Environ. Sci. Technol. **2003**, *37,* 5463–5470

Plastics Disassembly versus Bulk Recycling: Engineering Design for End-of-Life Electronics Resource Recovery

PEDRO RIOS,[†]
JULIE ANN STUART,*,[†] AND ED GRANT[‡]
School of Industrial Engineering and Department of Chemistry, Purdue University, 315 North Grant Street, West Lafayette, Indiana 47907-2023

Annual plastic flows through the business and consumer electronics manufacturing supply chain include nearly 3 billion lb of high-value engineering plastics derived from petroleum. The recovery of resource value from this stream presents critical challenges in areas of materials identification and recycling process design that demand new green engineering technologies applied together with life cycle assessment and ecological supply chain analysis to create viable plastics-to-plastics supply cycles. The sustainable recovery of potentially high-value engineering plastics streams requires that recyclers either avoid mixing plastic parts or purify later by separating smaller plastic pieces created in volume reduction (shredding) steps. Identification and separation constitute significant barriers in the plastics-to-plastics recycling value proposition. In the present work, we develop a model that accepts randomly arriving electronic products to study scenarios by which a recycler might identify and separate high-value engineering plastics as well as metals. Using discrete event simulation, we compare current mixed plastics recovery with spectrochemical plastic resin identification and subsequent sorting. Our results show that limited disassembly with whole-part identification can produce substantial yields in separated streams of recovered engineering thermoplastics. We find that disassembly with identification does not constitute a bottleneck, but rather, with relatively few workers, can be configured to pull the process and thus decrease maximum staging space requirements.

Introduction

An important green engineering strategy calls for design for materials separation throughout the life cycle of a product (*1*). Annual plastic flows through the electronics supply chain to the sink include nearly 3 billion lb of high-value engineering plastics derived from petroleum, a non-renewable resource (*2*, *3*). Yet, only a limited electronics recycling infrastructure exists today, and it focuses primarily on precious metals recovery (*4*, *5*). Although an increasing number of companies receive, remanufacture, and dispose end-of-life (EOL) electronics and appliances (*6*–*9*), less than 1% of the plastics from EOL electronics are processed for plastics-to-plastics recycling (*2*, *10*).

* Corresponding author telephone: (765)494-6256; fax: (765)494-1299; e-mail: stuart@purdue.edu.
[†] School of Industrial Engineering.
[‡] Department of Chemistry.

Tools to advance sustainable design and manufacturing strategies include green engineering (*1*), life cycle assessment (LCA) (*11*), streamlined LCA (*12*), and ecological supply chain analysis (EcoSCAn) (*13*). Strategic production planning models have been extended to consider product returns for repair and recycling (*14*–*16*). Research models to select EOL electronics disassembly levels seek to maximize product net revenue (*17*–*19*).

However, despite these research advances, current recycling strategies remain focused on producing low-value mixtures of plastics for waste-to-energy (*20*). For example, pilot studies have demonstrated the recovery of significant quantities of mixed plastics, but for the most part, the plastics collected were not identified or separated (*21*–*24*). Yet, these pilot studies involved an extensive disassembly depth that created a costly bottleneck. Although recycling processes in general seek to minimize disassembly depth (*6*–*9*, *25*–*30*), some such preprocessing may be necessary in certain cases to recover parts for resale or screen for hazardous materials. Figure 1 diagrams a typical processing stream for electronic materials recovery today.

Current Electronics Recycling Process Design That Produces Low-Value Mixed Plastics. As diagrammed in Figure 1, conventional processing starts in a staging area where products are sorted and queued in batches for shredding. At the shredding step, the recycler sometimes chooses to reprocess mixtures for a second cycle to improve materials separation (*31*). Magnetic separation, grinding, density separation, and manual sorting steps may follow shredding operations (*5*). The outputs from the electronics bulk recycling process in Figure 1 include ferrous metals, mixed metals, glass, mixed plastics, and mixed materials (*6*). Outputs such as mixed metals are sold for further separation (*32*–*34*). Recyclers seek to optimize the four performance metrics detailed in Table 1 to achieve the highest turnover in the staging space, the highest throughput, the highest material grade, and the lowest shipment fill time (*35*).

A significant barrier to achieving an optimum material grade for the plastics produced in such an operation is the commingling of plastic resins that occurs in bulk shredding. Mixed plastics have low or often substantially negative value. No resin-specific identification method exists that can support the complete separation of commingled resins in a shredded plastic mix. Purification methods based on physical properties, such as density, dielectric constant or surface tension, have limited (<90%) and often varying effectiveness for complex, real-world input streams. For whole parts, however, as suggested by ref *36*, the yield per measurement may justify the application of exacting spectrochemical techniques for resin identification. Thus, we consider an alternative scenario.

Alternative Electronics Recycling Process Design That Uses Plastics Identification and Separation. To meet the goal of achieving high material grade in recovered engineering plastic streams, a recycler must modify the typical electronics recycling process in Figure 1 in order to avoid mixing plastics initially or somehow identify and separate small pieces from shredded plastic mixtures (*3*, *6*–*9*, *25*–*30*, *37*). The problem of efficient identification and separation constitutes the single most significant barrier to plastics-to-plastics recycling. To address this problem, we consider a model for electronic materials recovery that accepts randomly arriving EOL goods and, in scenarios that include resin identification of disassembled plastic parts, seeks to determine what engineering design principles apply to recycling process design to

10.1021/es034675o CCC: $25.00
Published on Web 11/04/2003

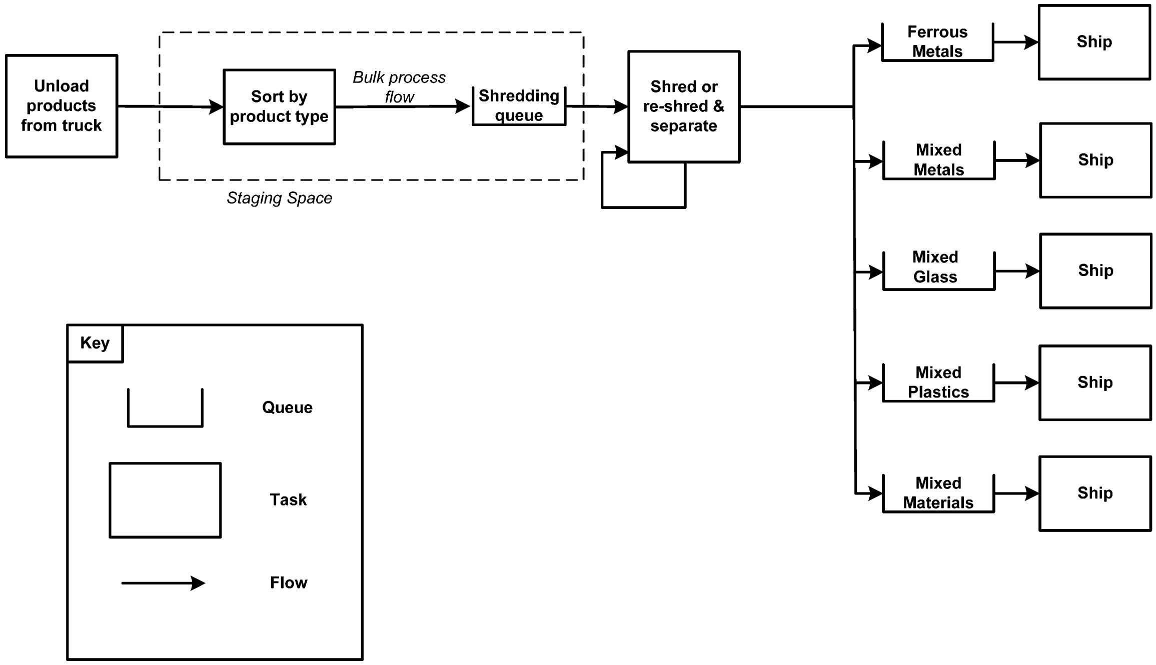

FIGURE 1. Typical materials recovery streams from electronics recyclers.

TABLE 1. Metrics To Evaluate Recycling Centers

metric	definitions	influencing factors
staging space requirement	maximum staging space required over time to store incoming products awaiting processing	product arrival rate variability and peak level marketing objective to increase staging space to prevent turning away incoming truckloads management objective to lower staging space for lean recycling operations product disassembly level number and size of sorting bins product feed rate to shredding product scheduling for processing
throughput	tons of material processed per year	arriving product quantities and compositions disassembly processing rate plastics identification processing rate shredding rate process design and equipment process planning including disassembly depth and scheduling for processing
material quality	out-going material purity as percent target resin and surface contamination	arriving product design complexity size reduction and material separation process level of disassembly level of reprocessing (re-entrant flow) material identification capability
shipment fill time	time interval between two consecutive shipments of a specific material	arriving product compositions size reduction and material separation rate level of reprocessing (re-entrant flow) product scheduling for processing shipment quantity (e.g., container size or truckload size)

optimally recover materials while managing staging space, material quality, and shipment fill time.

The principles of green engineering, including those discussed in refs *1* and *38*−*41*, offer a structure to evaluate product and process designs across scales and life cycle stages. A manifest goal in all cases is to design for separation and recycling in order to minimize life cycle energy and material consumption as well as waste generation. With respect to plastics in EOL electronics, we compare the disassembly/identification alternative to bulk recycling with plastics waste-to-energy conversion. The process diagram shown in Figure 2 details this alternative as we see it, which combines analytical chemistry and industrial engineering approaches to form an overall methodology with potential to improve the sustainability and economy of plastics separation by means of limited disassembly, spectrochemical identification, and sorting by material popularity and contaminant significance.

This process sorts incoming electronics such that metal-covered pieces go directly to the shredding queue while plastic-covered pieces go to the disassembly queue. As a result, the staging space in Figure 2 includes a staging queue, a metal cover sortation station, and a shredding queue. Disassembly planning necessarily includes an interval for

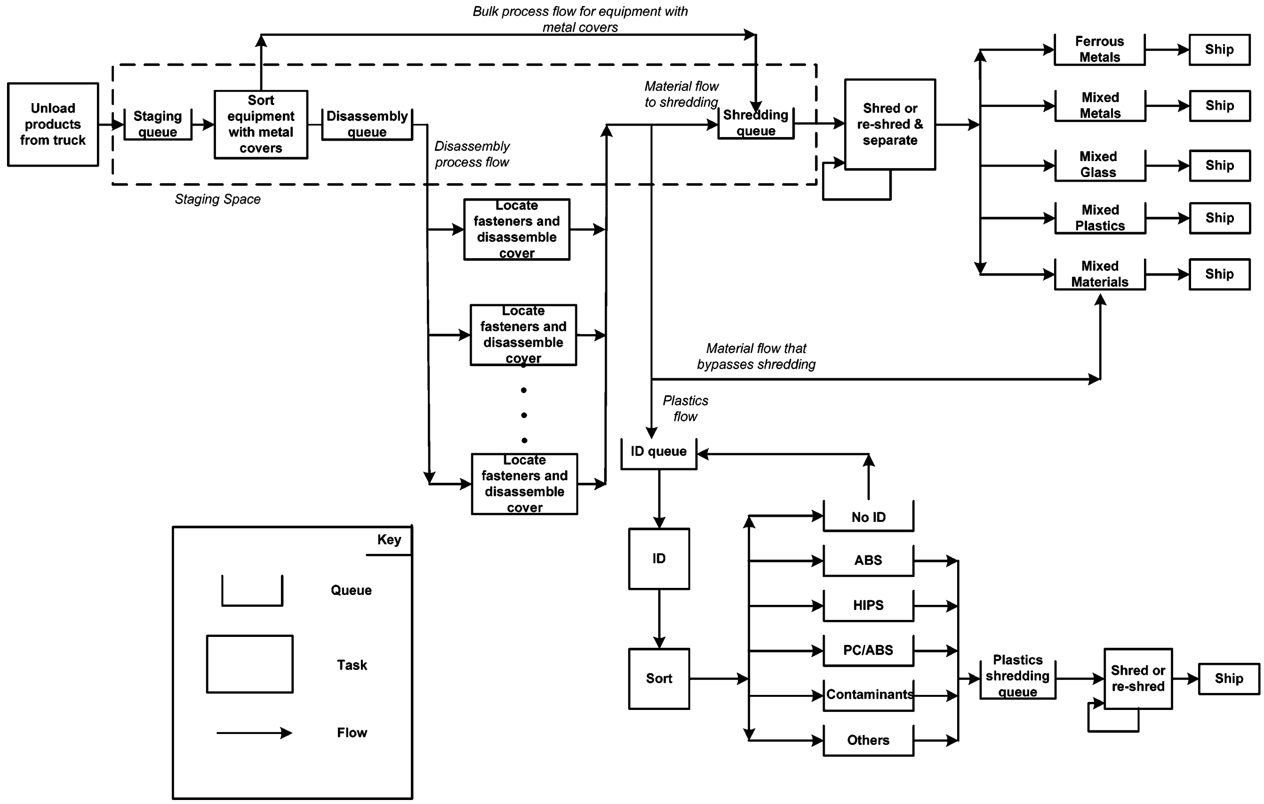

FIGURE 2. Electronics recycling with metal cover diversion, limited plastic part disassembly, and post-disassembly plastic identification.

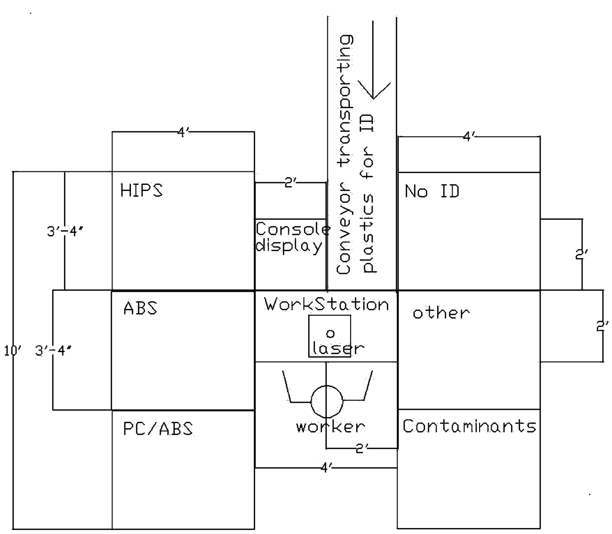

FIGURE 3. Identification workstation with mounted laser, Raman absorption spectra library, and plastic output bins.

the worker to locate fasteners in each case. This familiarization step may be reduced in the future with a new symbolic methodology proposed in ref *42*. New work in ref *43* defines a limited disassembly strategy, calling for removal of the back cover on monitors and televisions and removal of the entire cover on printers and computers. Average plastic separation rates for this optimal disassembly strategy reach as high as 1.3 kg/min. The associated disassembly depth is significantly smaller than that called for in refs *44*–*46*. We choose part dimensions of 1 by 0.5 cm as a minimum size for disassembly, identification, and recovery. Following disassembly, plastics pieces are accumulated and sent to an identification workstation illustrated in Figure 3.

This workstation is assumed to employ the same plastic resin identification method that we used to characterize the compositions of plastic parts in the 75-component set of scrap computers, printers, and monitors investigated in the experimental foundation for this study (*43*). This method uses the laser spectroscopic technique of Raman scattering to identify unknown plastic materials on the basis of their characteristic vibrational signatures. The instrument's Raman optical bench is enclosed in a fiber-optic probe that is configured to illuminate and collect light scattered from solid samples, much like a conventional bar code scanner (*47*).

A fiber-optic cable provides the optical interconnect to an instrument console, transmitting the scattered radiation from the probe to a spectrograph. The spectrograph resolves the Raman scattered radiation into frequency components that are distinctive for the vibrational signature of the plastic.

The instrument identifies an unknown material by comparing its Raman spectrum with a library of standards, which can easily be defined and constructed by the user to fit the distribution of incoming materials. Spectra, which can be quite distinctive for different materials, are identified by the multivariate classification scheme known as partial least squares (*48*). The result is an identification matrix in which the correlation between the sample and the library is represented by a set of distances on a normalized data sphere. A typical identification, requiring 1 s or less, will find the position of a sample vector on this sphere to lie within 0.01 normalized units from the mean of its corresponding vectors in a library and more than one such unit away from the others.

At the identification workstation, a worker scans plastic pieces by moving them flush over a fixed probe head. After checking the console display for plastic identification information, the worker tosses the piece into the appropriate bin labeled for ABS (acrylonitrile butadiene styrene); PC/ABS (polycarbonate/ABS); HIPS (high-impact polystyrene); Contaminants, which includes PVC (poly(vinyl chloride)) and acetyl; and Others. If a piece does not provide a positive identification after three scans, the worker tosses it into a box labeled “no ID” for future scanning. The identification

TABLE 2. Summary of Current Practice and New Option for Plastics Identification and Sorting in Electronics Recycling Operations

recycling scenario	description	plastics grade
bulk (Figure 1)	typical bulk recycling process	low grade of mixed plastics
disassembly (Figure 2)	add metal vs plastic cover sorting, limited disassembly, plastic piece identification, and plastic piece sorting	high grade of separated plastics

yield for first-entrant flow is high; typically fewer than 0.5% of disassembled parts are placed in the "no ID" box for re-entrant identification process flow in a separate shift. To analyze materials in re-entrant flow, the worker demounts the laser and scans housing interiors since an exterior paint or coating may have interfered with the first-entrant reading attempts. We assume a moderate identification yield on re-entrant flow. The fraction of the total identification process flow that remains after this step is added to the Others bin.

This research uses discrete event simulation models to measure the staging space requirement and shipment fill time for the recycling process designs summarized in Table 2 and illustrated in Figures 1 and 2. Figure 1 represents a typical electronics bulk recycling process, which serves as our control. The process diagrammed in Figure 2 adds steps that divert equipment with metal covers to bulk shredding and disassemble the others to recover their large plastic parts for identification and resin separation (*49*, *50*).

Experimental Section

Discrete Event Simulation Models To Compare Electronics Recycling Process Design Alternatives. To compare the performance of the above recycling scenarios, we model random truckload arrivals, finite processing capacities, division of multiple products into materials, random disassembly processing times, multiple-pass processing through the shredder, and shredder setup times to switch from hazardous material runs to nonhazardous material runs. In a discrete event simulation, we introduce probability distributions to randomly generate a truckload arrival and a disassembly processing time (*51*, *52*). Each such activity updates all of the variables of the simulation. For example, a random truckload arrival changes the state of the system, which is represented by variables such as staging space utilization. Likewise, completing the cover disassembly of a computer also changes the state of the system, as reflected in a modified variable for the number of pieces in the ID queue.

We carry out our simulations using ARENA 6.00.02 (*53*) set up for each of the two scenarios in Table 2. We investigate the sensitivity of arrival composition by testing the two recycling process scenarios with business equipment arrivals composed of computers, printers, and monitors (CPM) as well as residential arrivals composed of mostly televisions but also computers, printers, and monitors (T-CPM). Each combination is described in the experimental design in Table 3.

The truckload arrival compositions are based on pilot studies (*21*, *22*, *54*). Details about the different truckload compositions and distributions for interarrival times are given in Table S1, sections a and b, in the Supporting Information. Our material input consists of televisions, computers, printers, and monitors as detailed in Table S2 based on refs *21*, *22*, and *54*. To model the specific plastic composition of these goods, the data in Table 4 is based on refs *43* and *54*. The

TABLE 3. Experimental Design

scenario	arrival composition	recycling process design
1	computers, printers, and monitors (CPM)	bulk (Figure 1)
2	CPM	disassembly (Figure 2)
3	televisions, computers, printers, and monitors (T-CPM)	bulk (Figure 1)
4	T-CPM	disassembly (Figure 2)

TABLE 4. Average Product Cover Polymer Composition, and Revenue (*21*, *43*, *54*, *55*)

product type for covers	polymer: 1 ABS	2 HIPS	3 PC/ABS	4 Contaminants	5 Others
televisions (%)	5	81	0	0	13
monitor (%)	49	28	7	11	5
printers (%)	34	16	35	0	15
PC_P[a] (%)	77	0	20	0	3
recycled price ($/kg)	0.70	0.62	0.78	(0.04)	0.04

[a] PC_P represents computers with plastic covers.

recovered-plastic market value presented in Table 4 is taken from refs *21*, *54*, and *55*.

Disassembly in scenarios 2 and 4 use two and five disassembly workers, respectively. The distributions for the random processing times for disassembly and shredding in Table S3 are based on refs *6*−*9*, *25*−*30*, *35*, *43*, and *44*. The disassembly processing time includes both disassembly planning in which the worker familiarizes himself/herself with the product fasteners and disassembly actions in which the worker removes the cover for computers and printers and the back cover for monitors (*42*, *56*). The cover disassembly activities are scheduled according to disassembly scheduling rule SDT (space per disassembly time ratio), which has been shown to reduce staging space considerably (*35*). The average number of plastic pieces per cover is given in Table S4 according to the study in ref *43*. In the sample of 21 computers in ref *43*, 67% had plastic covers while the remainder had metal covers. In the disassembly process in Figure 2, only products with plastic covers are disassembled for materials recovery. Table S5 shows how the total plastic identification process time depends on the number of reads as well as material handling to position the piece and toss it in the correct bin in Figure 3. We determined the total plastics identification time using the methods time measurement (MTM) technique (*57*). The identification yield for first-entrant flow taken from our experience with a sample set of 75 EOL computers, monitors, and printers is assumed to be 99.5%; 0.5% are placed in the "no ID" box for re-entrant identification process flow in a separate shift. The identification yield on re-entrant flow is assumed to be 50%. The 0.25% of total identification process flow that is not identified by re-entrant analysis is added to the Others bin.

For bulk, whole-component, or disassembled plastic-part shredding, the sequence of goods or parts respectively determines whether a setup step is required to clean out the shredder to avoid contamination between batches. The setup requirement is 0.25 h for each successor product sequence and polymer sequence in Tables S6 and S7, respectively. The general material shredder operates at 2700 kg/h, and the plastics shredder operates at 2000 kg/h (*5*, *20*, *58*). For televisions, monitors and printers, the shredding time is

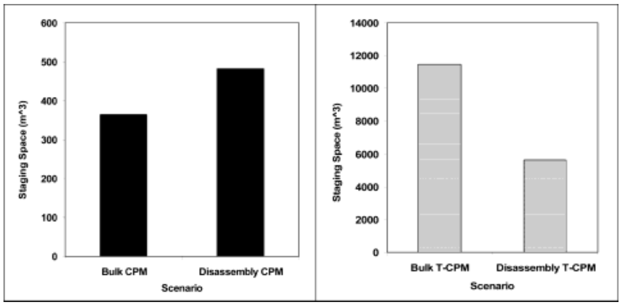

FIGURE 4. (a) Maximum staging space for bulk/CPM and disassembly/CPM scenarios. (b) Maximum staging space for bulk/T-CPM and disassembly/T-CPM scenarios.

scaled by a factor of 1.2 to account for re-shredding. The material truckload capacity is 13 600 kg, and the polymer shipment capacity is 3000 kg for our shipment accumulation fill times. To reduce changeover setup times, we batch 1200 products by category (i.e., television) for general materials shredding and 3000 kg of each plastic (i.e., ABS) for plastics shredding.

We ran the four scenarios in Arena 6.00.02 (*53*) for 100 replications with replication length of 4160 h and warmup periods of 2080 h on a Dell Optiplex GX260 Pentium 4/2.53Gh/1GB requiring computation times from 4.1 to 45.5 min. The average annual arrival quantities across scenarios were 35 400 computers, 38 826 monitors, and 16 689 printers. The average annual arrival quantities of televisions over the third and fourth scenarios was 96 017. The statistics for the random arrival quantities are provided in Tables S8, sections a and b.

Results and Discussion

On the basis of simulation runs with random interarrival times for EOL business equipment electronics, we compare the metrics staging space, throughput, material quality, and shipment fill times for bulk recycling versus disassembly plus bulk recycling. We further examine how these metrics vary when our two scenarios expand to accept consumer electronics as represented by televisions.

We consider first the metric of staging space. We initially expected that the disassembly recycling scenario would require a substantially higher maximum staging space. Referring to Figure 4a, however, we find that our simulation calls for a maximum staging space for the computer equipment disassembly scenario that is only 20% greater than that for bulk recycling.

The results are even more striking for scenarios that include televisions. With efforts focused on the removal of covers, the five disassembly workers in scenario 4 (disassembly/T-CPM) achieve a mean disassembly time of 2.9 min or approximately 100 televisions/h. This disassembly processing time compares with the shredding rate of approximately 100 televisions/h attained in bulk recycling. Moreover, the disassembly of televisions diverts television plastics to the plastics shredder following identification. As a result, the disassembly scenario for computer equipment and televisions requires at maximum 50% less staging space than bulk recycling. In other words, the five disassembly workers in scenario 4 pull equipment for limited disassembly at a rate comparable to the shredding rate. Adding a disassembly operation that is balanced with the shredding process significantly reduces the maximum staging space without a significant capital equipment investment to increase general shredding capacity. In addition, a portion of the staging space saved by the disassembly operation in Figure 4b may be allocated to the added disassembly process. These results provide evidence that disassembly does not

TABLE 5. Annual Material Throughput Shipped for Scenarios 1−4

material	95% CI for no. of trucks in 1 yr		95% CI for total weight in 1 yr (t)	
	lower bound	upper bound	lower bound	upper bound
Section a: Bulk/CPM (Scenario 1)				
ferrous	21.6	22.8	294	310
mixed metal	22.4	23.5	304	320
mixed glass	13.7	14.6	187	198
mixed plastics	11.9	12.6	162	171
mixed materials	0.0	0.0	0	0
Section b: Disassembly/CPM (Scenario 2)				
ferrous	21.4	22.4	291	305
mixed metal	22.2	23.3	302	316
mixed glass	13.7	14.5	187	197
mixed plastics	1.5	1.7	21	24
mixed materials	0.0	0.0	0	0
Section c: Bulk/T-CPM (Scenario 3)				
ferrous	70.4	74.9	957	1018
mixed metal	40.9	43.6	557	593
mixed glass	74.6	80.4	1015	1094
mixed plastics	41.4	44.2	563	601
mixed materials	28.6	31.1	389	424
Section d: Disassembly/T-CPM (Scenario 4)				
ferrous	67.9	73.1	923	994
mixed metal	40.6	43.5	552	591
mixed glass	70.8	76.8	963	1044
mixed plastics	4.2	4.6	57	62
mixed materials	27.2	29.7	370	404

produce a bottleneck but rather that a balanced disassembly operation adds capacity to increase product turnover in the staging area and reduce the likelihood of turning away truckload arrivals due to capacity constraints.

We measure throughput for each scenario in terms of the annual number of shipments and shipped weight for each material. Our discrete event simulation model reflects the impact of random arrivals and random processing times by combining the results of 100 replicate runs. Thus, we report our results as 95% confidence intervals (CI). By comparing Table 5, sections a and b, we see that these intervals for the number of truckload shipments and the shipped weight nearly match across scenarios for all materials but mixed plastics, which dramatically decrease when the plastic covers are sorted. Likewise, when televisions are included Table 5, sections c and d, shows that material shipments other than mixed plastics remain largely unaffected by disassembly. With disassembly, we ship nearly pure recovered resins, ABS, PC/ABS, HIPS, with mixed plastics labeled Contaminant, and Others in the quantities reported in Table 6, sections a and b. As anticipated, the HIPS and Others throughputs increase when televisions are added to the input, in accordance with the plastics composition profile of televisions as detailed in Table 4. The PC/ABS throughput derived from disassembled computer equipment covers remain the same in both disassembly scenarios, showing that the processing of televisions in the arrival mix does not perturb materials recovery from business machines.

To characterize material quality, we examine the output plastics compositions as reported in Figure 5. Bulk recycling scenarios ship plastics entirely as low-grade plastic mixtures. Both limited disassembly scenarios produce purified ABS, PC/ABS, and HIPS along with Contaminants (e.g., PVC) and unidentified Others in mixtures. When business equipment is processed in scenario 2, ABS dominates the sorted plastic output. Adding a 3-fold excess of televisions in scenario 4 rebalances the output in favor of HIPS. Figure 5a,b shows for both scenarios 2 and 4 that the mixed plastics remaining

TABLE 6. Annual Plastics Throughput Shipped for Scenarios 2 and 4

plastics	95% CI for no. of trucks in 1 yr: lower bound	95% CI for no. of trucks in 1 yr: upper bound	95% CI for total weight in 1 yr (t): lower bound	95% CI for total weight in 1 yr (t): upper bound
Section a: Disassembly/CPM (Scenario 2)				
ABS	22.1	23.3	66	70
PC/ABS	6.4	6.7	19	20
HIPS	10.0	10.5	30	32
Contaminants	2.9	3.1	9	9
Others	3.0	3.1	9	9
Section b: Disassembly/T-CPM (Scenario 4)				
ABS	27.1	28.9	81	87
PC/ABS	6.3	6.7	19	20
HIPS	101.8	110.7	305	332
Contaminants	3.2	3.5	10	10
Others	18.4	20.0	55	60

after limited disassembly constitute only 10% of the total plastics. In other words, limited disassembly recovers 90% of the mixed plastics that would be produced by bulk recycling in scenarios 1 and 3. Furthermore, referring to Table 4, at \$0.04/kg, the value of the average annual weight of the mixed plastics in scenarios 1 and 3 are worth only \$7318 and \$25 588, respectively. On the other hand, the value of the average annual weight of sorted plastics in scenarios 2 and 4 are estimated to be \$83 132 and \$275 504, respectively. The prices chosen for scenarios 2 and 4 reflect the transfer price in \$/kg to a blender rather than the market price of feedstock recyclate as might be paid by a molder. Thus, limited disassembly is shown to produce a result that is both environmentally beneficial and, in principle, economically viable. Recovered plastics divert to reuse instead of going to landfills or incinerators, and the labor costs of disassembly are mitigated by the commercial value of recovered materials and staging space savings.

Turning to our final metric, we find that shipment fill times for all materials except mixed plastics remain unaltered by the introduction of disassembly, as shown in Table 7, sections a and b. The shipment fill time for mixed plastics increases dramatically in the limited disassembly scenarios simply because most plastics are sorted for ABS, HIPS, or PC/ABS shipment. These results verify that adding a disassembly process with 50−70% average utilization does not slow the recovery of metals, but rather, metals shipment fill times remain the same and plastic shipment quality increases. Because limited disassembly scenarios identify and sort input plastics, mixed plastics output shipments occur less frequently and incur longer fill times in Table 7, sections a and b. As expected, adding HIPS-intensive televisions to the arrival composition decreases the HIPS shipment fill time in scenario 4 in Table 8. Likewise, the shipment fill times for ABS and Others decrease in Table 8 according to the plastics composition of televisions in Table 4. Importantly, the addition of televisions to the mix of products processed does not increase the shipment fill time of PC/ABS from computer equipment, showing again that the processing of consumer electronics with limited disassembly does not perturb the recovery of engineering plastics from business machines.

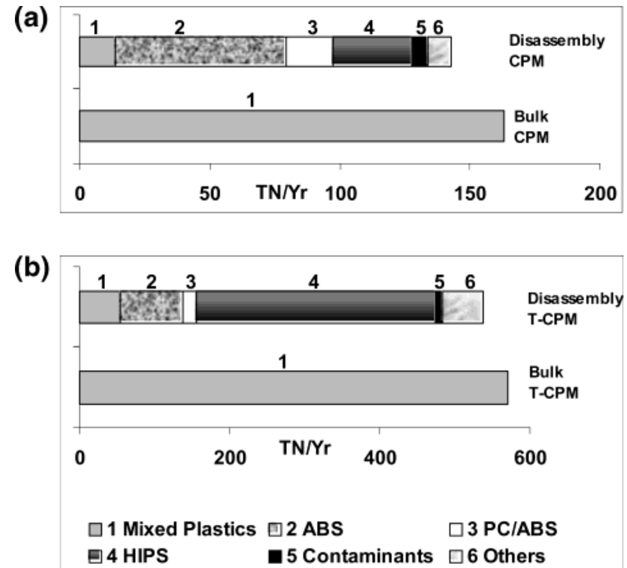

FIGURE 5. Materials plastic throughput for bulk recycling and limited disassembly scenarios for the processing of business machines alone (a) and business machines with televisions (b). Units of metric tons per year. Note the scale difference between panels a and b.

To conclude, we have shown that two disassembly workstations, an identification station, and a plastics shredder can annually convert 120 t of plastic business machine covers into high-value engineering plastics. With five disassemblers and an input stream that adds about 100 000 televisions/yr, the purified plastic output could exceed 400 t.

TABLE 7. 95% Confidence Interval for Materials Shipment Fill Time (d)

scenario	ferrous: lower bound	ferrous: upper bound	mixed metal: lower bound	mixed metal: upper bound	mixed glass: lower bound	mixed glass: upper bound	mixed plastics: lower bound	mixed plastics: upper bound	mixed materials: lower bound	mixed materials: upper bound
Section a: CPM										
bulk	11.6	12.2	11.2	11.7	18.1	19.1	21.1	22.1	0.0	0.0
disassembly	11.7	12.2	11.2	11.7	18.2	19.2	167.5	175.5	0.0	0.0
Section b: T-CPM										
bulk	3.5	3.8	6.1	6.5	3.3	3.6	6.0	6.4	8.6	9.4
disassembly	3.7	4.0	6.1	6.5	3.5	3.8	57.5	61.6	9.1	10.0

TABLE 8. 95% Confidence Interval for Plastics Shipment Fill Time (d)

scenario	ABS: lower bound	ABS: upper bound	PC/ABS: lower bound	PC/ABS: upper bound	HIPS: lower bound	HIPS: upper bound	Contaminants: lower bound	Contaminants: upper bound	Others: lower bound	Others: upper bound
2, disassembly CPM	11.4	12.0	39.7	41.7	25.1	26.4	87.3	94.2	85.0	90.6
4, disassembly T-CPM	9.1	9.7	39.5	41.8	2.4	2.7	77.0	82.4	13.4	14.6

This offers both an environmental benefit and an economic one. Environmental stewardship and green engineering principles motivate plastics-to-plastics recycling. Our model facility diverts tons of plastic from incineration/landfills and lowers materials consumption by facilitating reuse. Remolding of recovered thermoplastics is well-documented by studies such as ref *59* for HIPS, and the revenues from sales to such markets can help substantially to offset the cost of disassembly labor.

Thus, by addressing both the industrial engineering design of the recycling process in concert with the chemometric identification of recovered plastics by resin, we have shown that efficient disassembly, identification, and sorting increases a recovery system's value-added throughput. Furthermore, we establish that these added processes do not interfere with metals throughput but rather simply add output streams of high-value engineering plastics. Although shown to offer the potential for profit, margins for plastics recovery alone will be tight. However, the case for plastics-to-plastics recycling will only improve as plastic prices, disposal costs, and recycling infrastructure increase. In addition, plastics separation processes demonstrated here can be implemented to add value to processes developed to recover nonplastic materials. Our results offer insights that will help in capacity planning for recycling network design (*36*, *60*).

To achieve environmental and economic benefits from electronics recycling, good production design and operations management are critical. We have built the success of the system proposed in this paper based in part on our prior results for disassembly depth, plastics popularity, product batching for changeovers, and scheduling. Those results demonstrate that a disassembly depth strategy calling for whole plastic cover removal for computers and printers and plastic back cover removal for televisions and monitors yields an attractive plastics recovery rate (*43*). By sorting the most popular plastics, we efficiently accumulate shipment quantities (*43*) with low shipment fill times. By batching products for shredding, we lower the changeover times to clean out the shredders (*61*). Scheduling according to the ratio of volume to disassembly time reduces the staging space (*35*). Combining these industrial engineering designs with new chemometric technologies provide a powerful new process design and recycling management strategy for plastics-to-plastics recycling.

Acknowledgments

The authors appreciate the personal computer, printer, and monitor donations from United Recycling Industries; Resource Concepts, Inc.; IBM; and Wildcat Creek Solid Waste District. The authors thank Winston Bonawi-tan for assistance in preparing the tables and the reviewers for helpful comments. This material is based upon work supported by the National Science Foundation under Grants BES-0124761 and DMII-0049074. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Supporting Information Available

Tables providing detailed distributions of arrival times and product compositions as well as number of recovered parts per unit and identification steps per unit, all derived from separate studies of plastics recovery operations; a binary input designation for use in devising shredder changeover rules and the input statistics assumed for product arrival quantities. This material is available free of charge via the Internet at http://pubs.acs.org.

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Received for review June 29, 2003. Revised manuscript received August 27, 2003. Accepted September 11, 2003.

ES034675O