New Metrics and Scheduling Rules for Disassembly and Bulk Recycling

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***Abstract*—In recent years, growing quantities of end-of-life electronics have increased the amount of attention devoted to product recovery. Research on end-of-life electronics returns has primarily focused on manual disassembly operations. In this paper, we focus on the scheduling problem for a facility with staging, manual disassembly operations, and bulk recycling. In bulk recycling, shredding or grinding reduces the size of the material fragments while magnetic, eddy current or other density separation techniques separate the material fragments. Unlike production, there are often no due dates in materials recovery processing. Recyclers can sell the recovered materials to material commodity buyers at any time. However, recyclers wait to accumulate a shipment of material to reduce transportation costs and meet minimum sales quantities. Another important difference between production and recycling is that manufacturers purchase raw materials while recyclers may be paid to receive products. When due dates do not apply to scheduling products for materials recycling and product receipts generate revenue for recycling services, we propose two new metrics: the staging space turnover and the shipment fill time. We use our metrics to analyze new scheduling rules for disassembly and bulk recycling and to evaluate their performance. Using discrete-event simulation models, we test our scheduling rules on seven product families, where product families are defined based on material composition and separation operations. Of the rules we test, the disassembly scheduling rule which ranks product families based on the ratio of product size to disassembly time (SDT) most quickly empties the staging space. Shipment fill time is less sensitive to our scheduling rules. Our results illustrate how a recycler can reduce incoming product inventory with a new scheduling rule.**

***Index Terms*—Discrete-event simulation, electronics recycling, end-of-life product returns, scheduling, shipment fill time.**

I. INTRODUCTION

THE SALES and the number of discards for electronic equipment such as computers, televisions, and telecommunications equipment have increased in the USA, according to the National Safety Council [20]. Because electronics contain valuable materials as well as hazardous materials, such as lead solder alloys from the printed wiring boards and lead-impregnated glass from cathode ray tubes (CRT's), end-of-life (EOL) product returns centres have developed to divert discarded electronics from landfills [3], [19]. In this paper, we investigate the performance of scheduling rules for a facility with staging, manual disassembly operations, and bulk processing for materials recovery. First we review the literature on product recycling. Then, we compare metrics for scheduling in manufacturing with new metrics for scheduling in materials recycling. Next we define our new scheduling rules and evaluate their performance. Finally, we present the results of our study and discuss its implications.

We briefly highlight literature for disassembly planning because it includes the sequencing problem for manual disassembly of a product [8], [13], [15], [21]. This literature primarily focuses on how to select a disassembly level and generate an optimal disassembly sequence for a single product.

For weapons that have pre-determined disassembly sequences and levels [11] develop scheduling heuristics to schedule common facilities and personnel to maximize throughput subject to technician certification, technician exposure to hazardous substances, due dates, storage, and resource constraints. Limaye and Caudill [16] and Hesselbach and Westernhagen [10] use discrete-event simulation to analyze the sensitivity of material flow to resource capacity and layout configurations, respectively. These previous studies focus on manual disassembly, a labour-intensive process in which workers disassemble components from a single product. This research examined the net benefits of various disassembly levels and methods to reduce product disassembly time. An important gap in the research is identification of new metrics that apply to paid recycling services for a variety of different product returns and for which there are no due dates for the material commodities produced.

Unlike manual disassembly, bulk recycling is an equipment-intensive process flow in which materials are separated from multiple products for potentially multiple passes. In some instances, a combination of manual disassembly and bulk recycling equipment is used. Ploog and Spengler [23] present a mixed integer programming model to select discarded products for treatment, the disassembly level of each product, and whether to bulk recycle scrap components. For bulk recycling a single product Krikke, Harten *et al.* [12] present an algorithm for determining a recycling strategy in terms of high, low, or alternative materials recovery grades. For bulk recycling multiple products, Stuart and Lu [27] model when to separate mixed materials further to attain particular material grades in terms of single-pass versus continuous multiple-pass processing. In continuous reprocessing, a fraction of mixed material fragments is re-fed through the equipment for further separation. These previous bulk recycling studies do not address the sequence of products to demanufacture.

Sodhi *et al.* [26] present a dynamic program to sequence mixed materials for float-sink separation operations in bulk re-

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cycling. Because scheduling rules for an operation in which manual disassembly operations feed bulk processing operations are also needed, we initiated a study of disassembly scheduling rules that is detailed in [6]. The objectives of our investigation are summarized as follows.

1) To identify metrics to evaluate the performance of scheduling rules for materials recovery operations that include staging, disassembly, and mechanical size reduction for bulk recycling with a re-shredding and separation option for mixed output.
2) To define disassembly and materials recycling scheduling rules and evaluate their performance.

II. METRICS FOR MATERIALS RECYCLING

In this section, we begin by comparing scheduling metrics for manufacturing with new scheduling metrics for recycling. In Baker [2], production scheduling strategies typically seek good resource utilization, on-time response, and short-time response. In their review, MacCarthy and Liu [17] outline optimal and heuristic methods in production scheduling. According to Pinedo [22], scheduling in manufacturing optimizes metrics such as earliness, tardiness, or lateness. Tardiness and lateness are defined based on due dates. Unlike production, there are often no due dates in materials recovery processing. Recyclers can sell the recovered materials to material commodity buyers at any time. However, recyclers wait to accumulate a shipment of material to reduce transportation costs and meet minimum sales quantities. For example, a recycler accumulates a truckload quantity of ferrous metal to sell. A new metric, shipment fill time of a recovered material, is a cycle time metric for a recycler; it is measured from the time that the prior shipment departs until the current accumulation is picked up for shipment. This differs from a manufacturing cycle time that measures the time from the beginning to the end of the assembly process for a product. It also differs from batch-flow problems, where jobs may be batched to reduce delivery costs as discussed in [5] and [9]. We consider the case where large fixed shipment-sizes for each low-value material reduce shipment costs and meet the minimum shipment quantity of the customer. In practice, the accumulation time for a recycler to achieve a shipment-size load of a material may range from a few days to many months.

Another important difference between recycling and manufacturing is that the recycling service of accepting incoming products often generates more revenue than the sale of a shipment of recovered materials [4], [18],[25]. Since the shipment of products in manufacturing generates revenue, scheduling rules in manufacturing focus on increasing the efficiency of shipments according to due dates. For materials recovery, on the other hand, the focus is to accept, place, and remove products for materials recycling from the staging queue as quickly as possible. Therefore, the recycler seeks a high turnover in the initial staging queue space in the product returns centre.

Below we introduce notation for our process flow diagram shown in Fig. 1 and our scheduling rules. Our notation represents parameters that directly impact our decision metrics, staging space turnover and shipment fill time:

i	type of product family (e.g., monitors or personal computer towers);
j	output;
k	processing step;
t	time;
M_k	set of outputs j that can be recovered at processing step k;
$c_{i'i}$	product family changeover; if prior product family i' is hazardous and the subsequent family i is non-hazardous, then $c_{i'i}$ is 1; otherwise $c_{i'i}$ is 0;
e	empty run set-up time to clean out equipment for product family changeover;
f_{ik}	time factor that indicates the increase in processing time if re-shredding and separation are selected by the recycler for product family i at step k;
$L_{Q_{ik}}(t)$	current number of products of family i in queue prior to step k at time t;
p_{ik}	processing time per weight unit of product family i at processing step k;
r_j	net revenue per weight unit from recovered output type j;
s_i	cubic size of product family i;
w_{ij}	weight percentage of output type j in product family i.

Using our notation, we discuss the flow in a typical recycling process for EOL electronics recycling in Fig. 1. As shown in Fig. 1, incoming truckloads are unloaded and sorted into product families to queue for the first processing step, disassembly. Product families are defined based on material composition and separation operations. Two examples of product families in an EOL electronics recycling facility are monitors and personal computers (PC). Recyclers often group monitors separate from PC due to the leaded glass content of the monitors. From the queue prior to disassembly, product families are processed according to a scheduling rule. Multiple identical disassembly stations are available to disassemble any type of product. At the disassembly step in Fig. 1, the product family may be modified by removing output types, $j \ldots J$, for accumulation into shipment quantities. For example, a yoke may be removed from a monitor, bypass shredding, and be directly routed to shipment. Following disassembly, the modified families are queued prior to the second processing step, shredding, according to a scheduling rule. Similar to manufacturing, since product family changeovers may incur a set-up time, a large batch of a family may be selected [24].

We observed several recyclers with bulk processing equipment selecting between multiple-pass processing to recover fairly pure grade materials and one-pass processing to recover lower grade mixed materials [7]. With our notation, $f_{ik} > 1$ represents the increased percentage of time to continuously re-shred a mixture from family i at step k; while $f_{ik} = 1$ represents zero re-shredding for family i at step k. Once shredding is complete, each group of recovered outputs, $1 \ldots j-1$, is sorted and accumulated into shipment quantities.

III. NEW SCHEDULING RULES FOR RECYCLING

Next, we define new scheduling rules for staging queue and shredding queue in Table I. It is important to note in our sched-

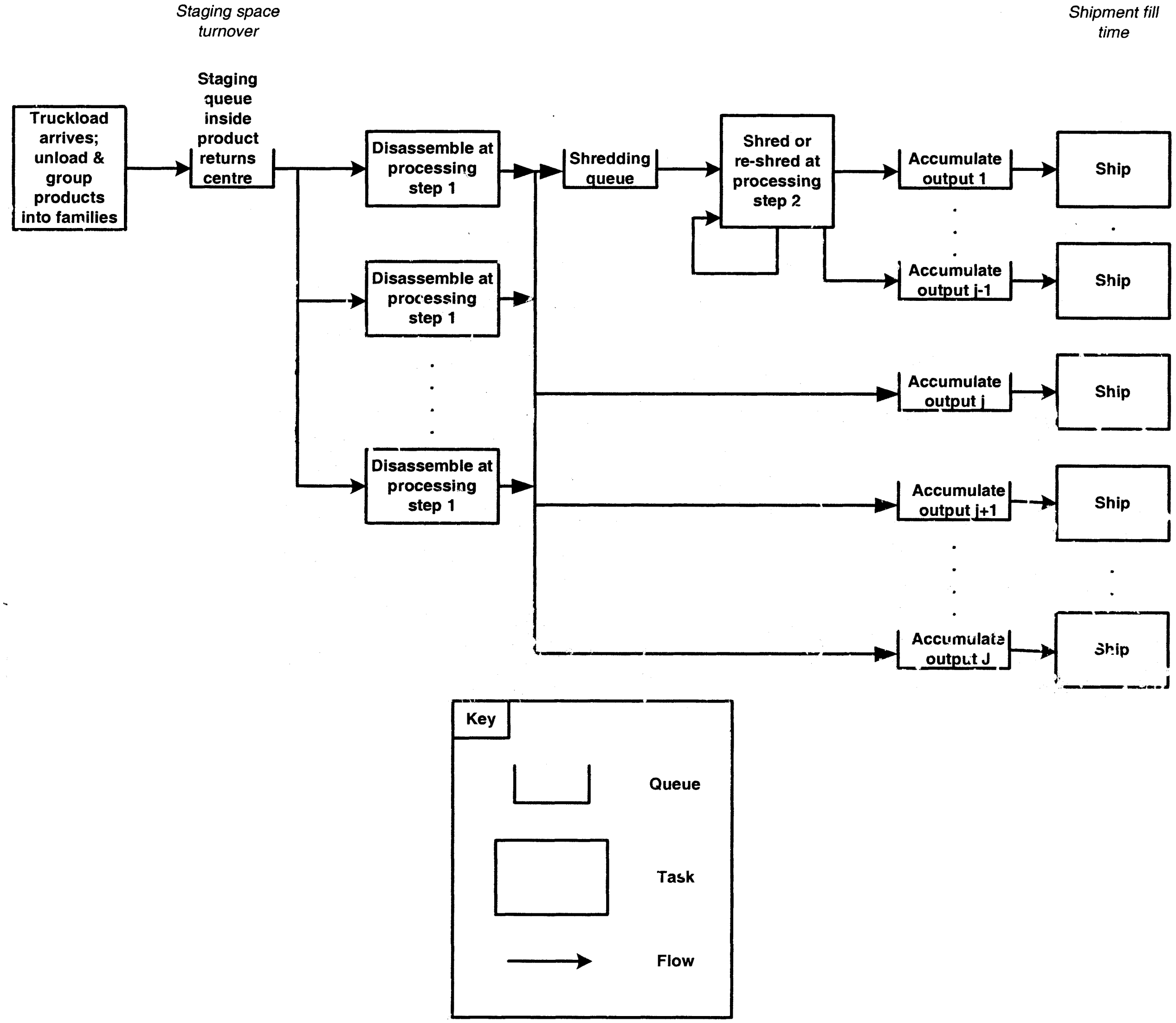


Fig. 1. Recycling centre process flow diagram.

uling rules that we do not want to fill all shipments faster; rather, we desire to fill valuable shipments faster. For example, a recycler may incur a cost to ship leaded glass to a smelter but may generate revenue to ship ferrous metals to a metals commodity broker. The objective of staging queue scheduling rules material recovery revenue per size (MRS) and material recovery revenue per disassembly time (MRDT) is to rank product families based on their potential to fill valuable material shipments. Our objective with staging queue scheduling rules, size per disassembly time (SDT) and size of staging space per family in disassembly queue (SSF), is to rank product families to empty the staging space quickly. For comparative purposes, we include rule disassembly time (DT), a shortest processing time rule. For shredding, we investigate rule revenue from bulk recycling queue per bulk recycling time (RBQBT), which ranks families to fill high value material shipments first.

As noted in Table I, the rankings for MRS, MRDT, SDT, and DT are calculated *a priori* based on historical data for disassembly time, product size, and material prices. On the other hand, SSF and RBQBT require real-time data for $L_{Q_{ik}}(t)$ and $c_{i'i}$. For the bulk processing scheduling rule RBQBT, we consider the number of each product family in the queue, the potential recycling revenue, and the processing, reprocessing, and changeover times. We emphasize recycling revenue in order to fill higher value shipments more quickly.

To test our scheduling rules, we seek to model finite processing capacities, demanufacturing of multiple products into materials, reprocessing, and set-up times for the switch from hazardous material runs to nonhazardous material runs. We use discrete-event simulation as described in the next section.

IV. EVALUATION OF SCHEDULING RULES FOR RECYCLING

In this section, we evaluate the performance of our scheduling rules for staging, disassembly, and bulk processing with continuous reprocessing options by using discrete-event simulation [14]. We developed our simulation model in ARENA 6.00.02® by Rockwell Software, Inc. [28] and ran our experiments on a Dell Optiplex GX260 desktop computer.

In our discrete event simulation evaluation, we make the following assumptions. In Table II, we used an EPA pilot study to construct the truckload compositions for eight arrival scenarios

TABLE I
NEW SCHEDULING RULES FOR DISASSEMBLY AND BULK PROCESSING

Application	Rule	Description	Rank	Priority Index
Staging queue	MRS	Materials recovery revenue per average product size in family *i* ranks families with the potential to fill valuable material shipments	Max	$\frac{\sum_{j\in M_k} r_j w_{ij}}{s_i}$ *a priori* rank
Staging queue	MRDT	Materials recovery revenue per disassembly time for family *i* ranks families with the potential to fill valuable shipments quickly	Max	$\frac{\sum_{j\in M_k} r_j w_{ij}}{p_{ik}}$ *a priori* rank
Staging queue	SDT	Ratio of average product size per disassembly time in family *i* ranks families to empty staging space quickly	Max	$\frac{s_i}{p_{ik}}$ *a priori* rank
Staging queue	SSF	Staging space occupied by family *i* in disassembly queue ranks families to remove the family occupying the largest amount of staging space first	Max	$s_i L_{Q_{ik}}(t)$ real time rank
Staging queue	DT	Disassembly time ranks families to process the shortest average processing (disassembly) time first	Min	p_{ik} *a priori* rank
Shredding queue	RBQBT	Ratio of material revenue from families in bulk recycling queue per bulk processing, reprocessing, and changeover time to rank families with the potential to fill high value material shipments more quickly	Max	$\frac{L_{Q_{ik}}(t)\sum_{j\in M_k} r_j w_{ij}}{(f_{ik} p_{ik} + ec_{i'i})}$ real time rank

TABLE II
TRUCKLOAD ARRIVAL RATE, COMPOSITION, AND PRODUCT FAMILY WEIGHT

			Truckload composition							
			1	2	3	4	5	6	7	8
Exponential arrival rate (h)			20	20	20	20	80	80	80	80
No.	Product family Description	Ave weight (kg)	Quantity (pieces)	Quantity (pieces)	Quantity (pieces)	Quantity (pieces)	Quantity (pieces)	Quantity (pieces)	Quantity (pieces)	Quantity (pieces)
1	Large TV/AC	28.49	13	13	21	18	33	76	64	59
2	Office equipment	3.17	8	4	36	16	48	78	102	60
3	Large electronic	2.65	73	33	89	41	261	187	150	191
4	PC	10.80	30	9	84	35	45	76	170	79
5	Monitor	5.94	87	25	183	94	61	92	101	114
6	Kitchen electronic	2.20	105	3	57	50	182	178	36	286
7	Small electronic	1.93	41	15	70	111	221	168	157	227
	Truckload weight	(kg)	1740	752	3203	1933	3460	4991	5472	4976
	Truckload volume	(m^3)	34.3	15.0	54.9	31.7	94.6	95.0	91.3	96.1

[29]. The first four truckload compositions in Table II represent the reported incoming quantities of each product family for the four EOL electronics one-day drop-off events in the EPA study. Because the reported quantities were less than truckload quantities, we formed an additional four full truckload quantities shown as truckload compositions five through eight in Table II. Truckload compositions five through eight have the same weight percentage as truckload compositions one through four but they are scaled to a full truckload quantity.

We assume exponentially distributed truckload arrivals with mean 20 h for the first four truckload compositions to represent biweekly transport from a drop-off collection point to the recycling centre and mean 80 h for the fifth through eighth truckload compositions to represent bimonthly transport from a drop-off collection point to the recycling centre.

We define the seven product families, large TV/AC, office equipment, large electronic, PC, monitor, kitchen electronic, and small electronic, according to a U.S. government pilot study [1], [29]. We defined the outputs recovered from the product families in Table III according to the United States Environmental Protection Agency [29]. The metals recovered were assigned to one of three output categories: ferrous, nonferrous, and mixed metal. Mixed metal may include printed wiring boards, fans, motors, disk drives, transformers, radiators, Freon tanks,

TABLE III
AVERAGE PRODUCT FAMILY COMPOSITIONS FROM UNITED STATES ENVIRONMENTAL PROTECTION AGENCY [29]

				Product Family						
				Large TV/AC	Office Equip.	Large Electr.	PC	Monitors	Kitchen Electr.	Small Electr.
Average product size/family (m^3)				0.28	0.09	0.23	0.08	0.08	0.03	0.04
Material		($/kg)	Shipment Weight(kg)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
1	Glass	$0.029	13600	14.00	0.00	0.00	0.11	37.00	0.00	3.42
2	Mixed plastic	$0.005	13600	11.02	39.69	37.12	20.59	20.13	38.17	43.61
3	Plastic	$0.086	13600	7.45	2.73	5.58	11.40	9.68	8.02	8.43
4	Mixed metal	$0.049	13600	21.20	35.10	21.00	18.20	1.12	13.70	9.06
5	Ferrous metal	$0.010	13600	25.70	15.60	32.10	45.00	20.80	32.30	17.90
6	Nonferrous metal	$0.244	1000	6.21	5.97	1.16	1.94	0.09	5.29	2.52
7	Wire	$0.083	13600	2.31	0.40	1.55	2.74	3.50	2.17	7.44
8	Yoke	$0.083	1000	2.24	0.00	0.00	0.00	6.65	0.00	0.54
9	Wood	-$0.039	13600	9.87	0.00	0.43	0.00	0.00	0.35	7.03
10	Other	-$0.039	13600	0.00	0.51	1.06	0.02	1.03	0.00	0.05

power supplies, and capacitors. Mixed plastic includes scrap plastic, plastic housings, and phone plastic. Scrap plastic refers to plastic pieces that are contaminated with paint, connectors, foam or other types of plastic. A yoke is a copper and steel metal assembly at the neck of the CRT.

In each of the runs, we use an equipment sequence of disassembly followed by a shredder with a magnetic sorter, air separator, and conveyors to output containers. The shredder reduces incoming products to material fragments ranging from 2.5–7.6 cm long. Equipment resources are assumed to be available with no breakdowns.

Disassembly includes removal of plastic housings, wood, wire, yokes, and other as defined in the American Plastics Council [1] and the United States Environmental Protection Agency [29]. The mean and standard deviation for disassembly times are in Table IV. We use a disassembly capacity of 35 labourers based on the capacity required to disassemble mean product arrivals in the mean disassembly time plus one standard deviation. The shredder processes 907 kg/h of PC, 1135 kg/h of kitchen electronics or small electronics, and 680 kg/h of large TV/AC, office equipment, large electronics, or monitors [4], [18], [25]. The reprocessing level, f_{ik}, is pre-determined using the continuous reprocessing decision model in [27].

To generate purer output and avoid contaminating nonhazardous materials with products that contain hazardous materials, recyclers sort, and bulk process by product families, including those modified by disassembly. In our case study, product families "large TV/AC" and "monitor," which contain lead-impregnated glass, incur a post-processing "empty-run" set-up time, e, equal to 15 min to clean out the shredder. We assume no pre-emption because we observed this in practice, there are no due dates for the various metals recovered, and the processing time for each product family in Table IV is relatively short.

TABLE IV
PRIORITIES FOR EACH PRODUCT TYPE FOR SCHEDULING RULES MRS, MRDT, SDT, AND DT

Family	Revenue/ piece ($)	Mean (std.dev.) disassembly time (min)	MRS Index ($/$m^3$)	MRDT Index ($/min)	SDT Index (m^3/min)	MRS Rank	MRDT Rank	SDT Rank	DT Rank
Large TVs/ACs	$10.54	19.8 (1.41)	$37.64	$0.53	0.0141	2	1	1	7
Office equipment	$1.71	16.2 (1.27)	$19.00	$0.11	0.0056	4	4	6	5
Large electronic	$0.63	18.0 (1.34)	$2.74	$0.04	0.0128	7	7	2	6
PC	$4.20	10.2 (1.01)	$52.50	$0.41	0.0078	1	2	4	3
Monitor	$0.58	12.0 (1.10)	$7.25	$0.05	0.0067	6	6	5	4
Kitchen electronic	$0.60	7.80 (0.883)	$30.00	$0.08	0.0026	3	5	7	2
Small electronic	$0.52	4.80 (0.693)	$13.00	$0.11	0.0083	5	3	3	1

Fixed shipment quantities for each output are based on reducing transportation cost and meeting the customer's minimum shipment weight. Once processing and reprocessing are complete, each group of recovered materials is allocated to its designated container to accumulate a shipment weight prior to departure. We assume that shipping truckload weight and volumetric capacities are 13600 kg and 97.86 m^3, respectively, with two exceptions; we assume less than truckload (LTL) shipment weight of 1000 kg for nonferrous metals and yokes due to their higher sales value. We indicate the shipment weights in Table III. Once processed outputs accumulate to form a shipment weight, the shipment is shipped immediately. Thus, maximum final output storage does not exceed the fixed shipment weights.

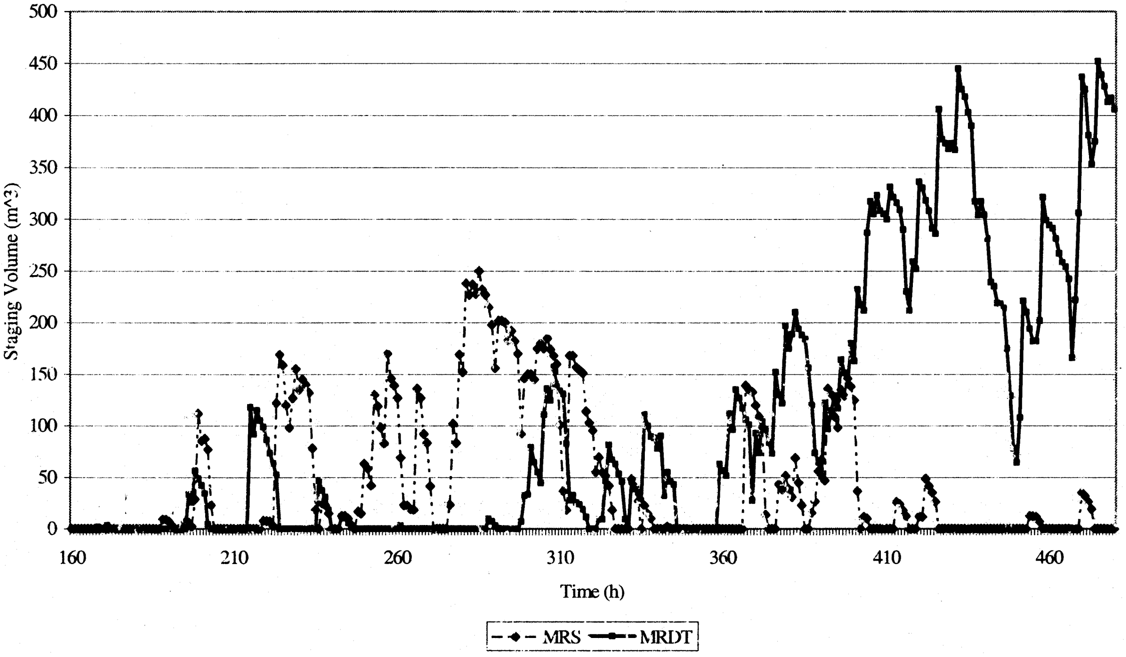
In Table IV, we calculate the MRS, MRDT, SDT, and DT ranks according to the formulas for the priority indices in Table I and the revenue data in the American Plastics Council [1] and the United States Environmental Protection Agency [29]. We see in Table IV that MRS ranks PC as the first priority family of products because it has the largest ratio of material recovery revenue to size. For MRDT and SDT, the large TV/AC product family is prioritised due to the larger ratios of material recovery revenue or size to mean disassembly time. DT, on the other hand, ranks small electronics first. Since SSF and RBQBT are based on real-time data $L_{Q_{ik}}(t)$ and $c_{i'i}$, we compare these rules using discrete-event simulation.

V. RESULTS AND ANALYSIS OF PERFORMANCE EVALUATION

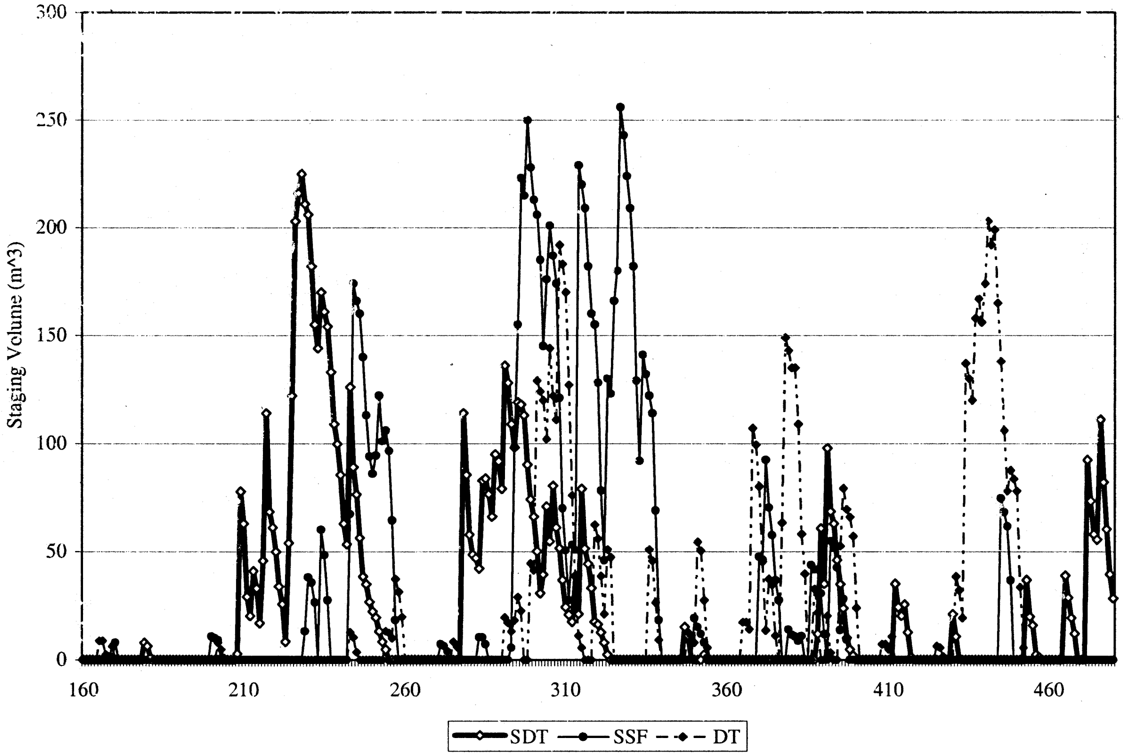
In our experimental runs, we simulate each scheduling rule for 320 h (eight 40-h/wk shifts). Using a graphical approach, we select a 160-h warm-up period. In Fig. 2(a) and (b), we show the variation in total staging volume versus time for 320-h (160-h to 480-h) after the 160-h warm-up period for the five scheduling rules in one of the 20 replications. Fig. 2(a) and (b) illustrate that scheduling rule SDT has the lowest maximum total staging volume as well as the lowest total staging volume over time.

The average total staging space is shown in Fig. 3(a) for a 95% CI range for 20 replications for each of the five scheduling rules. As shown in Fig. 3(a), the SDT scheduling policy has the lowest mean and CI width for average total staging volume. In Fig. 3(b), the scheduling rule SDT has the lowest maximum staging space at any one point in time. SSF and DT, on the other hand, require the largest maximum staging space at any one point in time. If the recycler wants to reduce the probability of incurring external storage and handling costs, then we recommend using our proposed, easy to implement scheduling rule SDT. Fig. 3(a) and (b) illustrate that a recycler may lower staging space requirements significantly through scheduling.

Because ferrous metal has the largest weight percentage in many of the families in Table IV, we track in Fig. 4 the 95% CI



(a)



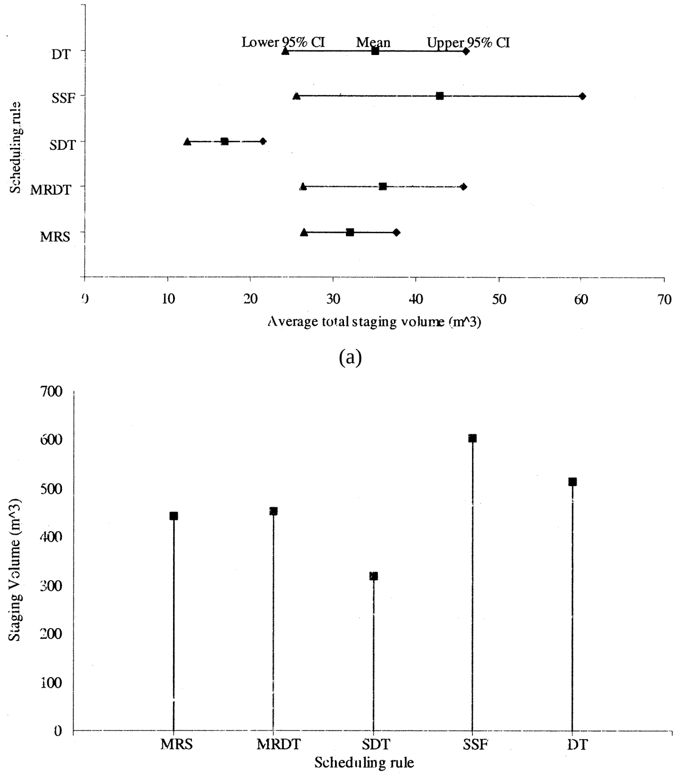
(b)

Fig. 2 (a) Total staging volume in replication 11 for scheduling rules MRS and MRDT. (b) Total staging volume in replication 11 for scheduling rules SDT, SSF, and DT.

for 20 replications for the average shipment fill time for ferrous metal for each scheduling rule. Although the SSF scheduling rule has the lowest mean for average shipment fill time over 20 replications, each of the other four scheduling rules incur means within 9% of the SSF scheduling rule. Furthermore, the CI overlap. In our scenario, shipment fill time is not significantly sensitive to the scheduling rule. In Figs. 2 and 3 we find that staging volume is much more sensitive to our scheduling strategies than shipment fill time in Fig. 4.

VI. CONCLUSION

We present an interesting contrast to manufacturing goals that seek to decrease *finished* product inventory levels. In recycling,



(a)

(b)

Fig. 3 (a) 95% confidence interval for average total staging volume for each scheduling rule over 20 replications. (b) Maximum staging volume that occurs over 20 replications.

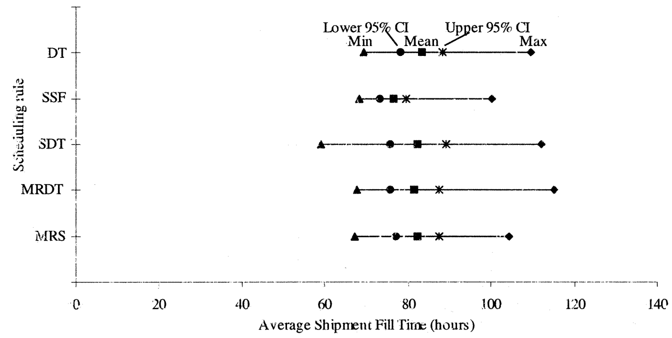


Fig. 4. 95% confidence interval for average shipment fill time for ferrous metal for each scheduling rule over 20 replications.

we focus on scheduling rules to increase *incoming* product inventory turnover. In the scenario we evaluated, average total staging volume was much more sensitive to scheduling strategy than average shipment fill time. Our studies show that scheduling rule SDT significantly reduces the maximum total staging volume. When acceptance fees for truckload arrivals of EOL electronics generate more revenue than the sale of recovered outputs, increasing the turnover in the staging area is economically more important than a faster shipment fill time, especially as electronics return volumes increase. Our results indicate that staging space turnover is more likely to decrease with consideration of the ratio of average product size to average disassembly time. In our simulation study, SDT incurs the tightest CI for average total staging space and is least likely to require rental of additional space. Furthermore, SDT is easy to implement.

In our study, we assumed a disassembly level and a bulk recycling processing level. An area for future study is to investigate integration of product sequencing decisions with disassembly and bulk processing level decisions to determine the grade of the material recovery.

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REFERENCES

[1] "A summary report from the electrical and electronics group of the APC: Plastics from residential electronics recycling," Tech. Rep., American Plastics Council, 2000.

[2] K. R. Baker, *Introduction to Sequencing and Scheduling*. New York: Wiley, 1974.

[3] P. Biocca, "Solder safety and disposal management," in *Proc. NEPCON W.*, Anaheim, CA, 1994, pp. 867–873.

[4] R. Chapman, CEO, Resource Concepts, Inc., Carrollton, TX, May 5, 2001.

[5] T. C. E. Cheng and V. S. Gordon, "Batch delivery scheduling on a single machine," *J. Opl. Res. Soc.*, vol. 45, no. 10, pp. 1211–1215, 1994.

[6] V. Christina, "Discrete-event simulation analysis of scheduling strategies for electronics recycling," M.S. Honors Thesis, The Ohio State Univ., Columbus, OH, 2001.

[7] L. D. Foley, Director of Operations, Aurora Plastics, Conklin, NY, Aug. 10, 2001.

[8] A. Gungor and S. M. Gupta, "Issues in environmentally conscious manufacturing and product recovery: A survey," *Comput. Ind. Eng.*, vol. 36, pp. 811–853, 1999.

[9] J. W. Herrman and C.-Y. Lee, "On scheduling to minimize earliness-tardiness and batch delivery costs with a common due date," *Eur. J. Operat. Res.*, vol. 70, pp. 272–288, 1993.

[10] J. Hesselbach and K. V. Westernhagen, "Systematic planning of disassembly with grouping and simulation," in *Proc. 2nd Int. Working Sem. Reuse*, 1999, pp. 151–156.

[11] E. A. Kjeldgaard *et al.*, "Swords into plowshares: Nuclear weapon dismantlement, evaluation, and maintenance at Pantex," *Interfaces*, vol. 30, no. 1, pp. 57–82, 2000.

[12] H. R. Krikke *et al.*, "On a medium term product recovery and disposal strategy for durable assembly products," *Int. J. Prod. Res.*, vol. 36, no. 1, pp. 111–139, 1998.

[13] A. J. D. Lambert, "Disassembly sequencing: A survey," *Int. J. Prod. Res.*, 2003.

[14] A. M. Law and W. D. Kelton, *Simulation Modeling and Analysis*. New York: McGraw-Hill, 1991.

[15] D.-H. Lee *et al.*, "Disassembly planning and scheduling: Review and further research," in *Proc. Inst. Mech. Eng.*, vol. 215 B, 2001.

[16] K. Limaye and R. J. Caudill, "System simulation and modeling of electronics demanufacturing facilities," in *Proc. IEEE Int. Symp. Electron. Environ.*, Danvers, MA, 1999, pp. 238–243.

[17] B. L. MacCarthy and J. Liu, "Addressing the gap in scheduling research: A review of optimization and heuristic methods in production scheduling," *Int. J. Prod. Res.*, vol. 31, no. 1, pp. 59–79, 1993.

[18] M. F. Magliaro, President, DMC Recycling, Newfields, NH, June 9, 1998.

[19] S. E. Musson *et al.*, "Characterization of lead leachability from cathode ray tubes using the toxicity characteristic leaching procedure," *Environ. Sci. Technol.*, vol. 34, no. 20, pp. 4376–4381, 2000.

[20] "Electronic product recovery and recycling baseline report: Recycling of selected electronic product in the United States," National Safety Council, Washington, D.C., 1999.

[21] B. O'Shea *et al.*, "State of the art literature survey on disassembly planning," *Concurrent Eng.*, vol. 6, no. 4, 1998.

[22] M. Pinedo, *Scheduling: Theory, Algorithms, and Systems*. Englewood Cliffs, NJ: Prentice-Hall, 1995.

[23] M. Ploog and T. Spengler, "Integrated planning of electronic scrap disassembly and bulk recycling," in *Proc. IEEE Int. Symp. Electron. Environ.*, San Francisco, CA, 2002, pp. 263–268.

[24] C. N. Potts and M. Y. Kovalyov, "Scheduling with batching: A review," *Eur. J. Operat. Res.*, vol. 120, pp. 228–249, 2000.

[25] S. M. Skurnac, President, Micro Metallics, Roseville, CA, Nov. 5, 1998.

[26] M. S. Sodhi *et al.*, "Modeling material separation processes in bulk recycling," *Int. J. Prod. Res.* , vol. 37, no. 10, pp. 2239–2252, 1999.

[27] J. A. Stuart and Q. Lu, "A refine-or-sell decision model for a station with continuous reprocessing options in an electronics recycling center," *IEEE Trans. Electron. Packag. Manufact.*, vol. 23, pp. 321–328, Oct. 2000.

[28] Arena 6.00.02, Rockwell Software, Inc., Sewickley, PA, 2002.

[29] EPA, "Residential collection of household end-of-life electrical and electronic equipment: Pilot collection project," United States Environmental Protection Agency, Region 1, Boston, MA, EPA-901-E-98-002, 1998.

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