proactively acquire them.²⁵

The present work determines the prices of reusable and recyclable components when the PRF passively accepts discarded products and proactively acquires them when necessary, in a multi-criteria environment where the PRF has to simultaneously maximize revenues and minimize various costs. Although Kongar *et al.*^{26,27} have addressed issues in a multi-criteria environment for PRFs, they haven't considered the pricing aspects in their study. Addressing this gap is the focal theme of this work and thus makes it unique.

2. PROBLEM DESCRIPTION

Usually in practice the PRFs simultaneously work towards multiple cost and revenue objectives. Pricing decisions under such a management policy are presented in this section. Some assumptions are made in formulating the analytical model: (a) PRF is operating in a monopolist environment; (b) price reservation of customers is inconsequential; (c) inventory is not replenished during selling horizon and excess demand is not backlogged; (d) demand is deterministic and strictly decreasing with price; (e) PRFs must abide by the local regulations that impose a fine on quantities exceeding the disposal limit; (f) contents of the discarded products are known to the PRFs before their disassembly; (g) discarded products contain no missing and upgraded components; (h) disassembly and sorting process yields are deterministic; (i) material recycling operations are not performed by the PRF; (j) there is market for all categories of components sold by the PRFs. Prices are posted only after the component yield is realized as it is a more profitable alternative than the case where price is posted before the product recovery yield is known.²⁰

PRFs passively accept single type discarded product returns as well as proactively acquire them when necessary. This production control strategy, an integration of both push and pull production systems, can ensure that the demand is always satisfied without backorders and can stabilize the plans for resources required to perform product recovery operations, remanufacturing, refurbishing, and processing of recyclable components. PRFs accept discarded products with no restrictions on their quantity and quality. This research proceeds with the assumption that the quantity of discarded products and their arrival time at the facility are known beforehand

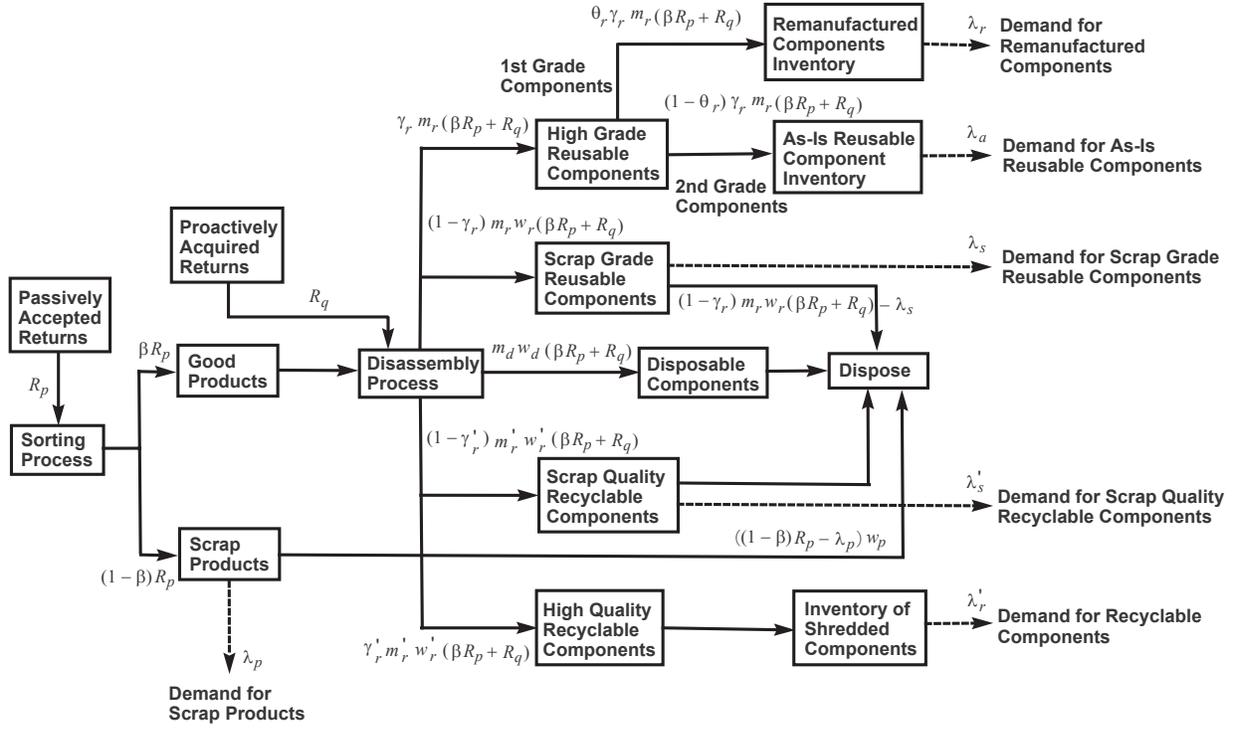


Figure 1. Production control model of the product recovery facility

to PRFs through forecasting techniques.²⁸ This allows PRFs to plan ahead on the acquisition of discarded products. They can be acquired directly from customers, retailers, and collection agencies if the forecasted returns are fewer or the on-hand inventory of returns is insufficient to satisfy the demand for recovered components. The acquisition process should be initiated by PRFs taking into account the time lags in acquiring returns and the lead times to process the recovered components in order to avoid delays in demand delivery. Obsolescence could catch up on remanufactured components if acquisition and lead times are long.²² Although PRFs can advertise their need for discarded products, unless incentives are offered to customers to return their products the acquisition process could be prolonged. The incentive offered, which depends on the demand for recovered components and regulated disposal limit, in effect determines the return quantity – more lucrative incentives yield better returns. PRFs may choose to give incentives only if the products meet certain specifications. This could enable PRFs to acquire products of specific quality levels which may eliminate the need to sort the good and damaged products.

3. ANALYTICAL MODEL

The schematic layout of the production control model implemented by the PRF is shown in Figure 1 (subscript i is dropped for ease of illustration). The passively accepted returns are first sorted and inspected to separate the good quality products from the scrap quality products which are characterized by inferior quality, blemished physical appearance, and low reuse and recycle potential. The scrap quality products are preferentially sold for recyclable material and the rest are disposed of at the end of the selling period. The good quality products and the proactively acquired products, if any, are fed to the disassembly production system which extracts the constituent components from the products. These components are segregated by skilled workers on the production line into various types of reusable, recyclable, and disposable components; if necessary these components are further tested. The reusable and recyclable components are categorized into four classes described below.

- *High grade reusable components:* These components are characterized by their good physical appearance and quality. They are further classified as first and second grade components on the basis of further tests on their reusability potential. The first grade components have more economic value when remanufactured or refurbished (refurbished components are also referred as remanufactured components in the remainder of the paper) than the second grade ones (referred as high grade as-is reusable) which are sold in as-is condition with some cosmetic changes. Inventory is carried for both grades of components.
- *Scrap grade reusable components:* These components are either physically blemished or functionally disabled but are good candidates for recycling.
- *High quality recyclable components:* These components can either be directly recycled or require minimal effort to obtain the actual recyclable components. Before stockpiling in the inventory, the components are subjected to operations such as shredding and crushing to facilitate processing at the recycling stage.
- *Scrap quality recyclable components:* These components require more effort and time to separate the actual recyclable components or have relatively less recycle value.

On the basis of their economic worth the PRF's prefers to sell, remanufactured, high grade as-is reusable, high quality recyclable, scrap grade reusable, and scrap quality recyclable components in this order. At the end of the selling period, the leftover scrap grade reusable and scrap quality recyclable components are disposed of, whereas the disposable components are disposed of as soon as their yield is realized. According to the disposal regulation, penalty is imposed if the disposed quantity exceeds the stipulated limit. Inventory is carried to absorb fluctuations in demand for remanufactured, high grade as-is reusable, and high quality recyclable components. These inventory levels are expected to be relatively low when returns are acquired and high when the passively accepted returns are substantial.

In the management policy to simultaneously minimize costs and maximize revenues, the costs include the acquisition cost of returns, disassembly cost of recovering components, processing and holding costs of the remanufactured, high grade as-is reusable, and high quality recyclable components, disposal costs of scrap quality products, scrap grade reusable, and scrap quality recyclable components; and revenues consist of sales from the four classes of components and scrap quality discarded products. Analytical expressions for revenue and costs are given below (see appendix for notation used).

Total Revenue:

$$R_T = \sum_{i=1}^{n_r} p_{ri} Q_{ri} + \sum_{i=1}^{n'_r} p'_{ri} Q'_{ri} + \sum_{i=1}^{n_r} p_{ai} A_{ri} + \sum_{i=1}^{n_r} p_{si} F_{ri} + \sum_{i=1}^{n'_r} p'_{si} F'_{ri} + p_p J \quad (1)$$

Total Disposal Costs:

$$\begin{aligned} C_D = & \sum_{i=1}^{n_r} (1 - x_{ri}) C_{di} G_{ri} + x_{ri} [C_{di} D_{ri} + C_{oi} (G_{ri} - D_{ri})] + \sum_{i=1}^{n'_r} (1 - x'_{ri}) C'_{di} G'_{ri} + x'_{ri} [C'_{di} D'_{ri} + C'_{oi} (G'_{ri} - D'_{ri})] \\ & + \sum_{i=1}^{n_d} (1 - x_{di}) C_{ddi} m_{di} w_{di} (\beta R_p + R_q) + x_{di} [C_{ddi} D_{ddi} + C_{odi} (m_{di} w_{di} (\beta R_p + R_q) - D_{ddi})] \\ & + (1 - x_p) C_{dp} K + x_p [C_{dp} D_p + C_{op} (K - D_p)] \end{aligned} \quad (2)$$

Total Preparation Costs:

$$\begin{aligned} C_P = & \sum_{i=1}^{n_r} C_{pi} \theta_{ri} \gamma_{ri} m_{ri} (\beta R_p + R_q) + \sum_{i=1}^{n'_r} C'_{pi} \gamma'_{ri} m'_{ri} w'_{ri} (\beta R_p + R_q) \\ & + \sum_{i=1}^{n_r} C_{ai} (1 - \theta_{ri}) \gamma_{ri} m_{ri} (\beta R_p + R_q) \end{aligned} \quad (3)$$

Total Holding Costs:

$$C_H = \sum_{i=1}^{n_r} C_{hi}(L_{ri} + LA_{ri}) + \sum_{i=1}^{n'_r} C'_{hi}L'_{ri} \quad (4)$$

Total Disassembly Costs:

$$C_A = C_r(\beta R_p + R_q) \quad (5)$$

Total Acquisition Costs:

$$C_Q = C_q R_q \quad (6)$$

Total Sorting Costs:

$$C_S = C_s R_p \quad (7)$$

Where, $Q_{ri} = \min\{\lambda_{ri}, \theta_{ri}\gamma_{ri}m_{ri}(\beta R_p + R_q)\}$, $Q'_{ri} = \min\{\lambda'_{ri}, \gamma'_{ri}m'_{ri}(\beta R_p + R_q)\}$,
 $A_{ri} = \min\{\lambda_{ai}, (1 - \theta_{ri})\gamma_{ri}m_{ri}(\beta R_p + R_q)\}$, $LA_{ri} = \max\{0, (1 - \theta_{ri})\gamma_{ri}m_{ri}(\beta R_p + R_q) - \lambda_{ai}\}$,
 $L_{ri} = \max\{0, \theta_{ri}\gamma_{ri}m_{ri}(\beta R_p + R_q) - \lambda_{ri}\}$, $L'_{ri} = \max\{0, \gamma'_{ri}m'_{ri}(\beta R_p + R_q) - \lambda'_{ri}\}$,
 $F_{ri} = \min\{\lambda_{si}, (1 - \gamma_{ri})m_{ri}w_{ri}(\beta R_p + R_q)\}$, $F'_{ri} = \min\{\lambda'_{si}, (1 - \gamma'_{ri})m'_{ri}w'_{ri}(\beta R_p + R_q)\}$,
 $G_{ri} = \max\{0, (1 - \gamma_{ri})m_{ri}w_{ri}(\beta R_p + R_q) - \lambda_{si}\}$, $G'_{ri} = \max\{0, (1 - \gamma'_{ri})m'_{ri}w'_{ri}(\beta R_p + R_q) - \lambda'_{si}\}$,
 $J = \min\{\lambda_p, (1 - \beta)w_p R_p\}$, $K = \max\{0, (1 - \beta)w_p R_p - \lambda_p\}$. The variable, $x_{ri} = 0$, if $G_{ri} > D_{ri}$, otherwise $x_{ri} = 1$; the same description applies to x'_{ri} , x_{di} , and x_p .

The demand for remanufactured and high grade as-is reusable components is in discrete quantities, while that of scrap grade reusable, high and scrap quality recyclable components is in terms of their weight. The demand constraints are given by equations 8–13.

$$\lambda_{ri} \leq \theta_{ri}\gamma_{ri}m_{ri}(\beta R_p + R_q), \forall i = 1, \dots, n_r \quad (8)$$

$$\lambda'_{ri} \leq \gamma'_{ri}m'_{ri}(\beta R_p + R_q), \forall i = 1, \dots, n'_r \quad (9)$$

$$\lambda_{ai} \leq (1 - \theta_{ri})\gamma_{ri}m_{ri}(\beta R_p + R_q), \forall i = 1, \dots, n_r \quad (10)$$

$$\lambda_{si} \leq (1 - \gamma_{ri})m_{ri}w_{ri}(\beta R_p + R_q), \forall i = 1, \dots, n_r \quad (11)$$

$$\lambda'_{si} \leq (1 - \gamma'_{ri})m'_{ri}w'_{ri}(\beta R_p + R_q), \forall i = 1, \dots, n'_r \quad (12)$$

$$\lambda_p \leq (1 - \beta)w_p R_p \quad (13)$$

The management wishes to determine the optimal acquisition price of discarded products and the optimal prices of remanufactured, high grade as-is reusable, high quality recyclable, scrap grade reusable, and scrap quality recyclable components which maximize the total revenue (eq. 1), minimize the total disposal cost (eq. 2), total preparation cost (eq. 3), total holding cost (eq. 4), total disassembly cost (eq. 5), total acquisition cost (eq. 6), and total sorting cost (eq. 7), under the demand constraints (eqs. 8–13). This multi-criteria decision making problem is solved using genetic algorithms in the next section.

4. GENETIC ALGORITHMS

Genetic algorithm is a heuristic search technique whose principles are rooted in the theory of evolution²⁹³⁰³¹. In a nutshell, a genetic algorithm starts with a population of individuals which are left to evolve under certain rules until the objective function (or fitness value) of the problem is optimized.

A multi-criteria based genetic algorithm is employed to solve the optimization problem presented in the previous section. A weighted sum approach is employed to obtain a single scalar objective function which is then maximized.³² The contribution of each criteria to the overall objective function (net profit), P_N , is given by their respective weights, w_i , $i = 1, 2, \dots, 7$. The function, P_N (eq. 14), is used as the fitness value in the genetic algorithm. The weighted sum technique is appropriate if the decision maker is knowledgeable of the contribution

of each criteria to the overall objective function, the same is assumed in this work. A judicious method of choosing the weights with the decision maker's knowledge is discussed in section 4.1.

$$P_N = w_1R_T - w_2C_D - w_3C_P - w_4C_H - w_5C_A - w_6C_Q - w_7C_S \quad (14)$$

The structure of the algorithm is briefly described here. Initially, each problem variable is encoded into a gene (for the problem at-hand encoding is not necessary) and a set of genes is called a chromosome which is a point in the problem's search space and a signature of an individual in the population. For the current problem, the acquisition price of products and prices of all components and scrap products compose a chromosome. The algorithm starts of by randomly choosing a set of chromosomes from the search space. Individuals (or parents) are chosen by some selection criteria which then are allowed to mate to produce offsprings. The rank based roulette wheel weighting technique is used in selecting the parents and the single point crossover method is used to obtain the offspring from a pair of parents during mating.³⁰ The current set of parents and offsprings constitutes a generation. At this stage, a certain percentage (mutation rate) of the population is allowed to mutate. Mutations which alter the composition of the chromosomes are necessary to explore the search region and avoid convergence at local optima. The algorithm is terminated if the desired fitness value is reached or a pre-specified number of generations have elapsed. Before starting the next generation, the chromosomes are sorted in the descending order of their fitness value and a certain percentage (selection rate) of the population is preserved to generate new offsprings.

4.1. Determination of criteria weights using the analytic hierarchy process

The analytic hierarchy process (AHP) is a decision making tool which exploits the decision maker's knowledge about the various criteria influencing a decision.³³ First, the various criteria are hierarchically arranged considering their interdependencies and the decision maker's perception of the relative importance of a criterion with respect to the other is captured on a quantitative scale between 1-10; the values 1, 3, 5, 7, and 9 respectively represent if a criterion is of equal, moderate, strong, very strong, and extreme importance with respect to other criterion, whereas the values 2, 4, 6, and 8 quantify the intermediary perceptions, and the reciprocals of these values represent the converse perceptions. After each criterion is weighted against the remaining criterion, a pairwise comparison matrix is generated. The weights of the criteria are obtained by employing techniques such as eigenvalue, mean transformation or row geometric mean to the pairwise comparison matrix. To determine the bias in the decision maker's perception of a criterion's relative importance, an index called the consistency ratio is computed. Usually the consistency ratio values less than 0.1 are acceptable otherwise a revision of the pairwise comparison matrix is undertaken.

5. NUMERICAL EXAMPLE

Assume that the PRF processes PCs with configuration shown in Table 1 and the associated data for its components listed in Table 2. Let the data for the PC be, $w_p = 5.95$ lb, $\beta = 0.8$, $C_s = \$9$, $C_r = \$15$, $C_{dp} = \$15$, $C_{op} = \$12$, $D_p = 300$ lb, $R_p = 20$, $R_q = 7C_q$, $\lambda_p = 30 - 2.4p_p$. Linear demand functions are assumed for the case example: $\lambda_{r1} = 125 - 1.2p_{r1}$, $\lambda_{r2} = 120 - 2.4p_{r2}$, $\lambda_{a1} = 70 - 2.5p_{a1}$, $\lambda_{a2} = 65 - 3.2p_{a2}$, $\lambda_{s1} = 18 - 5.2p_{s1}$, $\lambda_{s2} = 19 - 4.1p_{s2}$, $\lambda'_{r1} = 80 - 4.6p'_{r1}$, $\lambda'_{r2} = 90 - 2.1p'_{r2}$, $\lambda'_{r3} = 125 - 5.3p'_{r3}$, $\lambda'_{r4} = 110 - 8.5p'_{r4}$, $\lambda'_{r5} = 105 - 3.5p'_{r5}$, $\lambda'_{s1} = 18 - 2.2p'_{s1}$, $\lambda_{s2} = 12 - 1.9p_{s2}$, $\lambda_{s3} = 19 - 3.7p_{s3}$, $\lambda_{s4} = 11 - 4.5p_{s4}$, $\lambda_{s5} = 17 - 3.5p_{s5}$, $\lambda_p = 30 - 2.5p_p$.

The pairwise comparison matrix to compute the weights for each criteria using the AHP technique is shown in Table 3. The consistency ratio for the pairwise comparison matrix is found to be less than 0.093, which is clearly less than 0.1. The genetic algorithm is executed with number of generations = 400, mutation rate = 20%, selection rate = 50%, and population size = 12 chromosomes.

The following results are obtained from executing the genetic algorithm: price to acquire a PC (C_q) = \$3.58, number of returns to acquire (R_q) = 25.09 units, and the overall is profit \$1086.89; other parameters obtained are listed in Table 4.

Table 1. Product configuration

Index (<i>i</i>)	Component	Multiplicity	Weight	Yield	Yield	Disposal
(Recycle)				(γ_r/γ'_r)	(θ_r)	Limit (lb)
1	LCD 12.1"	1	1.10	0.85	n/a	26
2	Chassis	1	0.68	0.95	n/a	38
3	128 MB RAM	1	0.05	0.70	n/a	25
4	64 MB RAM	1	0.02	0.80	n/a	20
5	1.44 MB FD	1	0.68	0.75	n/a	19
(Reuse)						
1	24x CD-ROM	1	0.90	0.90	0.50	50
2	10 GB HD	2	1.30	0.70	0.60	90
(Dispose)						
1	150 MHz Processor	1	0.40	n/a	n/a	120

Table 2. Cost data

Index (<i>i</i>)	Component	Costs				
		Preparation	As-Is	Holding	Disposal	Disposal
(Recycle)						Penalty
1	LCD 12.1"	7	n/a	1.02	8	9
2	Chassis	9	n/a	1.01	9	6
3	128 MB RAM	8	n/a	0.95	7	4
4	64 MB RAM	9	n/a	1.03	7	6
5	1.44 MB FD	8	n/a	1.04	7	7
(Reuse)						
1	24x CD-ROM	12	3	1.05	6	8
2	10 GB HD	8	5	1.04	9	6
(Dispose)						
1	150 MHz Processor	n/a	n/a	n/a	10	14

Table 3. Pairwise comparison matrix

	R_T	C_D	C_A	C_P	C_H	C_Q	C_S	Weights (w_i)
R_T	1	1	5	4	5	4	8	0.3034
C_D	1	1	4	4	6	5	7	0.3009
C_A	1/5	1/4	1	1	3	5	7	0.1276
C_P	1/4	1/4	1	1	3	4	6	0.1201
C_H	1/5	1/6	1/3	1/3	1	4	6	0.0812
C_Q	1/4	1/5	1/5	1/4	1/4	1	1	0.0389
C_S	1/8	1/7	1/7	1/6	1/6	1	1	0.0279

Table 4. Results obtained from executing the genetic algorithm

Component	Price			Inventory		Disposed (lb)
	High grade/ quality	Scrap grade/ quality (\$/lb)	As-Is (\$)	High grade/ quality	As-Is (units)	
LCD 12.1"	9.38 (\$/lb)	5.39	n/a	1.58 (lb)	n/a	0.66
Chassis	30.43 (\$/lb)	5.74	n/a	0.45	n/a	0.31
128 MB RAM	23.33 (\$/lb)	5.07	n/a	0.08	n/a	0.38
64 MB RAM	12.91 (\$/lb)	2.42	n/a	0.42	n/a	0.09
1.44 MB FD	24.02 (\$/lb)	3.77	n/a	0.05	n/a	3.21
24x CD-ROM	88.93 (\$/unit)	2.75	20.60	0.22 (units)	0	0.05
10 GB HD	36.49 (\$/unit)	0.26	13.57	2.11 (units)	1.43	14.13
150 MHz Pro Computer	n/a	n/a	n/a	n/a	n/a	16.43
	n/a	2.64	n/a	n/a	n/a	0.14

6. CONCLUSIONS AND FURTHER RESEARCH

The disparity between the return flow of discarded products and the demand for reusable and recyclable components creates undue inventory level variations and affects the product recovery costs. In this work, PRFs passively accept discarded products normally but proactively acquire them when required to reduce the mismatch between product returns and component demand. Prices of reusable and recyclable components of various grades and acquisition price of discarded products are determined in a multi-criteria setting where the PRF has to maximize its financial returns while minimizing various product recovery costs such as, disposal cost, disassembly cost, preparation cost, holding cost, acquisition cost, and sorting cost. The multi-criteria problem is solved using genetic algorithms and AHP techniques. Further research is planned to extend the analytical model to multi-type products and a multi-period case. It would be interesting to study the impact of disassembly yield, product recovery costs, and disposal regulations on the sale and acquisition prices.

APPENDIX

Notation:

R_T Total revenue.

C_D Total disposal cost.

C_P Total preparation cost.

C_H Total holding cost.

C_A Total disassembly cost.

C_Q Total acquisition cost.

C_S Total sorting cost.

P_N Net profit.

n_r Number of unique reusable components in a discarded product.

n'_r Number of unique recyclable components in a discarded product.

n_d Number of unique disposable components in a discarded product.

m_{ri} Multiplicity of reusable component i .

m'_{ri} Multiplicity of recyclable component i .

m_{di} Multiplicity of disposable component i .
 w_{ri} Weight of reusable component i .
 w'_{ri} Weight of recyclable component i .
 w_{di} Weight of disposable component i .
 w_p Weight of discarded product.
 p_{ri} Selling price of remanufactured component i (\$/unit).
 p'_{ri} Selling price of high quality recyclable component i (\$/lb).
 p_{ai} Selling price of high grade as-is reusable component i (\$/unit).
 p_{si} Price of scrap grade reusable component i (\$/lb).
 p'_{si} Price of scrap quality recyclable component i (\$/lb).
 p_p Price of discarded product (\$/lb).
 λ_{ri} Demand for remanufactured component i .
 λ'_{ri} Demand for high quality recyclable component i .
 λ_{ai} Demand for high grade as-is reusable component i .
 λ_{si} Demand for scrap grade reusable component i .
 λ'_{si} Demand for scrap quality recyclable component i .
 λ_p Demand for damaged discarded products.
 β Yield of sorting process.
 γ_{ri} Yield of high grade reusable component i .
 γ'_{ri} Yield of high quality recyclable component i .
 θ_{ri} Yield of remanufacturable quality reusable component i .
 R_q Quantity of proactively acquired returns.
 R_p Quantity of passively accepted returns.
 C_s Cost to sort a discarded product.
 C_r Cost to disassemble a product.
 C_q Cost to acquire a discarded product (acquisition price) (\$/unit).
 C_{pi} Cost to remanufacture high grade reusable component i .
 C'_{pi} Cost to prepare (such as crushing) high quality recyclable component i .
 C_{ai} Cost to prepare high grade reusable component i for as-is sale.
 C_{hi} Holding cost for high grade reusable component i .
 C'_{hi} Holding cost for high quality recyclable component i .
 C_{di} Cost to dispose reusable component i .

- C'_{di} Cost to dispose recyclable component i .
- C_{ddi} Cost to dispose the disposable component i .
- C_{dp} Cost to dispose the discarded product.
- C_{oi} Penalty cost to dispose reusable component i .
- C'_{oi} Penalty cost to dispose recyclable component i .
- C_{odi} Penalty cost to dispose the disposable component i .
- C_{op} Penalty cost to dispose the discarded product.
- D_{ri} Disposal limit for reusable component i .
- D'_{ri} Disposal limit for recyclable component i .
- D_{di} Disposal limit for disposable component i .
- D_p Disposal limit for damaged discarded products.

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