Plastic Separation Planning for End-of-Life Electronics

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***Abstract*—Important challenges remain for sustainable design, manufacture, use, and recycling of electronics including materials selection and disassembly time. This paper examines the value relationship between the quantity of plastics separated and the time required for disassembly and segregation. Labor costs for disassembly can constitute a large portion of the total acquisition cost for a recycled material. We report work measurement studies conducted on the disassembly of 21 computers, 22 printers, and 32 monitors manufactured by 27 producers in the years from 1984 to 2001.**

Results include the weight per total separation time for each plastic part. Each recovered part is identified according to polymer resin using laser Raman spectroscopy by chemometric reference to a library of standards. We extrapolate time as well as the product input required to accumulate various specific types of plastic. We develop disassembly policies and show that they are effective for a variety of computer, printer, or monitor models, which is typical of the random product streams that arrive at electronics recycling facilities. The results demonstrate how new laser identification technology and work measurement can be used for plastics separation planning.

***Index Terms*—Disassembly, electronics recycling, plastics, Raman spectroscopy, work measurement.**

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I. INTRODUCTION

IMPORTANT challenges for the sustainability and green engineering design, manufacture, use, and recycling of electronics include materials selection, energy requirements during use, speed of product obsolescence, and disassembly time. In this paper, we investigate the impact of the materials selection and disassembly time on materials recycling from end-of-life electronics.

It is estimated that more than 20 million personal computers became obsolete in 1998 in the U.S.; however, only 11% of those computers were processed for recycling [1]. The U.S. National Safety Council predicts that the number of obsolete personal computers will continue to increase. As the cost of plastic becomes cheaper in comparison to metal, manufacturers are using more plastics in their products. This plastic represents a significant nonrenewable resource. However, its recovery presents serious logistical, transport, and personnel challenges. The total cost of collection and processing can well require recycled resin prices that are higher than virgin resin prices [2]. A further challenge is the fact that recyclate value is tied to purity, and more than 16 plastics can be found in demanufactured electronics [3]. This puts a premium on plastic resin identification and sorting. Plastic resin suppliers hesitate to offer recycled plastics without a consistent quality feed stream [2].

In current electronics recycling practice, products that arrive at the recycling facility are first sorted by product type. Once the sorting is completed, products are partially disassembled to remove valuable parts for resale or hazardous components such as batteries. Resale of components, such as hard drives and memory cards, and recycled materials, such as mixed plastics and metals, may not cover the separation costs. In order to generate net revenue, electronics recyclers often charge companies and municipalities for their recycling services.

The principles of green engineering require reduced material consumption by means of deliberate efforts in design, manufacturing process, product life cycle systems infrastructure, and recycling process [4]. In order to improve the product life cycle systems infrastructure and recycling process for electronics, it is critical to investigate the separation and identification of the materials in use. Since labor costs for disassembly can represent a majority of the total costs for recyclers, we focus this paper on the relationship between the amounts of labor required versus the plastics recovered.

In the sections to follow, we summarize previous research, define the problem scope, and propose new ratios for the relationship between specific materials recovered and time to separate materials. We offer an experimental design to test recovery ra-

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tios, and report findings following an application of this methodology to a sample stream of end-of-life electronic products consisting of 75 representative computers, monitors, and printers. The results provide a new look at costs and material values in the electronic material plastics supply cycle that will be of use in deciding recycling policy and practices for this sector.

II. Material Studied

A number of recent studies promote sustainability [5] by means of green engineering [4] and environmentally conscious manufacturing [6]. These studies and others call for product remanufacturing and reuse prior to material recycling in order to reduce material consumption and environmental impacts over the product life cycle [7]. Material separation for recycling may be characterized by the inclusion of a disassembly process [8], [9]. Including disassembly in the material separation process for recycling is preferable for environmental purposes to recover more valuable and usable materials, reduce hazardous waste, and minimize materials depletion [7].

Previous research on recycling electronic products for material separation has emphasized metal and glass recovery from bulk recycling processes that often do not include disassembly. [10] review magnetic, eddy current, and air table separation to recover metals. [11] review the various technologies available to recover cathode ray tube glass. In practice, electronics recyclers separate ferrous and nonferrous metals to sell to mills for reuse, glass to ship to lead smelters for glass-to-lead recycling [12], and mixed plastics to ship for waste-to-energy recovery [13], [14].

The research to date in the area of plastic recovery for reuse has focused mainly on the use of already separated plastic. For example, an electronics engineering thermoplastics recycled material characterization matrix is presented to classify plastics based on their quality grade, source, weight, color, contaminants, type, and physical properties [2]. The weight and strength of high-impact polystyrene (HIPS) and polybutylene terephthalate (PBT) obtained from disassembling versus shredding a television and a personal computer keyboard are evaluated in [15]. [16] states that "integrated plastics waste management ... includes source reduction, reuse, recycling, landfill, and waste-to-energy conversion." The materials recycling step for electronics requires separation of high-value engineering plastics. A major gap in the research is how to separate and identify the engineering plastics [17].

It is important now to evaluate disassembly for the purpose of recovering multiple types of plastics. New technologies to identify plastics include: X-ray [18], Infrared, near-infrared [19], Raman [20], and photoacoustic spectroscopy [21]. Among these, we believe that Raman spectroscopy occupies a distinctive position, owing to its simplicity of use, near universal applicability, and high discerning power [22], [23].

How can recyclers use new identification technology with expanded libraries and work measurement to improve plastics separation planning? This question will be addressed by specifically answering the following questions. What is the plastic recovery rate in terms of weight recovered per minute for electronic products? In other words, given 75 different personal computers, printers, and monitors, what plastics can be recovered, at what rates of recovery? Furthermore, what insight does the plastics recovery rate provide for recycling process design?

III. Methodology

This study proposes to determine the relationship between the plastics recovered and the time to separate the materials. [24] created two metrics for designers to evaluate manual or mechanical separation techniques. The first metric is the value removal rate (VRR), which is the weight of the material multiplied by the value of the material divided by the time to separate the material. The designer may compare the VRR with the cost per hour for disassembly to predict the recycling profitability. However, as the authors point out, the designer does not necessarily know the value of the material at the time of design. The second metric, the material removal rate (MRR), does not require the material value. The MRR is the weight of the material divided by the time necessary to separate it. This study extends the MRR metric to specific plastic types, where we refer to it as the plastic recovery rate (PRR). To define PRR in (1), we let W_j be the weight of each specific type of plastic j and D_k be the disassembly time for product k. In order to determine specific PRR values for the samples studied in this work, we identified the plastic resin type of each disassembled part by means of point-and-shoot Raman spectroscopy [25]

$$\mathrm{PRR} = \frac{W_j}{D_k}. \tag{1}$$

To determine the time required to remove material, we performed work measurement studies using the methods time measurement (MTM) technique [26]. Our inclusion of predisassembly product evaluation, presorting, tooling selection decision analysis, and plastics identification [27] distinguishes this study's MTM metrics from previous work in the literature [28], [29].

IV. Experimental Design

The performance of these work measurement studies required several assumptions, which were confirmed by personal communication with recyclers [30], [31]. We first assumed that workers operated at the peak of the disassembly learning curve, which we defined to be at least 2000 repetitions. Next, we assumed that workers disassemble at an hourly pace that is not incentive based. Necessary tools, such as electric screwdrivers, are suspended two feet above the worker. The Raman probe gun is located two feet away from the worker. When the pieces are disassembled, the worker's arm extends fully (two feet) to throw the pieces into bins labeled by material type. The remaining parts are sent to shredding.

This study defines three disassembly levels: cover, basic, and extended. Cover disassembly may include the whole housing or a specific portion of the housing. For computers and printers, we denote cover disassembly as whole housing disassembly. Since the back cover of monitors is usually the largest housing component and requires the least disassembly activity, we specify back cover disassembly for monitors. In basic disassembly, the housing is removed, hazardous components such as a battery are separated, and valuable components such as a memory card or hard drive are removed for resale. Extended disassembly involves additional steps to separate the remaining components, except those plastic components with glued foam, metal inserts, or other time and process prohibitive plastic mixtures. This study defines time prohibitive as greater than 30 s per part and process prohibitive as separation requiring tooling beyond a screwdriver and pliers. The plastic mixtures are sent to bulk recycling. For both the basic and extended disassembly scenarios, D_k in (1) represents aggregate disassembly times that include separation of valuable components for reuse. If D_k is disaggregated, then the portion of the separation time for plastics increases the ratio of material per time unit for material-focused recycling.

The work measurement studies were performed on a variety of computers, printers, and monitors representing a diversity of electronics manufacturers. Computer refers to CPU in this study; we did not evaluate cables or external accessories such as keyboards and mice. Our computer sample includes models from the top three global computer manufacturers in the mid 1990s [32] as well as the top four global computer manufacturers who captured 46% of the global computer market in 1999 [33].

The plastic parts from disassembled computer, printer, and monitor samples were analyzed to determine their resin composition by means of Raman spectroscopy. We used a Spectracode model RP-1 system which has been developed commercially for point-and-shoot materials identification. This device employs a manually-triggered hand held probe containing an optical train for a laser illuminating a sample and collecting back-scattered radiation for spectroscopic analysis. Laser radiation (1 W, 800 nm) is carried to and Raman signal collected from the probe head via 5-m fiber-optic umbilical. The sample material is identified by multivariate comparison with a library of standards using the chemometric technique of partial least squares (PLS) [34]. The total elapsed time required for analysis is typically one second or less.

Tables I–III list the computers, printers, and monitors that were disassembled and evaluated. Computers are denoted by "C#" in Table I, while printers are labeled with "P#" in Table II, and monitors are labeled with "M#" in Table III. In Tables I–III, if a date sticker was not available on the housing, an "*" indicates that the year of manufacture was based on the oldest memory chip year of manufacture.

TABLE I
COMPUTERS DISASSEMBLED AND EVALUATED

Number	**Computer**	**Year** (*Estimate)
C1	Epson Equity II +	1986*
C2	Macintosh II si	1990*
C3	IBM PowerStation 320	1991
C4	Northgate SlimLine 333	June 1991
C5	Compaq Deskpro 3/33i	1992*
C6	Elegance ZXP	July 1992
C7	AST Advantage! Pro (486SX/25)	April 1993
C8	Power Macintosh 7200/90	1994*
C9	Macintosh Perfoma 631CD	1995*
C10	Cannon MT 4900	May 1995
C11	Hewlett Packard Vectra XU	1996*
C12	Hewlett Packard Vectra VE	1996*
C13	IBM Power PC	February 1996
C14	IBM Personal Computer 750	July 1996
C15	Gateway Tower 2000	December 1996
C16	IBM Personal Computer 365	January 1997
C17	Micron Millenia LXA	May 1997
C18	Gateway Tower E3100	June 1997
C19	Gateway Desktop E3000	January 1998
C20	IBM Personal Computer 300 PL	September 1998
C21	Dell OptiPlex GX1	October 1998

TABLE II
PRINTERS DISASSEMBLED AND EVALUATED

Number	**Printer**	**Year** (*Estimate)
P1	IBM Proprinter II	1985
P2	Okidata Microline 320	1987*
P3	OKI Microline 395	1988*
P4	OKIDATA Microline 591	1988*
P5	DEC laser 2100	1990*
P6	HP LaserJet III	1990*
P7	HP LaserJet IIP	March 1990
P8	IBM PPS 2 2830	1991
P9	HP LaserJet IIIP	October 1992
P10	HP Laser Jet 4P	October 1993
P11	HP DeskJet 1200C	1994*
P12	Lexmark Color Jet 2050	1994*
P13	Cannon BJ-100 Bubble Jet	1995*
P14	HP Deskjet 600	June 1995
P15	Canon BJC-80 Color BubbleJet	1996*
P16	HP DeskJet 1600C	1996*
P17	Eltron International (UPS label printer)	September 1996
P18	HP DeskJet 870Cse	May 1997
P19	HP LaserJet 6L	July 1997
P20	HP Deskjet 890C	October 1997
P21	Lexmark 5700	1998*
P22	HP Deskjet 695 C	August 1998

V. RESULTS AND DISCUSSION

For our study of 21 computers, 22 printers, and 32 monitors, the average weight of each type of plastic is shown in Fig. 1 for the basic computer case and the extended monitor and printer cases. Our study finds that acrylonitrile butadiene styrene (ABS) is the most popular plastic for computers, printers, and monitors. In some cases, ABS is enhanced with polycarbonate (PC). Because ABS is the most popular plastic in our study, we focus on it in the PRR analysis.

The percentage of machines from which plastic parts were disassembled that weighed greater than 50 g is graphed across plastic types in Fig. 2. For example, over 75% of the printers have at least one piece of ABS that weighs at least 50 g while 50% of the monitors have at least one piece of HIPS that weighs at least 50 g. The percentages over each product type do not sum to one because a product may contain more than one type of plastic.

TABLE III
MONITORS DISASSEMBLED AND EVALUATED

Number	**Monitor**	**Year** (* Estimate)
M1	IBM 5894000	October 1984
M2	Atari	July 1985
M3	HP	October 1985
M4	Datapoint 1500	1985*
M5	Macintosh SE	1986
M6	Telex	April 1988
M7	Infowindow	October 1989
M8	Commodore	January 1990
M9	Apple Color High Resolution RGB	January 1990
M10	IBM Infowindow	May 1990
M11	Packard Bell	November 1990
M12	NEC	January 1991
M13	NEC Multi Sync 5FG	November 1991
M14	IBM 8512	July 1992
M15	Memorex Telex	December 1992
M16	IBM	May 1993
M17	IBM	November 1993
M18	Gateway 2000 1776IE	April 1994
M19	Memorex Telex	August 1994
M20	Sun	November 1994
M21	NEC Multi Sync XE15	December 1994
M22	Samsung Sync Master 17GL	January 1995
M23	WYSE	September 1995
M24	HP ErgoUltra UGA	December 1995
M25	IBM InfoWindow II 3153	March 1996
M26	CSV 1500PS	May 1996
M27	IBM 6543-301	July 1996
M28	IBM	April 1998
M29	Miracle 14" Mono	September 1998
M30	Elo ETC1706	November 1999
M31	M20DAP1KO	December 1999
M32	Miracle 9" SVGA	March 2001

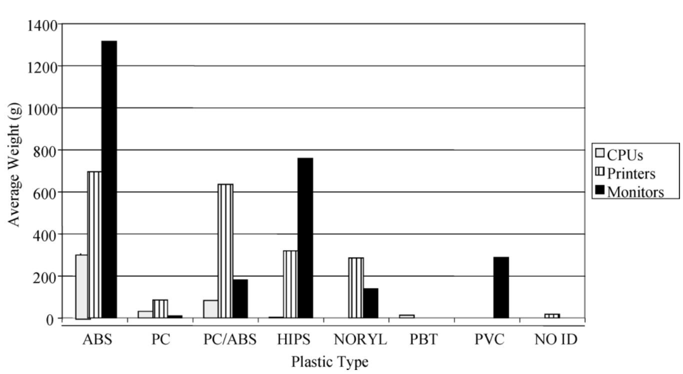

Fig. 1. Plastic type by average weight.

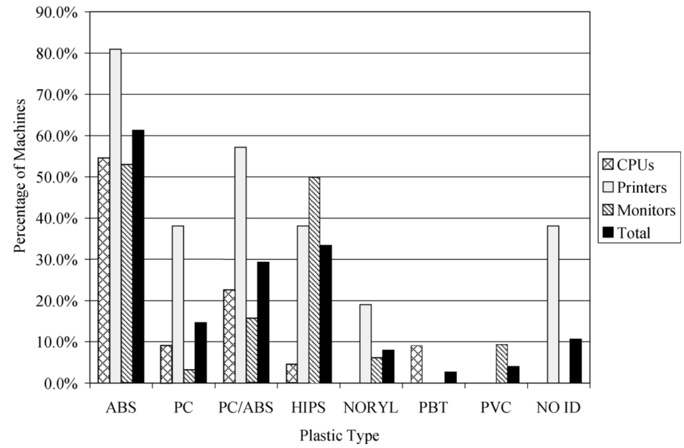

Fig. 2. Percentage of machines from which plastic pieces (>50 g) were disassembled for each plastic type.

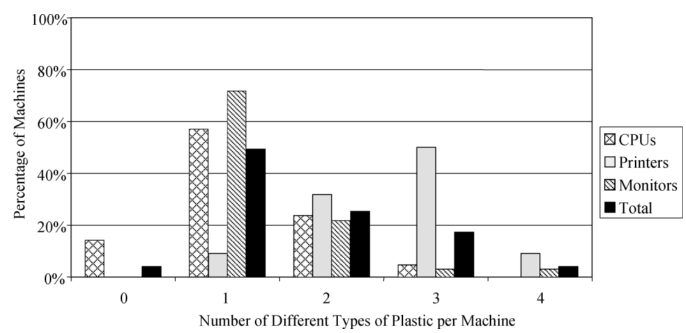

Fig. 3. Frequency of multiple plastics per machine.

The frequency of more than one plastic appearing in a single machine is illustrated in Fig. 3. As anticipated, printers contain the greatest variety of plastic types due to their complexity, arising from the mechanical demands of moving parts and the transport of print media.

The MRR is calculated for each piece of equipment to evaluate the total amount of plastic separated in basic and/or extended disassembly in Tables IV–VI for computers, printers, and monitors, respectively. Because ABS is the most popular plastic in this study, the weight and PRR for ABS is also shown in Tables IV–VI. ABS as the dominant plastic type in computers is consistent with the results reported in [12]. In Table IV, the weight and PRR for ABS is shown for the basic case since the extended case lowered the PRR and MRR in nearly all the cases. In our study, the MRR for the basic disassembly ranges from a low of 0 (C5, C6, C10) to a high of 1025 (C2) for computers. For the extended disassembly, the MRR ranges from 0 (C5, C6, C10) to 619 (C2) for computers. Furthermore, the MRR decreases significantly for extended disassembly in 16 out of 21 cases; C8 and C12 are the only computers to increase MRR with extended disassembly in our study.

The PRR values are calculated for each type of plastic removed from equipment in the study. Matches of sample Raman spectra with the chemometric reference library served to identify ABS, PC, PC/ABS, HIPS, Noryl (polphenylether polystyrene alloy), and polyvinyl chloride (PVC). We found two plastic parts for which there was not a match in the library of standards employed. These parts, which were encountered as components of C14 and C16, were both labeled with manufacturer molding stamps as polybutylene terapthalate (PBT). Tables IV–VI present the PRRs found in the study for ABS plastic, which was found to occur most frequently, as shown in Fig. 1 and 2. The results of the individual PRRs agree with the conclusions for the overall MRR; extended disassembly does not result in significant additional quantities of plastic. Only the PRR for the basic disassembly is given in Table IV.

TABLE IV
PLASTIC RECOVERY RATE FOR COMPUTERS

Equip-ment	Cover Disassembly: Cover Weight (g)	Cover Time (min)	CMRR	Basic Disassembly: Plastic Weight (g)	Time (min)	MRR	ABS Weight (g)	ABS PRR	Extended Disassembly: Total Plastic Weight (g)	Total Time (min)	MRR
C1	267	1.505	177	267	2.539	105	267	109	272	3.765	72
C2	1077	0.322	3343	1077	1.050	1025	1077	1123	1077	1.738	619
C3	0	0	0	759	1.505	504	0	0	824	2.841	290
C4	236	1.681	140	236	2.778	85	236	88	238	4.655	51
C5	0	0	0	0	1.557	0	0	0	0	2.121	0
C6	0	0	0	0	1.513	0	0	0	0	2.234	0
C7	0	0	0	45	1.550	29	45	29	75	2.870	26
C8	195	0.535	365	236	1.627	145	236	163	412	2.773	149
C9	1160	0.551	2108	1160	1.704	681	1160	933	1160	2.608	445
C10	0	0	0	0	0.934	0	0	0	0	1.604	0
C11	467	1.021	458	479	2.276	210	316	166	575	3.189	180
C12	0	0	0	49	1.288	38	0	0	144	2.645	54
C13	642	1.067	602	642	1.251	513	0	0	718	2.482	289
C14	585	0.756	774	585	1.371	427	0	0	691	3.121	222
C15	337	0.889	379	337	1.325	254	337	273	427	3.386	126
C16	587	0.710	827	587	1.547	379	0	0	632	3.031	208
C17	280	0.295	949	280	1.407	199	280	213	280	2.449	114
C18	2144	1.395	1537	2144	3.238	662	2144	747	2144	4.561	470
C19	531	1.467	362	531	2.286	232	531	264	531	3.861	137
C20	0	0	0	42	1.389	30	0	0	42	2.350	18
C21	87	1.120	78	87	1.308	67	87	72	110	2.527	44
Average	▲614	▲0.951	▲864	454	1.688	266	320	199	493	2.896	167
Total	8595	13.314		9543	35.440		6716		10352	60.811	

▲ Indicates that the average cover weight, average cover time, and average cover MRR do no include equipment with metal covers.

TABLE V
PLASTIC RECOVERY RATE FOR PRINTERS

Equip-ment	Cover Disassembly: Plastic Cover Weight (g)	Plastic Cover Time (min)	CMRR	Extended Disassembly: Total Plastic Weight (g)	Total Time (min)	MRR	ABS Weight (g)	ABS PRR
P1	1667	2.335	714	1681	2.3348	720	0	0
P2	719	1.004	716	2422	6.1055	397	2256	370
P3	3447	5.408	637	3845	5.4079	711	323	60
P4	1047	0.787	1330	3293	5.9418	554	0	0
P5	1656	2.062	803	1912	3.8699	494	1656	428
P6	2844	2.364	1203	3064	2.3635	1296	3064	1296
P7	1604	3.163	507	1790	3.1633	566	1729	547
P8	1865	3.643	512	2254	3.6430	619	717	197
P9	1390	0.936	1486	1391	0.9357	1486	1391	1486
P10	1309	7.599	172	2290	7.5988	301	0	0
P11	2631	1.836	1433	2821	1.8864	1495	150	80
P12	842	1.514	556	1513	3.5620	425	297	83
P13	691	0.973	710	1198	2.0793	576	1001	481
P14	1120	1.715	653	1251	2.1076	594	0	0
P15	301	1.321	228	514	1.3210	389	335	254
P16	2485	1.850	1343	2556	1.8498	1382	9	5
P17	218	1.426	153	737	1.9115	386	564	295
P18	1261	0.984	1282	1894	1.2929	1465	626	484
P19	1371	2.881	476	1654	3.2173	514	328	102
P20	1323	1.415	935	1948	2.8303	688	58	20
P21	585	0.957	611	1495	1.7913	835	0	0
P22	1008	1.517	665	1186	1.8201	652	88	48
Average	1427	2.168	778	1941	3.0470	752	663	283
Total	31384	47.690		42709	67.034		14592	

TABLE VI
PLASTIC RECOVERY RATE FOR MONITORS

	Back Cover Disassembly				Extended Disassembly				
Equipment	**Back Cover Plastic Weight (g)**	**Back Cover Time (min)**	**Back Cover Plastic**	**BCPRR**	**Total Plastic Weight (g)**	**Total Time (min)**	**MRR**	**ABS Weight (g)**	**ABS PRR**
M1	1813	1.010	PS	1795	2638	2.3401	1127	0	0
M2	1292	0.831	ABS	1554	1844	3.2458	568	1844	568
M3	1353	0.337	ABS	4018	2927	25.5398	115	1788	70
M4	2454	0.304	PC/ABS	8084	2999	4.3785	685	0	0
M5	1857	1.077	PC	1723	2043	10.5709	193	2043	193
M6	1013	1.120	ABS	904	3411	4.3796	779	3411	779
M7	1524	0.478	ABS	3189	2553	2.0094	1271	2553	1271
M8	1312	0.653	ABS	2009	2155	2.5880	833	1312	507
M9	1487	0.599	ABS	2480	2762	6.0087	460	2762	460
M10	1513	1.065	ABS	1421	2465	2.1707	1136	2465	1136
M11	1811	0.696	PPO	2603	2411	2.5974	928	0	0
M12	1599	0.715	PS	2237	2368	4.5261	523	0	0
M13	■1919	■8.392	PS	229	5158	10.2025	506	0	0
M14	1487	0.949	PS	1566	2474	6.0835	407	0	0
M15	■1275	■3.461	ABS	368	1971	3.4614	569	1971	569
M16	2806	2.028	PVC	1384	3828	3.8725	989	0	0
M17	2148	2.169	PVC	990	2759	5.1006	541	0	0
M18	2022	1.222	PPO	1655	3014	5.0505	597	0	0
M19	1265	0.597	ABS	2119	3624	3.0570	1185	3624	1185
M20	1664	0.714	ABS	2329	3671	5.6129	654	3671	654
M21	1489	0.353	PS	4221	2243	8.0808	278	0	0
M22	1855	0.939	ABS	1975	3351	6.1604	544	3351	544
M23	720	1.113	PS	647	1957	2.4672	793	393	159
M24	1013	0.870	ABS	1164	2876	3.0768	935	2876	935
M25	■1086	■0.727	PS	1494	1852	3.3501	553	0	0
M26	1381	0.808	ABS	1710	2553	2.4105	1059	2193	910
M27	1477	1.598	PVC	924	2658	4.3477	611	0	0
M28	2352	0.827	ABS	2845	3477	3.2053	1085	3477	1085
M29	817	0.992	PS	823	1484	2.8705	517	0	0
M30	1647	0.596	ABS	2765	2859	2.5891	1104	2363	913
M31	1904	0.591	PS	3224	2793	5.2372	533	0	0
M32	658	0.457	PS	1440	852	1.4874	573	0	0
Average	1563	1.197		2059	2688	4.940	708	1316	373
Total	50013	38.288			86030	158.079		42097	

■Indicates that back cover represents an accumulated cover weight and time because other cover pieces had to be removed prior to the removal of the back cover piece.

Our results for MRR and PRR values for 75 computers, printers, and monitors illustrate significant variations in the quantity of plastics separated versus the disassembly time. Therefore, we sought an element of product disassembly commonality to exploit in order to create simple disassembly policies with improved weight to time ratios. Since each type of equipment we studied had a large housing that frequently was composed of plastic, we evaluated removal of housing pieces—front, back, pedestal, and other—on each type of equipment. We defined two new ratios, whole cover MRR (CMRR) and back cover PRR (BCPRR), in (2) and (3), respectively. W'_c represents the plastic weight of cover c, and W''_{jb} represents the weight of plastic j in back cover piece(s) b, while D'_c and D''_b represent the disassembly time for cover c and back cover piece(s) b, respectively,

$$\mathrm{CMRR} = \frac{W'_c}{D'_c} \tag{2}$$

$$\mathrm{BCPRR} = \frac{W''_{jb}}{D''_b}. \tag{3}$$

Tables IV and V contain the CMRR for the covers of computers and printers, respectively, in our sample. Since the front cover of monitors provides an opening for the screen and requires additional disassembly for separation from the cathode ray tube, its CMRR value is often low compared to the back cover. As a result, we studied the BCPRR disassembly of the back cover, which is included in Table VI. For over 90% of the monitors in our sample, the back cover is the first cover piece disassembled. However, for less than 10% of the monitors, other cover pieces had to be removed prior to the back cover; these cases are indicated by an "■" in Table VI. For these cases, the back cover disassembly time is the accumulated back cover time.

Table VII summarizes the MRR for each policy and each equipment combination. The highest average ratio is the

TABLE VII
RECOVERY RATE FOR EACH POLICY AND EACH EQUIPMENT COMBINATION

Type of Equipment	Average Weight to Time Ratio for Cover Disassembly (g/min)	Average MRR for Basic Disassembly (g/min)	Average MRR for Extended Disassembly (g/min)
Computer	CMRR: 864	266	167
Printer	CMRR: 778	---	752
Monitor	BCPRR: 2059	---	708

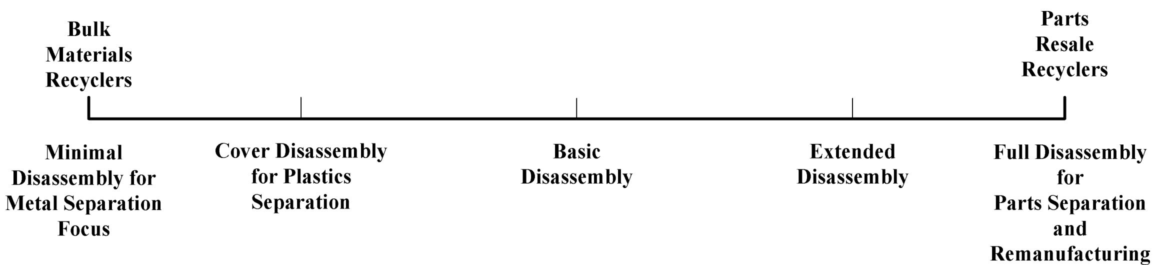

Fig. 4. Disassembly continuum.

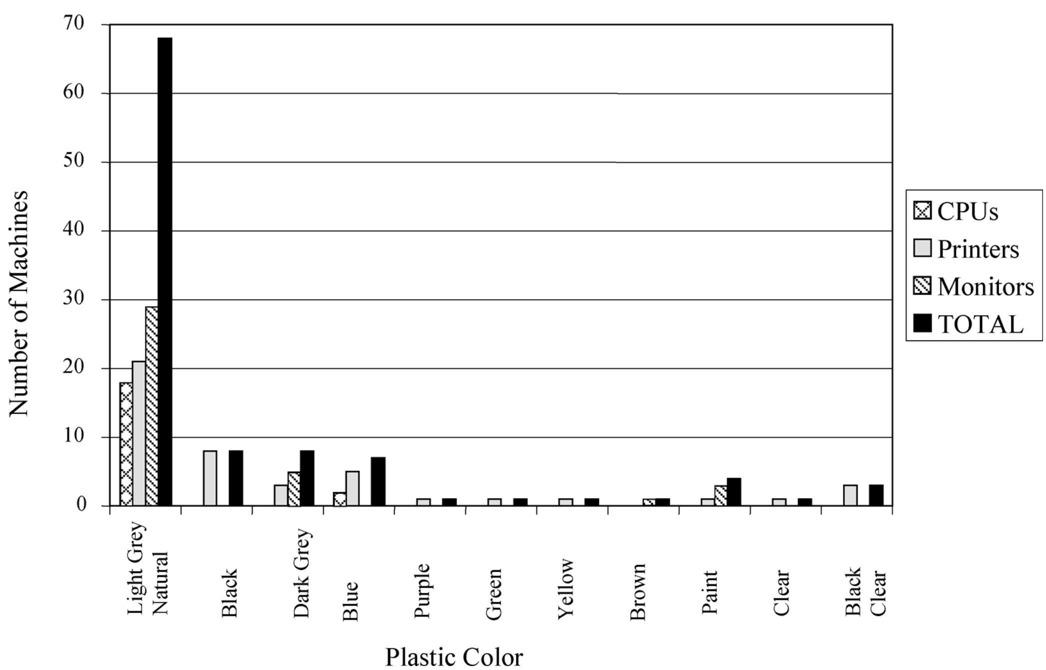

Fig. 5. Plastic color frequency.

BCPRR for monitors. We also point out that the CMRR for computer covers is more than five times higher than the computer extended MRR. On the other hand, the CMRR for printer covers is nearly the same as the printer extended MRR. Table VII is useful in comparing policies across disassembly levels as well as across product groups.

Our results indicate different disassembly policies to recover plastics from computers, printers, and monitors as illustrated for different recycling businesses in Fig. 4 and described in Table VII. For recyclers transitioning from bulk recycling to limited disassembly for plastics identification and separation, we recommend cover disassembly as summarized in Table VII as a starting point. As recycled plastic markets develop, bulk recyclers may increase the disassembly level to basic or extended disassembly in Table VII. For recyclers who are already disassembling computers, printers, and monitors for parts resale, our research indicates an additional opportunity to identify and separate high-value engineering plastics for resale.

Our study also offers insight on the current frequency of various plastic colors as illustrated in Fig. 5. Printers exhibit greater color variability than computers or monitors, owing to the need to guide user requirements to load paper and replace ink cartridges. For our study, equipment dated from 1984 to 2001 corresponded to a range of years in which manufacturers did not vary housing color as part of their marketing strategy. In a future sample of equipment from 2002 onward, we anticipate a greater frequency of color variation. From the electronics recycler's perspective, color separation may fall into two categories: light grey/natural for high-grade sale to mold new light-colored products and other colors of plastics for mixed color sale to mold new dark-colored products.

TABLE VIII
PLASTIC WEIGHT SEPARATED FOR THE TOTAL SAMPLE

Level of Disassembly	Total Plastic Weight Separated (kg)
Whole covers (computers and printers) and back covers (monitors)	89.992
Basic (computers) and Extended (printers and monitors)	138.282
Extended (computers, printers, and monitors)	139.091

VI. CONCLUSION

In conclusion, from extrapolating the time as well as the product input required to accumulate specific types of plastic, we can recommend sound strategies for plastic separation planning. The disassembly policies that we propose in Table VII are practical to implement, yet they can significantly increase plastics-to-plastics recycling. As summarized in Table VIII, bulk recycling of the 75 computers, printers, and monitors in our sample results in 139.091 kg of mixed plastics-to-energy recovery while implementation of our cover and back cover policies in Table VII with identification by Raman spectroscopy results in 89.992 kg of plastics-to-plastics recycling. Likewise, for a recycler recovering parts for resale and selling mixed plastics, our basic policy for computers and extended policy for monitors and printers in Table VII combined with identification by Raman spectroscopy results in 138.282 kg of plastics-to-plastics recycling. In this paper, we show that our policies are effective for a variety of computer, printer, or monitor models, which is typical of the random product streams that arrive at electronics recycling facilities. With larger libraries of plastics identification standards, our approach may be applied to a growing number of end-of-life electronics to increase plastics-to-plastics recycling.

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