A Refine-or-Sell Decision Model for a Station with Continuous Reprocessing Options in an Electronics Recycling Center

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***Abstract*—Electronic product recovery centers face challenging materials separation decisions. They must evaluate the trade-offs between processing costs, holding costs, and fluctuating commodity markets for recovered materials from electronic products. As legislation and landfill costs rise, electronic product recovery centers need quantitative tools to evaluate how much processing is optimal. In this paper, the authors present an optimization model for a station with options to refine electronic scrap once or continuously. The model determines at what point materials are refined and at what point they are sold. The authors demonstrate the use of the model for refine-or-sell materials recovery decisions for a case with discarded computers and monitors.**

***Index Terms*—Bulk recycling, electronics product take-back, end-of-life product returns, mixed integer programming, production planning.**

I. INTRODUCTION

AT THE same time that product customization and complexity are challenging materials recovery from discarded electronic products, voluntary initiatives and legislation for product recycling are increasing in various regions [1]–[5]. "Design-for-Recycling" initiatives call for fewer types of materials and more easily separable materials in new electronic products [6]. However, design tools to incorporate design for recycling initiatives are still in the development phase [7]–[14]. Thus, electronic product recovery centers are faced with challenging materials separation decisions.

As illustrated in [15], electronic product recovery centers have several options for materials separation for appliances and electronics: manual disassembly or bulk recycling or a combination of both. Manual disassembly is preferred for spare parts recovery or removal of hazardous components. The degree of disassembly may be determined using models based on graph theory [16]. For bulk recycling, the electronic product recovery center must decide how much size reduction and materials separation to perform on-site. Thus, the recycler must evaluate the choice between extensive processing in order to sell fairly pure materials or limited processing to sell mixed materials to another party to further refine. The recycler's refine-or-sell decision is similar to the manufacturer's make-or-buy decision [17], [18].

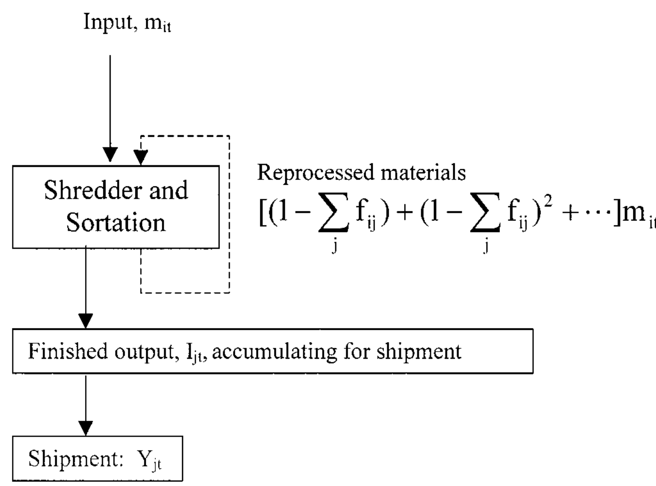

Fig. 1. Example of continuous reprocessing decision for bulk recycler.

For the refine-or-sell decision, the recycler may choose various levels of purity through different processes or through reprocessing on the same equipment. The reprocessing option may be discrete or continuous. In the former case, the recycler accumulates output and reprocesses later; while in the latter case, the recycler continuously refeeds the mixed output back through the process until it is separated according to the capabilities of the equipment. These decisions are illustrated in Fig. 1.

Only a few papers address bulk recycling of municipal wastes or discrete goods. Lund *et al.* [19] presents a linear programming model for a linear municipal waste material-recovery process to determine how far through the line to sort mixtures. A single product analysis of recycling using goal programming is proposed in [20]. In [21], goal programming is used to maximize the profits of automotive disassembler and shredder subject to inventory balance constraints. Krikke *et al.* [22] develops a dynamic program for disassembly planning and a cost algorithm to maximize revenue from material recycling. In [23], dynamic programming is used to sequence float-sink operations to separate materials by density. These models provide useful insights into single cycle bulk recycling; however, they do not address reprocessing decisions for recycling. Only [24] models dependence between processing and discrete

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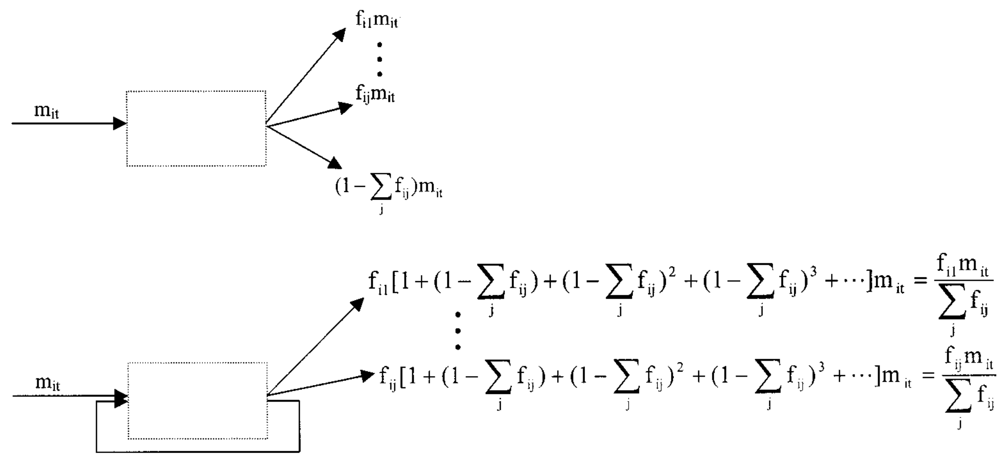

Fig. 2. Continuous reprocessing at one equipment step.

reprocessing cycles at various stations. In this paper, we present a model that evaluates the refine-or-sell decision for a recycler with continuous reprocessing options.

II. Problem Statement

According to a study presented in [25], currently more than 75 percent of end-of-life (EOL) electronic products returned to recyclers in the US come from original equipment manufacturers (OEM's) and large-scale users of electronic equipment. In these systems, OEM's and large-scale users contract with the take-back centers to discard their EOL products with similar material compositions. Bayus presents statistical analyzes that show from 1974 to 1992 OEM's did not regularly reduce the time between market introduction and withdrawal for desktop personal computers [26]. Contracts and forecasts of OEM market lifetimes can help the recycler forecast the demand of their services. However, several issues complicate the forecast of product returns:

1) marketplace with both new and established computer manufacturers;
2) marketplace with various generations of computer technology [26];
3) tendency for users to store computer equipment that is no longer in use [27].

To analyze the sensitivity of the recycler's processing decision to product take-back rates, disposal costs, and material commodity prices, a mathematical model is presented in the next section.

Our problem is to determine for discarded products with estimated compositions, take-back quantity, disposal and material commodity prices, whether to reprocess materials continuously at a processing step. Thus, for our problem statement, a recycler with a shredder and air separator may ask the following questions illustrated in Fig. 1.

1) Should the take-back center shred mixtures from computers once or continuously?
2) Should the take-back center shred mixtures from cathode ray tubes once or continuously?

Since we are analyzing short-term process planning decisions, we assume that the processing equipment is fixed. Processing costs are assumed linear and include energy consumption, labor, materials, emissions collection, and other activity-based operating costs [28]. In this paper, we evaluate the continuous reprocessing option at each processing step independently. Modeling dependence between processing and discrete reprocessing cycles at various stations is shown in [24].

We assume that the purity level of the output is a function of the type of equipment through which it is processed. We assume that the composition of the incoming products is randomly distributed so that from processing and reprocessing, constant percentages of output types are recovered. If the composition of the incoming products is not randomly distributed within the products, then manual disassembly may be cost effective in recovering concentrated amounts of more valuable materials. Models to determine whether manual disassembly is cost justified are provided in [16], [29]–[33]. If output materials are reprocessed, then they are reprocessed continuously. We define f_{ij} to be the fraction recovered in each pass from input i that meets specifications for output type j. Then, the total load for continuous (infinite) reprocessing may be expressed mathematically as a series

$$1+\left(1-\sum_j f_{ij}\right)+\left(1-\sum_j f_{ij}\right)^2+\left(1-\sum_j f_{ij}\right)^3+\cdots$$
$$=\frac{1}{1-\left(1-\sum_j f_{ij}\right)}=\frac{1}{\sum_j f_{ij}}.$$

As shown for the "no reprocessing" option in Fig. 2(a), if m_{it} is the amount of material from input i in period t, then the amount of output 1 from m_{it} that meets specifications after one cycle is $f_{i1}m_{it}$. Likewise, as shown in Fig. 2(a), the amount of output j from m_{it} that meets specifications after one cycle is $f_{ij}m_{it}$. The term $(1-\sum_j f_{ij})m_{it}$ in Fig. 2(a) represents the mixture that did not meet specifications for separation after the first pass. In Fig. 2(b), the continuous reprocessing option is shown to produce an amount of output j equal to $(f_{ij}m_{it})/(\sum_j f_{ij})$. For the continuous reprocessing option, the mixture that does not separate in the first pass is sent back through that same equipment. In the next section we present additional notation and our refine-or-sell decision model for single station operations with continuous reprocessing options.

III. Optimal Refine-or-Sell Decision Model for Processing and Continuous Reprocessing Options for a Single Station

In this section, we present a mixed-integer programming model to determine whether or not to reprocess continuously at a particular station. A station may be defined to include one or multiple tasks. Our model considers the continuous reprocessing option, accumulation of output for shipment, and the number of shipments per period. Recyclers with two to three stations that are predominantly independent may apply this model to each station. The following notation is used in the single station model with parameters defined first.

- i Type of input.
- j Type of final output material mixture.
- t Time period (week).
- m_{it} Quantity of input i processed in period t (lb/week).
- f_{ij} Percentage of material j that is recovered from total weight of input i from initial pass processing.
- π_{ij} Percentage of material j that may be recovered at specified purity level with unlimited processing of input i. Thus, $\pi_{ij} = (f_{ij})/(\sum_j f_{ij})$.
- p_i Time to process weight unit of input i (hours/lb).
- r_j Price/cost of each shipment of material j ($/shipment).
- h_j Holding cost of each weight unit of material j for one time period $lb*week).
- c Processing cost of each weight unit of products/materials ($/hr).
- d Disposal cost of each weight unit of waste materials ($/lb).
- S_j Unit shipment load quantity for material j (lb/shipment).
- Q Processing capacity for each time period (hours/week).

Variables

- B_i $\begin{cases} 1 & \text{select to reprocess output of input } i \\ 0 & \text{otherwise} \end{cases}$.
- I_{jt} Quantity of material j waiting for shipment at the end of time period t (lb).
- Y_{jt} Number of shipments achieved for material j in time period t (#).

Maximize

$$\sum_t \sum_j r_j Y_{jt} - \sum_t \sum_j h_j I_{jt} - \sum_t \sum_i cp_i \cdot \left[\frac{m_{it}}{\sum_j f_{ij}} B_i + m_{it}(1-B_i) \right] - \sum_t \sum_i dm_{it} \cdot \left(1 - \sum_j f_{ij}\right)(1-B_i) \quad (1)$$

such that

$$\sum_i p_i \left[\frac{m_{it}}{\sum_j f_{ij}} B_i + m_{it}(1-B_i) \right] \le Q \qquad \forall\, t \quad (2)$$

$$I_{j,t-1} + \sum_i [\pi_{ij} m_{it} B_i + f_{ij} m_{it}(1-B_i)] = I_{jt} + S_j Y_{jt} \qquad \forall\, j, t \quad (3)$$

$$I_{jt} \le S_j \qquad \forall\, j, t \quad (4)$$

$$I_{j0} = 0 \qquad \forall\, j \quad (5)$$

$$Y_{jt} \quad \text{integer} \qquad \forall\, j, t \quad (6)$$

$$B_i \quad \text{binary} \qquad \forall i. \quad (7)$$

The model (1)–(7) is a mixed-integer programming model that captures a continuous reprocessing choice. The objective function (1) maximizes net profit from material recovery of discarded products for a single station. We define net profit to be the revenue from shipments minus the processing, reprocessing, holding, and disposal costs. If reprocessing is not selected, then the total output not meeting specifications is either disposed at cost d or sold for a lower price than materials meeting specifications. Inequality (2) represents the capacity of the equipment. Equation (3) represents the inventory balance equation for the output each period. Inequality (4) represents the shipment capacity. The shipment capacity, S_j, will usually represent full truckload (FTL) to minimize transportation costs. The shipment capacity constraints are also important to ensure shipments when the revenues for shipping materials may be negative. For example, if material j is hazardous or of lower value than the shipping cost, then inequality (4) forces the model to move material j out of the plant in S_j (FTL) increments. Equation (5) sets the initial inventory values. Constraints (6) and (7) define the integer variables in the model.

TABLE I
TYPICAL APPLICATION SIZES

		Example				
Description	Indices	1	2	3	4	5
Type of input	I	4	10	10	20	20
Type of final output material mixture	J	6	6	8	10	10
Time period (week)	T	4	4	4	8	16
Number of binary variables		4	10	10	20	20
Number of general integer variables		24	24	32	80	160
Number of nonnegative continuous variables		24	24	32	80	160
Number of constraints (excluding integrality/nonnegativity)		86	92	118	278	526

The values of some materials are so low that they incur a cost for recovery. If corporate goals are to avoid landfilling, then model (1)–(7) can evaluate the choices between selling materials for salvage and paying for external materials recovery. This decision is analogous to the make-or-buy decision in assembly. Thus, we have labeled it the "refine-or-sell" decision in recycling.

Although mixed-integer programs are NP-complete, small instances can often be solved using branch and bound algorithms [34]. Typical problem sizes for applications of the model (1)–(7) are shown in Table I. In Section IV, the model is illustrated on a typical application of the size of example 1 in Table I.

IV. APPLICATION

In order to illustrate the potential application of this model, we studied several published case studies and pilot project reports of electronics recycling [25], [35]–[42]. We also communicated with several companies about the electronics recycling processes [43]–[46]. Based on the information, we formed the data set for the sample problem.

For the sample problem, we assumed that there are four types of incoming product groups and six types of output material mixtures as shown in Tables II and III. Table II provides the general description, weight per unit, and typical incoming quantities. Table III shows the characteristics of the six output materials as well as their prices. If the costs for processing, handling, and transporting the output materials exceed their market value, then the output material price is negative in Table III. Negative material prices may occur if a material is hazardous or of very low market value.

The processing equipment we modeled included a shredder that reduces incoming products to material fragments ranging from 1 in to 3 in (2.54 cm to 7.62 cm) long. We assumed that the shredder could process approximately 1500 lbs/h (3300 kg/h) of cathode ray tubes (CRT) or 2000 lbs/h (4400 kg/h) of PC systems. The processing time capacity is assumed to be 40 h/wk. The processing costs for the shredder and manual sortation are assumed to be \$60/h. Each group of incoming products is run separately in the designated time period (wk) for the processing capacity of the equipment.

TABLE II
INCOMING PRODUCT DESCRIPTION AND QUANTITY

Index i	Product Description	Weight/unit lb. (kg)	Incoming Quantity units/week
1	21" CRT	48.16 (105.95)	200
2	17" CRT	27.75 (61.05)	300
3	14" CRT	14.7 (32.34)	400
4	PC system	44 (96.8)	900

TABLE III
OUTPUT MATERIALS CHARACTERISTICS

Number (j)	Output Characteristics	Price (US\$/lb.)
1	Ferrous metal mixture (≥90% by weight)	0.0225
2	Non-ferrous metal mixture (≥90% by weight)	0.28
3	Plastic mixture (≥90% by weight)	-0.0245
4	PWA* mixture (≥90% by weight)	0.8
5	Wire & Cable--Cu dilute mixture (≥50% by weight)	0.05
6	Glass mixture (≥90% by weight)	-0.0843

The output is determined according to the capabilities of the equipment. In this case, the equipment is capable of separating the electronics equipment into ferrous mixtures that are at least 90% pure. In Table IV, we provide the separation capabilities of the equipment on the first pass. For example, on the first pass, the process is able to separate a 21-in CRT into four outputs: 32% ferrous mixture (>90%), 0.8% wire and cable, 63% glass,

TABLE IV
OUTPUT CHARACTERISTICS ON FIRST PASS (f_{ij})—NO REPROCESSING OPTION

f_{ij}	Ferrous metal j=1	Non-ferrous metal j=2	Plastic j=3	PWA j=4	Wire & cable j=5	Glass j=6	$1-\sum_j f_{ij}$
i=1 21" CRT	32.0%	0.0%	0.0%	0.0%	0.8%	63.0%	4.2%
i=2 17" CRT	30.0%	0.0%	0.0%	0.0%	2.5%	64.0%	3.5%
i=3 14" CRT	20.0%	0.0%	0.0%	0.0%	3.5%	71.0%	5.5%
i=4 PC system	20.0%	30.0%	25.0%	10.0%	8.5%	0.0%	6.5%

TABLE V
OUTPUT CHARACTERISTICS FOR CONTINUOUS REPROCESSING OPTION (π_{ij})

π_{ij}	Ferrous metal j=1	Non-ferrous metal j=2	Plastic j=3	PWA j=4	Wire & cable j=5	Glass j=6
i=1 21" CRT	33.4%	0.0%	0.0%	0.0%	0.8%	65.8%
i=2 17" CRT	31.1%	0.0%	0.0%	0.0%	2.6%	66.3%
i=3 14" CRT	21.2%	0.0%	0.0%	0.0%	3.7%	75.1%
i=4 PC system	21.4%	32.1%	26.7%	10.7%	9.1%	0.0%

and 4.2% unseparated mixture. As shown in Table V, if continuous reprocessing is selected, then the unseparated mixture is processed until it is separated into ferrous mixture, wire and cable, and glass.

V. COMPUTATIONAL RESULTS

Since the model presented is a mixed-integer programming model, we can create different runs by varying parameters to test the sensitivity of the reprocessing decisions. In our numerical experiments, we did 20 experimental runs by varying the holding costs, shipment sizes, and disposal costs. The disposal costs could represent shipping costs to another recycler for further processing if the initial recycler does not have the necessary capabilities.

Table VI contains the shipping information for each type of recovered material, including the estimated price and shipment size as well as the holding cost information. Since the value associated with recovered material is very low, the holding costs mainly consist of overhead and maintenance costs for storage space. We converted a constant per square foot holding cost to a per weight unit holding cost using the density of each type of material.

The model was solved using the commercially available CPLEX 6.5 Linear Optimizer on a DELL Pentium III 600 personal computer. We generated ten runs with various combinations of disposal costs, holding costs, and shipment sizes. The results of the experimental runs are shown in Table VII.

The disposal costs vary widely in different states and countries. An average US$29.25/ton tipping fee is charged for non-hazardous landfill disposal in the city of Columbus, OH [47], [48] while the average landfill tipping fee in the state of New York in the U.S. is U.S.$83.24/ton [49]. According to a disposal company in the industry, if the end-of-life products contain any hazardous materials, such as leaded glass, the disposal costs

TABLE VI
REVENUE AND SHIPMENT INFORMATION

Index j	1	2	3	4	5	6
Materials Description	Ferrous Metal	Non-ferrous Metal	Plastic	PWA	Wire & Cable	Glass
Price (US$/lb.)	0.0225	0.28	-0.0245	0.8	0.05	-0.0843
High shipment S_j (lbs./shipment)	50000	25000	10000	20000	15000	40000
Low shipment S_j (lbs./shipment)	25000	12500	5000	10000	7500	20000
High holding cost H_j (US$/lb.)	0.00250	0.00833	0.02000	0.01250	0.01667	0.00263
Low Holding cost H_j (US$/lb.)	0.00050	0.00167	0.00400	0.00250	0.00333	0.00053

TABLE VII
EXPERIMENTAL RUNS

Data Input				Result--Reprocessing options (O No reprocessing ● Reprocessing)			
Run	Holding cost	Shipment Size	Disposal cost (US$/ton)	i=1	i=2	i=3	i=4
1	Low	Low	85	O	O	O	●
2	Low	Low	90	●	●	●	●
3	Low	High	85	O	O	O	●
4	Low	High	90	●	●	●	●
5	High	Low	90	O	O	O	●
6	High	Low	100	●	●	O	●
7	High	Low	105	●	●	●	●
8	High	High	90	O	O	O	●
9	High	High	100	●	●	O	●
10	High	High	105	●	●	●	●

may be as high as U.S.$300–500/ton in order to stabilize the hazardous content. We tested our model in situations with different disposal costs. The results show that disposal costs as low as U.S.$90/ton may result in reprocessing of all four inputs if the holding cost is low. When the holding cost is high, then holding materials longer for reprocessing becomes less economical. If the disposal cost increases above U.S.$105/ton, the model will select to reprocess all the incoming products for both of the levels of incoming product quantity, holding cost, and shipment sizes tested. Table VII demonstrates that different combinations of incoming quantity, holding costs, and shipment sizes will determine the threshold of disposal cost that changes the reprocessing decisions.

VI. CONCLUSIONS

In conclusion, recyclers with a continuous reprocessing option on their equipment may use the model presented in this paper to determine when it is best to reprocess and when it is best to process only once for various product take-back rates, materials commodity prices, holding costs, and disposal charges. In the application tested, the model was most sensitive to disposal costs. In practice, countries with limited landfill space and high disposal costs are testing bulk processing and materials recovery options [50], [51]. Thus, the model may be helpful in determining the sensitivity of the processing decisions to important parameters, especially those affected by legislation, commodity markets, or transportation costs.

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