An Investigation of Bulk Recycling Planning for an Electronics Recycling Facility Receiving Industrial Returns Versus Residential Returns

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***Abstract*—Since most end-of-life electronics equipment contain hazardous materials such as lead solder alloys or lead-impregnated glass, it is important to divert them from landfills. For end-of-life products that are not repairable and do not contain reusable parts, bulk recycling is an alternative to recover base materials. In this paper, we contrast production and recycling planning and distribution decisions, activities, and costs. We reveal that while a traditional production facility connects suppliers and customers, a recycling facility connects both "input" and "output" customers. As a result, decisions in short-term bulk recycling planning include what products to accept, what products to process and reprocess, and what products to carry in inventory. Many recyclers set prices to receive "input" based on experience. For various prices to receive "input," we use a new analytical model to investigate the sensitivity of the short-term bulk recycling planning decisions in products from two different sources: industrial returns versus residential returns. The results of the case study show that different decisions are recommended for the industrial returns versus the residential returns when the total quantity of the incoming products is equal.**

***Index Terms*—Bulk recycling, electronics product take-back, industrial returns, production planning, residential returns.**

NOMENCLATURE

AC	Air conditioners.
CRT	Cathode ray tube.
EOL	End-of-life.
OEM	Original equipment manufacturer.
PC	Personal computer.
Production facility	Facility that receives raw materials that are assembled into products for sale.
PWA	Printed wiring assembly.
Recycling facility	Facility that receives end-of-life products which are processed to separate materials for resale.
SBRP	Short term bulk recycling planning model (Fig. 2).
TCLP	Toxic characteristics leaching procedure.
TV	Television.

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Notation for Indices

b	Reprocessing cycle; an indicator for the number of cycles a product is processed for materials separation.
i	Incoming product return category.
j	Outgoing material category.
k	Equipment type.

I. INTRODUCTION

BECAUSE most electronics contain printed wiring boards with lead solder alloys and cathode ray tubes (CRTs) contain lead-impregnated glass, they commonly fail the U.S. Environmental Protection Agency's Toxicity Characteristic Leaching Procedure (TCLP) [1], [2]. One increasingly challenging aspect of asset management for industrial and government users is the recycling, or proper disposal, of end-of-life (EOL) electronic equipment. Municipal solid waste authorities also seek alternatives to landfill for discarded electronic equipment. The magnitude of the problem is expected to increase. For example, the number of personal computers (PCs) alone in the United States is expected to rise steadily from an estimated 41.9 million in 2001 to 61.3 million by 2007 according to the U.S. National Safety Council's Environmental Health Center [3].

As a result, bulk recycling planning is important to determine how to balance processing capacity, recycling goals, and net revenues. In this paper we begin by contrasting the structure of production and recycling activities. Next, we contrast the economics of production and recycling and discuss the sources and infrastructures for product returns. Using a recently developed bulk recycling planning model, we vary prices to receive products and investigate the sensitivity of bulk recycling planning to two different sources of returns: industrial returns versus residential returns. In our discussion of the results, we identify parameters that may be sensitive to the returns source and market conditions.

II. COMPARISON OF TRADITIONAL PRODUCTION PLANNING AND BULK RECYCLING PLANNING

Fig. 1 illustrates functions and flows in a bulk recycling facility. After the products are received and unloaded, a preliminary sortation and disassembly is performed to group the products and parts into batches. The recyclers may choose not to

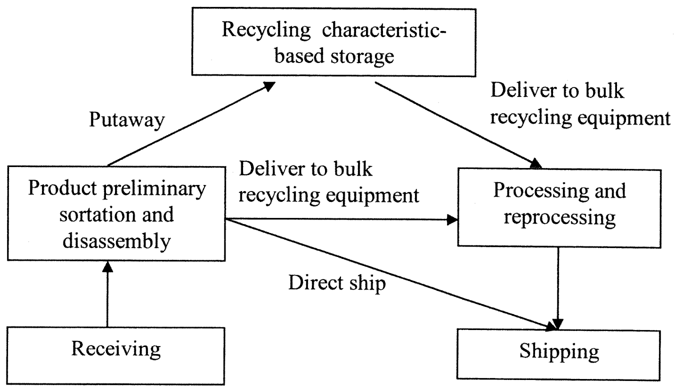

Fig. 1. Functions and flows for an electronics bulk recycling facility.

keep all the EOL products received; they may choose to directly ship some products for proper disposal or recycling at another facility. After disassembly, the accepted products are either sent directly to the bulk recycling equipment, or placed in temporary storage before bulk recycling.

In forward production and distribution, products with a high turnover may be stored in adjacent locations that are easily accessible to reduce material handling time [4], [5]. In the bulk recycling facility in Fig. 1, a new storage policy is proposed to reduce the storage space requirements and retrieval times to fulfill the capacity order. This new storage policy, referred to as *characteristic-based storage policy* in Fig. 1, may be based on criteria such as customer source, type of equipment, set-up time for recycling and product size. For industrial customers who require bulk recycling of their items separate from other customers' items, adjacent storage of items by source may reduce the material handling for retrieving products from storage to processing equipment. The set-up time in recycling refers to a clean-up time between product batches in order to reduce contamination such as leaded glass from monitors.

A comparison of the traditional production operations with the bulk recycling operations is shown in Table I. In production, suppliers ship raw materials in unit load quantities to the production facility. On the other hand, a unit load inbound shipment to a recycling facility may contain different types of products. Unlike production where raw materials are planned purchases, the reverse supply is random. Additional sources of variability in recycling include product differences in age, model, manufacturing technology of different manufacturers, and condition. The variety of products, their vintages, and conditions is much greater for residential returns than for industrial returns. Thus, when the EOL products arrive at the recycling facility, they have to be sorted first into different categories before they are put away to storage or sent to processing. In a bulk recycling facility, a batch is currently defined based on customer source, type of equipment, and the processing capacity of the recycling equipment, where only one product category is processed at a time. Industrial customers may require that their order be processed separately while products from residential collections do not require any source separation. As contrasted in Table I, in production and distribution operations, a batch may also depend on due date [6].

TABLE I
COMPARISON OF STORAGE AND RETRIEVAL PROCESSES IN A TRADITIONAL PRODUCTION FACILITY AND A BULK RECYCLING FACILITY

	Traditional Production Operations	Bulk Recycling Operations	
		Industrial Returns	Residential Returns
Incoming raw materials	Each unit load received contains *one* type of material.	Each unit load received may contain *more than one* type of product composed of different materials.	Each unit load received contains *many different types* of products from various vintages composed of different materials.
Batch criteria	A production batch is based on set-up time, customer due date, product size, and processing capacity.	The recycling batch is based on the customer source, type of equipment, set-up time, product size, and processing capacity.	The recycling batch is based on the type of equipment, set-up time, product size, and processing capacity.
Finished goods	Products are stored for make-to-stock operations or directly shipped for make-to-order operations.	Materials are separated to accumulate for immediate shipment.	Materials are separated to accumulate for immediate shipment.

The economics of production and recycling are different. The inventory costs in production are usually represented as proportional to the value of inventory [7], [8]. However, in recycling, when the potential materials recovery value cannot cover the processing costs, recyclers may charge to receive products with low materials recovery value to ensure positive net revenue. In this case, since there is no capital cost tied up in the incoming products, the inventory cost is dominated by the space and handling needed [9], [10].

Furthermore, as shown in Fig. 1, the recycling facility not only receives, sorts, stores, and ships but also adds value through processing and reprocessing operations. The purpose of these operations is to separate the materials in the products. Therefore, the recycling facility has both "input customers" and "output customers." For the "input customers," the recycling facility must determine what products to accept and the purchase prices or charges depending on their potential for materials recovery. For the "output customers," the recycling facility must determine what products to process to recover materials and to what extent is necessary to separate the mixed materials. These decisions must be made subject to resource constraints, recycling goals, and profit objectives.

III. SHORT-TERM PRODUCTION PLANNING MODEL FOR BULK RECYCLING

The investigation described in this paper uses a new analytical tool, the short-term bulk recycling planning (SBRP) model to determine the short-term production planning strategies for both industrial return and residential return scenarios. The SBRP model is a mixed integer programming model that maximizes a recycler's profit by accounting for incoming product net revenues, high-value output material sales, equipment processing costs, clean-up costs, inventory costs, and low-value output material disposal costs. The profit maximization is

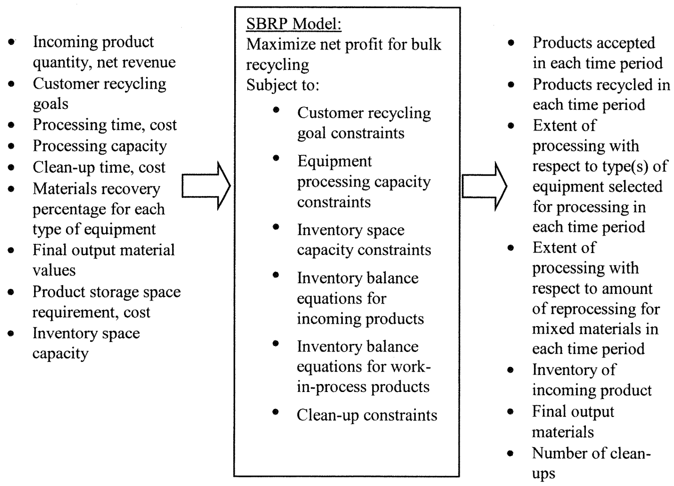

Fig. 2. Structure of SBRP model.

constrained by mathematical expressions for the "input" customer's recycling requirement, equipment processing capacity, and inventory space capacity for incoming products. Fig. 2 shows the inputs, outputs, and general structure of the model. The SBRP model provides a framework for short-term planning in an electronics bulk recycling facility. The model helps recyclers make the following decisions.

1) Determine processing and reprocessing levels.
2) Select products to accept or to ship directly.
3) Select products to process and to carry in inventory.

The SBRP model decision variables represent the products accepted, which products are recycled using what equipment and to what extent each time period, the products stored for processing in a future time period, the number of clean-ups (set-up), and the final output materials. More detailed information on the mathematical structure of the model is described in [9]–[11].

As shown in Fig. 2, the inventory space capacity is an important input parameter for bulk recycling planning decisions. In scenarios where recyclers have regular "input customers" and the quantities of the incoming products are steady, recyclers may choose to maintain a low inventory space capacity for a lean recycling process. On the other hand, if the input quantity is cyclic and unsteady, recyclers may choose to maintain a large inventory space capacity to reduce the impact of the variations of the input quantity over time. For example, for the special-event drop-off residential collection, a large quantity of EOL products may arrive in a short amount of time. In this case, the recyclers may carry a large inventory until processing capacity is available.

The case study instances of the SBRP model are solved using a branch-and-search algorithm. An additional heuristic is used to generate a lower bound for the branch-and-search procedure to improve the computational efficiency. More detailed information on the mathematical structure and solution methodology of the model are in [9], [10]. In this paper, we perform a case study to demonstrate the use of the SBRP model for two different scenarios. In the first scenario, the bulk recycling facility receives products from industrial returns. In the second scenario, the bulk recycling facility receives products that are collected from residential returns.

TABLE II
CASE STUDY INVESTIGATION

Category	Case Study Questions	Investigation Approach
Products accepted	What products are accepted by the recycling facility in what quantities each period? On the other hand, which products are directly shipped to a different entity (eg, recycler or disposal)?	Product acceptance variables in the SBRP Model
Products processed	Which products are processed on which equipment each period? Which material mixtures are reprocessed on equipment?	Processing and reprocessing variables in the SBRP Model
Recycling charge	How sensitive are the product acceptance and processing questions to the recycling charge?	Case study runs with different recycling charges
Product source	How sensitive are the product acceptance and processing questions to the product source (eg, industrial versus residential)?	Case study runs with different product sources

TABLE III
EXPERIMENTAL DESIGN FOR THE CASE STUDY

		Receipt Charges ($/unit)		
Run	Source of Product Returns	PC	Monitor	Large TV/AC
1	Industrial	5	10	-
2	Industrial	2	5	-
3	Residential	5	10	50
4	Residential	2	5	35
5	Residential	10	40	50
6	Residential	10	20	35

IV. CASE STUDY

In our case study, we investigate the questions categorized in Table II. We test the sensitivity of the product acceptance and reprocessing decisions to the charges to receive incoming products and the source of the returns shown in Table III. For both industrial and residential returns in the case study, we assume recyclers charge to receive all the incoming EOL products.

For both industrial and residential returns, the carrying cost, $\$0.5/(\mathrm{ft}^2 * \mathrm{week})$, is dominated by the storage space cost and the temporary storage space for products waiting for bulk recycling is 1000 ft^2. We assume that the minimum acceptance goal for the recycler is 80%. Thus, the recycler strives to accept at least 80% of the returns for processing or storage and direct ships less than 20% of the remaining unprocessed products.

For our case study, the two types of equipment in the bulk recycling process are the same regardless of the source of the returns. The first set of equipment, indicated by $k = 1$, includes a shredder, a magnetic sorter and manual sortation along a conveyor. We assume that the shredder processes CRTs, large TV/ACs, and large electronics at a rate of 1500 lbs (682 kg) per hour while it processes PCs and office equipment at a rate of 2000 lbs (909 kg) per hour. The shredder reduces incoming products to material fragments ranging from 1 to 3 in (2.5 to 7.6 cm) long. The second set of equipment, indicated by $k = 2$, includes a grinder and an air separator, which can separate the printed wiring assembly (PWA) into PWA metal and PWA laminates. The grinder and air separator process approximately 3000 lbs (1363 kg) of PWAs every hour and reduce incoming fragments to particles approximately 0.05 to 0.20 in (0.13 to 0.51 cm) in diameter. We consider one reprocessing cycle for each set of equipment. Processing costs for the first and second sets of equipment are \$60/h and \$25/h, respectively. The clean-up time for the shredder is assumed to be 15 min for CRTs, monitors, large TV/ACs, and large electronics; while the clean-up time is assumed to be 10 min for PCs and office equipment. The processing time capacity is assumed to be 40 h/week for both pieces of equipment.

The incoming product and materials recovered categories differed for industrial and residential returns. Therefore, we describe these two scenarios separately in the next two sections.

A. Industrial Returns

Currently industrial returns dominate the sources for EOL electronic product returns in many recycling facilities. Industrial returns may include pre-production test products, dealer inventory returns, warranty returns, lease returns, and obsolete original equipment manufacturer (OEM) inventory. We formed a data set for our case study by reviewing several published studies of electronics recycling [12]–[15] and from plant visits and communication with industrial collaborators [16]–[22].

In our sample problem, we select four computer equipment categories as the incoming products for the industrial returns at a generic computer recycling facility. We define our four input groups for product index i as 21″ CRTs, 17″ CRTs, 14″ CRTs, and PCs, respectively. The industrial monitor returns are disassembled into four components: PWA, yoke, housing, and CRT. Only the CRT is sent to bulk recycling. Table IV shows the average product weight and shipping density and a typical quantity of each product category received by a computer recycling facility each week. The shipping density is defined by the number of CRTs, monitors, large TV/ACs, or large electronics typically packed on a pallet or the number of PCs or office equipment typically packed in a Gaylord.

There are seven types of output materials after the four incoming products are processed in the recycling facility. Table V shows the characteristics for the seven output materials. The negative revenues for the plastic mixtures and the glass mixtures indicate that these recovered materials have higher distribution costs than material sales revenues. For $k = 1$, we assigned the same values to outputs $j = 6$ and $j = 7$ since PWA metals mixture and PWA laminates mixture are still blended together after shredding. After grinding and air separation at $k = 2$, however, the PWA metals mixture is separated from the laminates and has a higher salvage value since the purity is greater. Table VI shows typical material compositions for the four incoming product categories received by a computer recycling facility.

B. Residential Returns

Government and volunteer organizations in the United States have organized several pilot projects to collect residential electronic products in the United States [23]–[25]. Compared to industrial returns, the age of the products received from residential collection have a higher variance. Furthermore, the age difference often results in material composition differences due to design changes over time.

TABLE IV
CASE STUDY QUANTITY AND CHARGES OF INCOMING PRODUCTS IN A GENERIC BULK RECYCLING FACILITY WITH INDUSTRIAL RETURNS

	Average Product Weight (lbs/unit)	Shipping Density (lbs/ft.^{2})	Total Weight of Products Received of Type i in Week t (lbs/week)				Ratio of Receipt Charges to Weight ($/unit/lb.)	
			t = 1	t = 2	t = 3	t = 4	Run 1	Run 2
i = 1 (21" CRT)	70	13	10403	11443	12587	13846	0.14	0.07
i = 2 (17" CRT)	45	17	8991	9890	10879	11967	0.22	0.11
i = 3 (14" CRT)	24	11	6350	6985	7684	8452	0.42	0.21
i = 4 (PC)	44	100	42768	47045	51749	56924	0.11	0.05
Total Weight			68512	75363	82899	91189		

Note: The receipt charges are provided in Table III.

TABLE V
CASE STUDY OUTPUT MATERIAL CHARACTERISTICS FOR INDUSTRIAL RETURNS

Index (j)	Output Characteristics for Industrial Returns	Price ($/lb.) (b=1, k=1)	Price ($/lb.) (b=1, k=2)
1	Ferrous metal mixture (≥90% by weight)	0.023	--
2	Non-ferrous metal mixture (≥90% by weight)	0.280	--
3	Plastic mixture (≥90% by weight)	-0.025	--
4	Glass mixture (≥90% by weight)	-0.084	--
5	Cu dilute mixture (≥50% by weight)	0.050	--
6	PWA metal mixture	0.080	1.400
7	PWA laminates mixture	0.080	0.050

TABLE VI
CASE STUDY MATERIAL COMPOSITION FOR EACH PRODUCT CATEGORY FROM INDUSTRIAL RETURNS

	j=1	j=2	j=3	j=4	j=5	j=6	j=7
i=1	33.7%	0.0%	0.0%	64.9%	1.3%	0.0%	0.0%
i=2	31.5%	0.0%	0.0%	65.8%	2.7%	0.0%	0.0%
i=3	22.1%	0.0%	0.0%	73.1%	4.8%	0.0%	0.0%
i=4	23.2%	31.8%	26.0%	0.0%	9.0%	3.0%	6.8%

There are four different scenarios in residential collection: special event drop-off collection, on-going drop-off collection,

TABLE VII
CASE STUDY QUANTITY AND CHARGES FOR A GENERIC BULK RECYCLING FACILITY WITH RESIDENTIAL RETURNS

	Average Weight (lbs/unit)	Shipping Density (lbs/ft.^{2})	Total Weight of Products Received of Type i in Week t (lbs/week)				Ratio of Receipt Charges to Weight ($/unit/lb.)			
							Run			
			t = 1	t = 2	t = 3	t = 4	3	4	5	6
i = 1 (PC)	50	33	18921	20820	22907	25203	0.10	0.04	0.20	0.20
i = 2 (Monitor)	15	13	9785	10755	11848	13027	0.67	0.33	2.67	1.33
i = 3 (Large TV/AC)	140	50	27490	30238	33257	36589	0.36	0.25	0.36	0.25
i = 4 (Office Equipment)	15	100	3018	3322	3646	4011	0.33	0.33	0.33	0.33
i=5 (Large Electronics)	80	50	9298	10228	11241	12359	0.19	0.19	0.19	0.19
Total Weight			68512	75363	82899	91189				

regularly scheduled curbside pick-up, and shipment collection [26], [27]. Special event drop-off collections are usually organized by government and volunteer organizations [23]–[25], [28]–[31]. Residents take their EOL products to a designated site on an advertised collection day. In this scenario, the recyclers will receive a large amount of EOL products in a short period of time for which they will need adequate temporary storage. On-going drop-off collection refers to a scenario in which a local entity, government or private, provides drop-off containers with easy access 24 h per day and 7 days per week [32]–[35]. This scenario requires regular pick-up to minimize overflow at the collection site. On-going drop-off collection and regularly scheduled curbside pick-up result in more stable collection rates for recyclers [36], [37]. Shipment collection occurs when the residents ship their EOL product(s) to a recycler [38]. For example, a new IBM program charges $29.99 to cover shipping and recycling expenses for a personal computer [39].

Because data is unavailable for the other three types of residential collection, we use the published special event drop-off data [24], [25]. We form a data set assuming that the recyclers receive products that can be grouped into the five categories shown in Table VII with their average weight and shipping density. The quantity of these five product categories arriving at the recycling facility is also shown in Table VII. We will use our model from [9], [10] to investigate the impact of the charge to residents on the product acceptance decisions and reprocessing decisions. The receipt charges we test are also shown in Table VII. When comparing Tables IV and VII, we point out that for industrial returns the 14″, 17″, and 21″ CRTs are on average 24, 45, and 70 lbs, respectively; however, the older, smaller monitors received from residential returns are on average only 15 lbs.

TABLE VIII
CASE STUDY OUTPUT MATERIAL CHARACTERISTICS FOR RESIDENTIAL RETURNS [24]

Index (j)	Output Characteristics for Residential Returns	Price ($/lb.) (b=1, k=1)	Price ($/lb.) (b=1, k=2)
1	Mixed Glass	-0.084	--
2	Mixed Plastic (plastic pieces that are contaminated with paint, connectors, or foam or have 2 types of plastic molded together)	0.018	--
3	Plastic (clean plastic is plastic that is homogenous and free of all contaminants)	0.175	--
4	PWA metal from refine boards (a higher grade of boards with much more metals value such as PWA, mother board, processors)	0.080	1.00
5	PWA laminates from refine boards	0.080	0.05
6	Ferrous Metal	0.076	--
7	Wire & Cable	0.170	--
8	Non Ferrous Metal (mostly aluminum and copper)	0.380	--
9	Yoke (a copper and steel metal assembly at the neck of the CRT)	0.170	--
10	Wood	-0.080	--

TABLE IX
CASE STUDY MATERIAL COMPOSITION FOR PRODUCTS RECEIVED FROM RESIDENTIAL COLLECTION [24]

	j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8	j=9	j=10
i=1	0.1%	20.6%	11.4%	5.6%	12.6%	45.0%	2.7%	1.9%	0.0%	0.0%
i=2	37.5%	20.1%	10.2%	0.3%	0.8%	20.8%	3.5%	0.1%	6.7%	0.0%
i=3	14.0%	11.1%	7.5%	6.5%	14.7%	25.7%	2.3%	6.2%	2.2%	9.9%
i=4	39.7%	2.7%	35.5%	4.8%	10.8%	0.4%	6.1%	0.0%	0.0%	0.0%
i=5	0.3%	37.2%	5.8%	6.4%	14.5%	33.1%	1.6%	1.2%	0.0%	0.0%

Similarly, shipping densities for PCs from residential returns are lower than for industrial returns because we observed that they are packed in a less organized manner.

The characteristics for the ten possible output materials from processing the five incoming product categories from residential returns are shown in Table VIII. The category definitions included in Table VIII are from [24]. Since none of the products from residential collection are disassembled before bulk recycling, the output and subsequent prices in Table VIII differ from the output and prices in Table IV for industrial returns. The negative prices for the mixed glass and mixed wood indicate that these recovered materials have higher distribution costs than material sales revenues.

As we discussed earlier, in residential returns the material composition of the same product category may be different due to design changes over time. Table IX presents an average material composition for each product category based on the data from four residential collection projects [24].

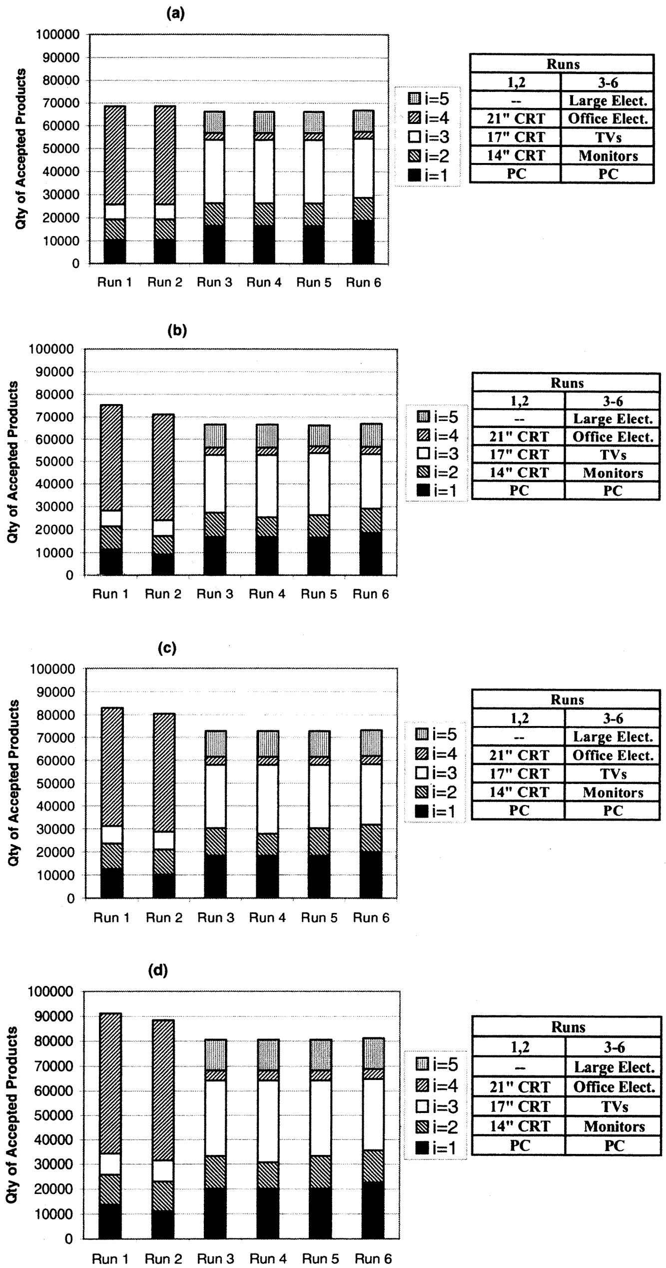

Fig. 3. Case study quantity of accepted products in different runs.

C. Case Study Results

We investigate the impact of the source of the returns and the charge for the returns in the six runs defined in Table III. As defined in Tables IV and VII, the inputs for industrial and residential returns differ; therefore, care should be taken in comparing the six runs. Fig. 3(a)–(d) show the quantity of the accepted products in each time period for each run. Although we kept the total quantity of the incoming products for industrial and residential returns unchanged throughout the runs, the quantity of accepted products from industrial returns are greater than that from residential returns in Fig. 3(a)–(d). More products from residential returns are shipped directly. For residential returns, the total quantities of products accepted are the same for runs 3 to 5, while more products are accepted in run 6. The quantity accepted in each product category differs in each run due to different receipt charges. For example, in run 3, less PCs and more TVs are accepted than in run 6 for all four time periods. This corresponds to the Table VII ratio of PC receipt charge to TV/AC receipt charge of 0.10 and 0.28 for runs 3 and 6, respectively.

TABLE X
CASE STUDY COMPUTATIONAL TIMES AND RESULTS FOR SIX DIFFERENT RECEIPT CHARGE SCENARIOS

Run	Iterations	Nodes	Branch-and-Search Solution Time (sec.)	Weight of Products Accepted (lb.)	Percentage of Output Selected for Reprocessing at Specified Equipment
1	40	6	0.11	317,963	86% PWA metal at k=2
2	35	6	0.09	308,410	92% PWA metal at k=2
3	89	12	0.17	286,078	82% non-ferrous metal at k=1 77% PWA metal at k=2
4	89	13	0.17	286,078	82% non-ferrous metal at k=1 78% PWA metal at k=2
5	95	10	0.20	286,078	78% non-ferrous metal at k=1 70% PWA metal at k=2
6	98	10	0.21	288,111	78% non-ferrous metal at k=1 70% PWA metal at k=2

We run the model using CPLEX 6.0 with Mixed Integer Solver on a Dell Pentium III 600 personal computer [40]. The results of the sample runs, including the net revenue, are shown in Table X. Table X also shows the CPU time required by CPLEX optimization software to find the lower bound and complete the branch-and-search solution method described in [9], [10]. For all six runs, the model chooses to reprocess PWA metal mixture in the grinder and air separator. For residential source products, runs 3 to 6, the model also chooses to reprocess nonferrous metal for the shredder and sortation. However, as shown in Table X, not all of the selected materials are reprocessed due to the limited processing capacity.

For the sample runs, Table XI shows the cost and revenue breakdown for the recycling facility operations. Collection costs are not included. As we discussed in Section II, when recyclers charge to receive incoming products and no investment is tied up in the inventory, the carrying cost is dominated by the storage and handling cost. For all six runs in Table XI, the inventory carrying costs are relatively low compared to the inventory carrying costs for a production operation of a similar scale. The inventory costs are lower for the industrial returns in runs 1 and 2 due to better shipping densities. The receipt charge to weight ratios in Tables IV and VII and the quantity of accepted products in Fig. 3 provide insights into which products are more likely to be accepted. For example, PCs are ranked least (fifth) attractive for receipt charge to weight ratio in runs 3 and 4 but are ranked fourth in runs 5 and 6; their acceptance quantity is highest in run 6. The case study results demonstrate that receipt charges may dominate the product acceptance decisions that impact the processing, reprocessing, and storage decisions.

Table XI also illustrates that the revenue from the final output material sales cannot cover the processing, reprocessing, clean-up, and inventory costs for any of the six runs. However,

TABLE XI
CASE STUDY VARIABLE COSTS AND REVENUES FOR RECYCLING OPERATIONS FOR SIX DIFFERENT RECEIPT CHARGE SCENARIOS

	(1)	(2)	(3)	(4)	(2)+(3)+(4)	(1)+(2)+(3)+(4)
Run	Incoming Product Receipt Revenue ($)	Processing, Reprocessing, and Clean-up Costs ($)	Inventory Carrying Costs ($)	Final Output Material Sales ($)	Net Revenue without Receipt Charge ($)	Net Revenue with Receipt Charge ($)
1	105,492	-43,453	-782	26,983	-17,252	88,240
2	70,782	-46,053	-633	28,238	-18,448	52,334
3	158,007	-45,281	-816	29,733	-16,363	141,644
4	123,155	-44,669	-814	30,480	-15,003	108,152
5	261,585	-47,665	-823	29,733	-18,755	242,830
6	183,590	-44,671	-818	30,089	-15,401	168,189

a receipt charge can cover the bulk recycling process costs for the current technologies. Furthermore, capital costs for the processing equipment have not been considered. Inclusion of capital costs will result in even higher receipt charge requirements.

V. CONCLUSION

The functions and flows for production and recycling operations differ. While a production facility connects suppliers and customers, a recycling facility connects both "input" and "output" customers. As a result, the economics and operations management of production and recycling differ. For example, the recycling facility may charge to receive products from input customers.

Currently most recyclers rely on instinct and experience to determine which products to accept when EOL products arrive at the recycling facility. After recyclers accept the EOL products, they need analytical tools to determine when to recycle the products, how much reprocessing to employ, and what products to store until processing capacity is available. Our research provides a framework for this planning in a bulk recycling facility.

In this paper, we investigate recycling scenarios for both industrial and residential returns. The results of the case study show that different reprocessing options are chosen for the industrial versus the residential returns when the total quantity of the incoming products is equal. Interestingly, the results show that the product acceptance versus direct shipment, processing, reprocessing, and inventory decisions are sensitive to the prices recyclers charge for incoming products. For example, for runs 1 and 2, the price changes; as a result, the number accepted and reprocessed changes.

In conclusion, the SBRP model is computationally attractive as shown in Table X. In this paper, we have shown that the model can help a recycler identify what decisions are sensitive to the return sources and market conditions. The framework we present may also be helpful for policymakers considering legislation for mandatory product take-back.

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