A Model for Discrete Processing Decisions for Bulk Recycling Of Electronics Equipment

Julie Ann Stuart and Qin Lu

***Abstract*—Discarded electronics equipment returns provide an opportunity for the diversion of landfill-bound goods through bulk materials recycling. In this paper, we develop a decision model to select bulk recycling processing and reprocessing options for a take-back center that receives large quantities of similar products. We demonstrate the model's use for a generic take-back center example. The model is computationally tractable and provides sensitivity analysis on key parameters such as the metals commodity prices.**

***Index Terms*—Bulk recycling, electronics product take-back, end-of-life product returns, linear programming, multicommodity flow models, production planning, sensitivity analysis.**

I. INTRODUCTION

HUNDREDS of millions of computers, televisions, telecommunications equipment, automotive electronics, and appliances are sold worldwide each year [1], [2]. Because the technology changes rapidly, electronics are often replaced before the end of their functional life. Electronics may be refurbished for secondary markets or stored indefinitely. This makes the task of forecasting product take-back rates difficult [3], [4]. Discarded electronics may be reused or recycled in order to reduce new materials consumption and prevent landfill disposal of leachable lead from tin/lead solders and cathode ray tubes (CRTs) [5]–[7]. In the 1980s and early 1990s, discarded mainframe computers contained precious metals that were recovered by recyclers [8], [9]. However, current personal computer (PC) models contain less precious metal content and more plastic content [10], [11]. Diversion of millions of discarded electronics from landfills has more recently been motivated by legislation, voluntary initiatives, and obsolete product returns from leases [12]–[17]. Therefore, an approach to help recyclers determine how to recover materials more economically from millions of low-value PCs and CRTs is needed.

Design for environment (DFE) tools help manufacturers include environmental considerations in their design process in order to reduce the future costs of reuse and recycling [18]–[21]. In addition, production planning models have been extended to include environmental considerations in the manufacturing, reuse, or materials recovery phases of the product life cycle [22]–[25].

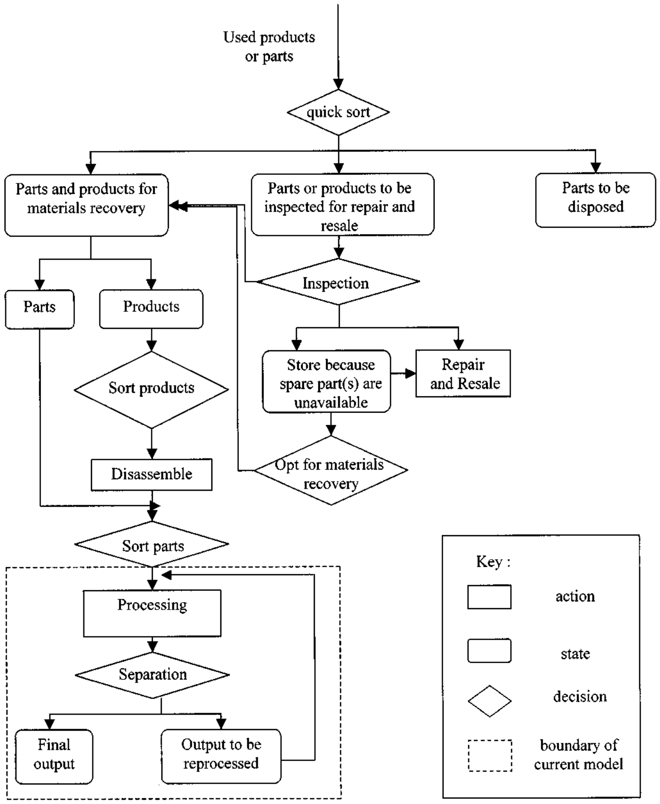

Fig. 1. Decision diagram of end-of-life product strategies for take-back center.

The benefits of DFE product features will be further realized as the infrastructure and operations of the reverse supply chain are improved. In [26], a decision hierarchy for the reverse supply chain is illustrated. Decisions in the top level focus on the collection system. In the next level, the take-back center must make initial decisions between reuse and materials recovery. The decision hierarchy within the take-back center is illustrated in Fig. 1.

For the repair and resale option in Fig. 1, products are batched and inspected. At the inspection stage, the recycler must decide whether to repair the product, store the product until spare parts are available, or send the product to materials recovery. For the repair option, researchers have developed models to manage capacity, inventory, and new-part procurement for a single-product system [27]–[30]. Important to either repair or labor-intensive materials recovery processes is the development of a disassembly strategy [31]. For the materials recovery option, the recycler batches the products and determines both how much processing and how much reprocessing to schedule.

Manuscript received March 10, 2000; revised August 25, 2000. This work was presented in part at the Recycling 2000 Conference, Toronto, ON, Canada, June 5–9, 2000. This work was supported by an Ameritech Grant and National Science Foundation Grant DDM-9734310.

J. A. Stuart is with the School of Industrial Engineering, Purdue University, West Lafayette, IN 47907 USA (e-mail: stuart@ecn.purdue.edu).

Q. Lu is with The Ohio State University, Columbus, OH 43210 USA (e-mail: lu.102@osu.edu).

Publisher Item Identifier S 1521-334X(00)11074-2.

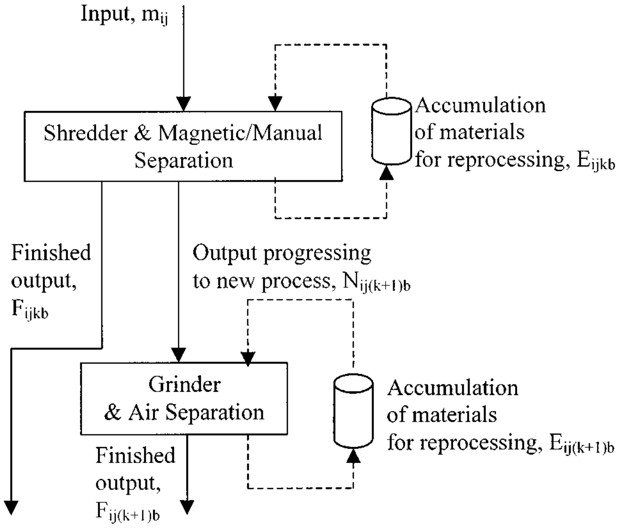

Fig. 2. Example of processing and reprocessing decisions for bulk recyclers (notation is defined in Section II-B).

Integrated disassembly and materials recovery approaches have been developed. Spengler, *et al.* use mixed integer programming to determine the level of dismantling and quantity of material to recycle by a given method [32]. Krikke, *et al.* use stochastic dynamic programming for disassembly planning and cost analysis for materials recycling planning [33]. Several researchers use goal programming to optimize profitability with other recycling goals [34], [35]. Sodhi and Knight use dynamic programming to determine the sequence of operations for float–sink materials separation by density [36].

To date, no decision models for materials recovery have focused on the challenge of allocating limited processing capacity to re-entrant material flows. As shown in Fig. 2, when recyclers mechanically reduce the size of materials in preparation for magnetic, fluid, or air separation techniques, they must also decide how much size reduction and materials separation is economically best. Each mechanical reduction and separation "run" incurs processing costs and cycle time requirements that decrease the economic gains realized from higher value of finer and more pure output.

In the next section, we introduce notation and a new multicommodity flow model that is computationally attractive for planning for discrete bulk recycling. Then we conduct sensitivity analysis on the model to demonstrate its use for uncertain materials commodity markets. Use of the model will provide a recycler with the threshold materials sale price for reprocessing.

II. DISCRETE PROCESSING AND REPROCESSING MATERIALS RECOVERY MODEL

A. *Objective and Assumptions*

Our problem focus is the take-back center that handles large quantities of similar products. For example, take-back centers may have contracts with large manufacturers or may batch similar products from mixed waste streams. As shown in Fig. 1, typical take-back centers make decisions after "quick sort," "sort products," "sort parts," and "separation." The system boundary considered for our model is also shown in Fig. 1. We develop a multicommodity flow model that can be used by a take-back center to select processing and reprocessing options for materials recovery. The objective of the model is to maximize net revenue subject to the constraints of processing capacity and inventory capacity of in-process products.

Our problem is to determine for bulk materials recovery what processing steps to include and whether any of those steps should be repeated. For our problem statement, the recycler is asking questions such as the following.

1) Should a take-back center shred laminate-rich mixtures from printed wiring assemblies (PWAs)? Once? Multiple times? Should they grind laminate-rich mixtures? Once? Multiple times?
2) If reprocessing enhances product value less with repeated cycles, at what point do diminishing returns preclude reprocessing?

For our model, we assume that the compositions of the incoming product groups (such as CRT, PC, or PWA) are known for take-back centers that receive significant quantities of similar products. This is the case for take-back centers with contracts with original equipment manufacturers or large-scale users (i.e., an insurance company upgrading their equipment on a regular basis). The grouping criteria are determined prior to the processing and reprocessing decision analyzed here [21]. A group of products may be characterized by similarities in material composition, processing requirements, size, current inventory, or other criteria. For a take-back center handling municipal take-back, the variation in material composition and quality may require composition probabilities.

We assume that the value of the output is a function of the equipment through which it is processed. Since we are analyzing short-term process planning decisions, we assume that the processing equipment is fixed. Unlike manual disassembly costs and processing times, the materials recovery processing costs and time per cycle are assumed linear with respect to the quantities of material processed per cycle. The processing costs may include energy consumption, labor, materials, emissions, and other activity-based operating costs [37].

Since materials recovery requires size reduction and materials separation, there are strong precedence relationships between processing steps. Thus, we assume that all products start at the same initial size reduction equipment, $k = 1$. The output from each separation equipment step may be finished, saved for reprocessing, or transported to the next separation step. This is illustrated in Fig. 3 for the sample problem. There are two options for modeling the number of cycles: an integer decision variable and an *a priori* limited index range. Using an integer decision variable significantly increases the complexity of the model and the solution approach [38]. On the other hand, if the number of cycles is formulated as an index, then the model size may increase dramatically with problem size since the number of constraints depends on the maximum number of cycles. However, since the amount of material that may be reprocessed in the same equipment decreases with each succeeding cycle, it is reasonable in practice to use an *a priori* limited index range, which is represented by β_{ik} in the model. If the equipment is equipped with automatic feeders that provide a continuous reprocessing option, a third approach that selects between no reprocessing

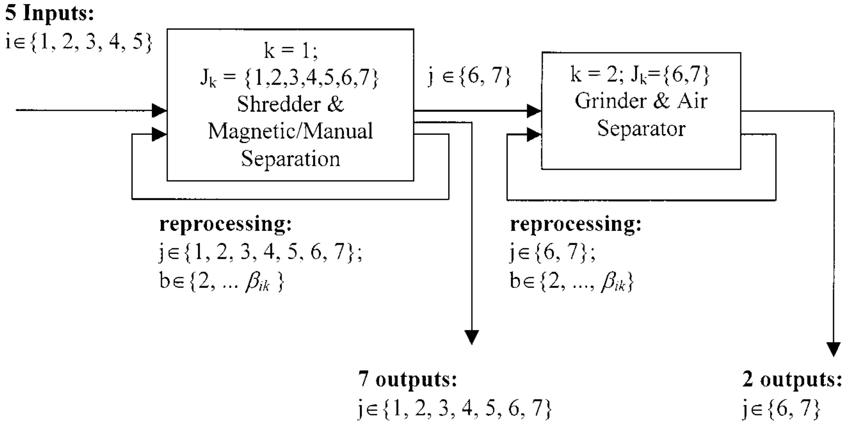

Fig. 3. Process flow chart for sample problem.

and continuous reprocessing may be employed as demonstrated in [39].

Another important concept included in our choice of indices is that the output purity depends on the material compositions, the processing requirements, and the number of cycles. Thus, the model may include the scenario in which output purity increases with diminishing returns.

B. Notation

To answer questions about processing and reprocessing, we present a multicommodity flow model. We introduce the following notation.

Indices and sets:

i	Incoming group (such as CRT, PC, or PWA); $i \in \{1, \cdots, I\}$.
j	Output (such as specified mixture or component); $j \in \{1, \cdots, J\}$.
k	Equipment and tooling; $k \in \{1, \cdots, K\}$.
b	Number of processing cycles; $b \in \{1, \cdots, \beta_{ik}\}$.
J_k	$\{j\|$ output j may feasibly be processed on equipment $k\}$.

Parameters and coefficients:

r_{ijkb}	Revenue for output j from group i after processing on equipment k for b cycles ($/weight unit).
m_{ij}	Weight of output j from group i (weight unit).
c_k	Processing cost per hour on equipment k ($/hour).
p_{ijk}	Processing time required per weight unit of output j from group i on equipment k (hrs/weight unit).

Limits:

q_k	Processing hours for equipment k per week (hrs/week).
β_{ik}	Maximum number of cycles that group i may be processed on equipment k.

Variables:

F_{ijkb}	The quantity of finished product of output j from group i through processing on equipment k after cycle b (weight unit).
E_{ijkb}	The quantity of in-process product of output j from group i through processing on equipment k after cycle b (weight unit).
$N_{ij(k+1)b}$	The quantity of in-process product of output j from group i that progresses to processing equipment $(k+1)$ at the end of cycle b (weight unit).

The objective function of this model, shown in (1), is to maximize the profit of material recovery of end-of-life products. The profit equals the revenue from final output materials minus the processing costs on all the equipment (see (2) and (3)

Materials Recovery Discrete Reprocessing Linear Programming Model: See (1)–(9) at the bottom of the next page.

As shown in [26], the structure of the recycling production planning problem is very similar to that of the traditional production planning problem with inventory balance equations. However, there are also differences between the two problems. In a traditional production planning model, inventory balance equations are used to represent inventory of finished goods carried from one period to the next period [40]. In our reprocessing model, inventory balance (4)–(8) are used to represent in-process inventory carried from one cycle to the next cycle on a piece of equipment. Because some product outputs may progress to additional processing equipment, (4)–(8) also include distinctions for the processing sequence. The model evaluates the benefits and costs of additional processing and assigns values to the E_{ijkb} and N_{ijkb} variables accordingly. For all $b = \beta_{ik}$, $E_{ijkb} = 0$, since no reprocessing will take place after the final cycle (see (9)).

Because the model is formulated as a linear program, it may be solved quickly using the simplex method and it provides capabilities for sensitivity analysis of different system characteristics [41]. The model enables the decision-maker to determine the sensitivity of the solution to changes in parameters such as the material compositions, processing costs, and material revenues. For example, the model may be used to analyze the sensitivity of the reprocessing decision to the metal commodity prices, especially the volatile prices of precious metals.

C. Sample Problem

Initial tests were run to demonstrate the insights that the model may provide. The authors formed a sample data set by studying several published case studies of electronics recycling [42]–[48] and from communication with industrial collaborators [10], [11], [49]–[53].

The sample problem includes five inputs, seven outputs, and two different types of recycling equipment as shown in Fig. 3 and Table I. In our sample problem, we defined our five input groups for index i as 21″ CRTs, 17″ CRTs, 14″ CRTs, PCs, and PWAs, respectively. The negative revenues for the plastic mixtures and the glass mixtures indicate that these recovered materials have higher distribution costs than material procurement costs. For $k = 1$, we assigned the same values to outputs $j = 6$ and $j = 7$ since printed wiring assembly (PWA) metals mixture and PWA laminates mixture are still blended together after shredding. After grinding and air separation, however, the PWA metals mixture is separated from the laminates and has a higher salvage value since the purity is greater.

Each group of incoming products is run separately in the designated time period (week) for the processing capacity of the equipment. We assume that the shredder can process approximately 1500 lbs (682 kg) of CRTs, or 2000 lbs (909 kg) of PCs, or 2500 lbs (1136 kg) of PWAs every hour and that it reduces incoming products to material fragments ranging from 1″–3″ (2.5–7.6 cm) long. The grinder and air separator can process approximately 3000 lbs (1363 kg) of PWAs every hour and reduces incoming fragments to particles approximately

TABLE I
SAMPLE PROBLEM OUTPUT CHARACTERISTICS

No. (j)	Output Characteristics	Price ($/lb.) (b=1, k=1) r_{ij11}	Price ($/lb.) (b=1, k=2) r_{ij21}
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	Glass mixture (≥90% by weight)	-0.0843	--
5	Cu dilute mixture (≥50% by weight)	0.05	--
6	PWA metal mixture	0.08	1.4
7	PWA laminates mixture	0.08	0.05

$$\mathrm{Max}\left\{\sum_{i}\sum_{k}\sum_{j\in J_k}\sum_{b=1}^{\beta_{ik}} r_{ijkb}F_{ijkb} - \sum_{k} c_k \sum_{i}\sum_{j\in J_k} p_{ijk}\left[m_{ij} + \sum_{b=2}^{\beta_{ik}} E_{ijkb} + \sum_{b=1}^{\beta_{i(k-1)}} N_{ijkb}\right]\right\} \tag{1}$$

Equipment processing capacity constraints:

$$\sum_{i}\sum_{j\in J_k} p_{ijk}\left[m_{ij} + \sum_{b=2}^{\beta_{ik}} E_{ijkb}\right] \le q_k \qquad k = 1 \qquad \text{First processing equipment capacity} \tag{2}$$

$$\sum_{i}\sum_{j\in J_k} p_{ijk}\left[\sum_{b=2}^{\beta_{ik}} E_{ijkb} + \sum_{b=1}^{\beta_{i,(k-1)}} N_{ijkb})\right] \le q_k \qquad \forall k,\ 1 < k \le K \qquad \text{Subsequent processing equipment capacity} \tag{3}$$

Inventory balance equations:

$$m_{ij} = E_{ij12} + F_{ij11} + N_{ij21} \qquad \forall i,\ j \qquad \text{First processing equipment, first cycle} \tag{4}$$

$$\sum_{b=1}^{\beta_{i(k-1)}} N_{ijkb} = E_{ijk2} + F_{ijk1} + N_{ij(k+1)1} \qquad \begin{array}{c}\forall i,\ j \in J_k,\\ \forall k = 2, \cdots, K-1\end{array} \qquad \text{Subsequent processing equipment, first cycle} \tag{5}$$

$$\sum_{b=1}^{\beta_{i(K-1)}} N_{ijKb} = E_{ijK2} + F_{ijK1} \qquad \forall i,\ j \in J_K \qquad \text{Last processing equipment, first cycle} \tag{6}$$

$$E_{ijkb} = E_{ijk(b+1)} + F_{ijkb} + N_{ij(k+1)b} \qquad \begin{array}{c}\forall i,\ j \in J_k,\\ \forall k = 1, 2, \cdots, K-1\\ \forall b = 2, \cdots, \beta_{ik}.\end{array} \qquad \text{All except last processing equipment, subsequent cycle} \tag{7}$$

$$E_{ijKb} = E_{ijK(b+1)} + F_{ijKb} \qquad \begin{array}{c}\forall i,\ j \in J_K,\\ \forall b = 2, \cdots, \beta_{iK}.\end{array} \qquad \text{Last equipment, subsequent cycle} \tag{8}$$

$$E_{ijkb} \ge 0,\ F_{ijkb} \ge 0,\ N_{ijkb} \ge 0 \qquad \forall i,\ k,\ j \in J_k,\ b \qquad \text{Non-negativity constraints} \tag{9}$$

TABLE II
QUANTITY OF SPECIFIED MIXTURES OF INCOMING PRODUCTS PER WEEK FOR GENERIC COMPUTER RETURNS CENTER (lbs/WEEK)

m_{ij} (lbs./week)	j=1	j=2	j=3	j=4	j=5	j=6	j=7	Total quantity of product units or weight received
i=1 (21" CRT)	271	136	300	782	17	54	122	25 units
i=2 (17" CRT)	584	292	850	1825	75	191	435	100 units
i=3 (14" CRT)	650	325	1425	3225	210	251	574	300 units
i=4 (PC)	6857	3429	4862	0	1683	570	1301	425 units
i=5 (PWA)	0	0	0	0	0	153	348	500 lbs.

TABLE III
EXPERIMENTAL RUNS AND RESULTS

	Data Input			Results
Run	c_1 ($/hr)	Percentage revenue increase for b=2	Percentage revenue increase for b=3	Reprocessing k=1; j=2
1	60	10%	2%	No
2	50	10%	10%	No
3	40	10%	10%	Yes
4	45	10%	10%	No
5	60	20%	5%	Yes
6	60	30%	10%	Yes

0.05″–0.2″ (0.13–0.51 cm) in diameter. In our model we assumed that the air separator deposits outputs into containers where they accumulate for shipping or reprocessing. The processing time capacity, q_k, is assumed to be 40 h/week for both pieces of equipment. Quantities of incoming products for the sample problem are given in Table II.

Processing costs for the shredder, c_1, are given in Table III. Processing costs for the grinder and air separation step, c_2, are $25/h. To demonstrate sensitivity analysis for the model, we ran the model under varying cost and revenue conditions as shown in Table III. We varied the diminishing returns for reprocessing by changing the percentage increase in revenue for additional cycles. We also varied the processing costs for the shredder.

The model was solved using the commercially available CPLEX 6.5 Linear Optimizer on a DELL Pentium 600 personal computer [54]. The results that varied for the runs are also shown in Table III.

For output $j = 6$, reprocessing at $k = 2$ was selected for all runs. For outputs $j = 1$, 3, 4, 5, and 7, no reprocessing was selected for either type of equipment. The sensitivity of the choice to reprocess output $j = 2$ (nonferrous metals) is significant since it exhibited a volatile price history as seen in Fig. 4 [55]. The point at which the nonferrous metal price changes the decision from processing once to processing more than once at the shredder is graphed in Fig. 5.

III. CONCLUSIONS

The reprocessing decision model captures the costs and capacity restrictions for the materials recycling processes for discrete reprocessing. The new model presented in this paper can help recyclers make more cost effective decisions regarding the level of bulk recycling for both high-value electronic components such as PWAs and low-value electronics such as CRTs and PCs. The model may also be used to analyze recycling process options for appliances or other discrete goods for which the materials recovery costs and time are approximately linear with respect to the input processed per cycle.

However, the preceding steps of part and product sorting shown in Fig. 1 are not considered in the current reprocessing decision model. The authors are currently studying the effects of *a priori* part and product sorting on the reprocessing decision for take-back centers processing highly variable returns from sources such as municipal solid waste streams. Because the reprocessing decision model is a deterministic model, the stochastic nature of product return composition characteristics is not captured. Nonetheless, batching for similar product composition characteristics should lessen this variability. Furthermore, sensitivity analysis allows for exploration of the ranges for uncertain data points.

The materials recovery production planning decision model provides insights into the complexity of take-back center operations management. The effects of different processing options,

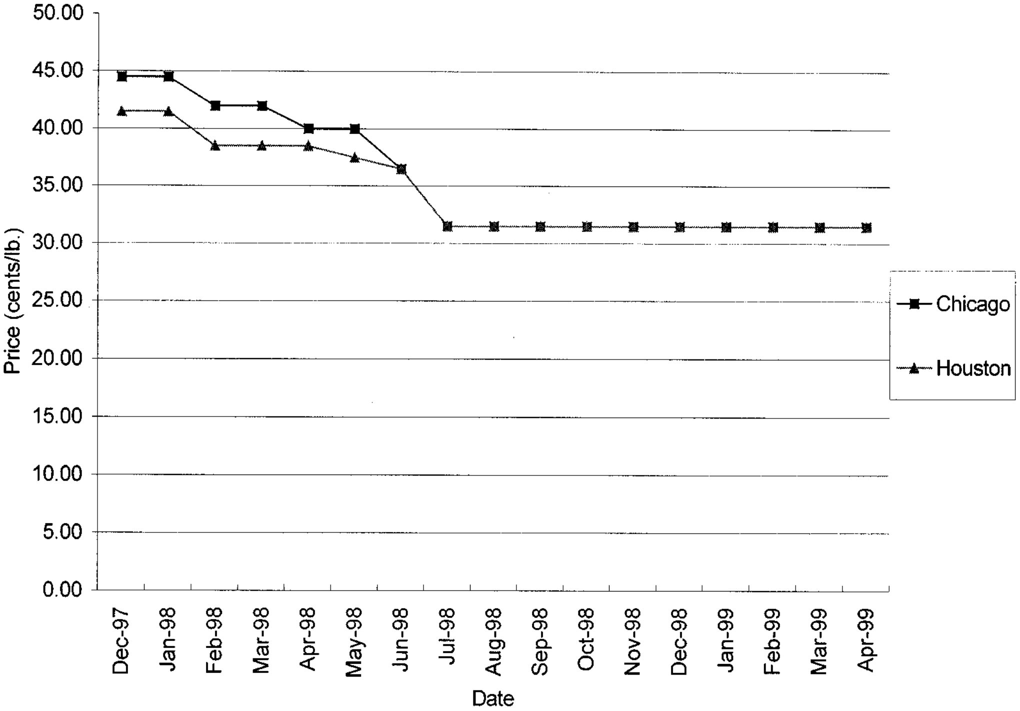

Fig. 4. Scrap mixed aluminum prices [55].

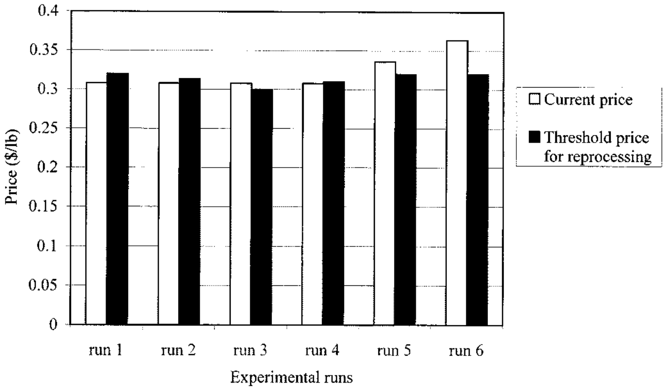

Fig. 5. Sensitivity analysis: nonferrous metal price threshold for reprocessing.

including their value added, processing cost, processing time, and capacity are contrasted from a production planning perspective. The multicommodity flow model is computationally attractive. As a result, this paper describes a useful framework for modeling discrete processing and reprocessing decisions for product take-back centers.

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Julie Ann Stuart received the M.S. and Ph.D. degrees in industrial and systems engineering from the Georgia Institute of Technology, Atlanta.

She is an Assistant Professor in the School of Industrial Engineering, Purdue University, West Lafayette, IN. Her research and teaching interests focus on forward and reverse production planning, forward and reverse distribution, and facilities design. Before beginning her current position, she was an Assistant Professor at The Ohio State University, Columbus.

Dr Stuart received the National Science Foundation (NSF) CAREER Grant in Production Systems, an NSF/Lucent Technologies Industrial Ecology Fellowship, and an Ameritech Faculty Fellowship. She is a member of IIE, INFORMS, and SME.

Qin Lu received the B.S. degree with a double major in automatic control and engineering economics from the Shanghai Jaio Tong University, Shanghai, China and is currently pursuing the Ph.D. degree in the Department of Industrial, Welding, and Systems Engineering, The Ohio State University, Columbus. Her current research interests focus on developing strategic decision tools and operational production planning models for electronics take-back centers. She has studied product take-back operations first-hand at take-back centers in Ohio and Texas.

Ms. Qin is a member of INFORMS.