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A Symbolic Methodology To Improve Disassembly Process Design

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Millions of end-of-life electronic components are retired annually due to the proliferation of new models and their rapid obsolescence. The recovery of resources such as plastics from these goods requires their disassembly. The time required for each disassembly and its associated cost is defined by the operator's familiarity with the product design and its complexity. Since model proliferation serves to complicate an operator's learning curve, it is worthwhile to investigate the benefits to be gained in a disassembly operator's preplanning process. Effective disassembly process design demands the application of green engineering principles, such as those developed by Anastas and Zimmerman (*Environ. Sci. Technol.* **2003**, *37*, 94A−101A), which include regard for product complexity, structural commonality, separation energy, material value, and waste prevention. This paper introduces the concept of design symbols to help the operator more efficiently survey product complexity with respect to location and number of fasteners to remove a structure that is common to all electronics: the housing. With a sample of 71 different computers, printers, and monitors, we demonstrate that appropriate symbols reduce the total disassembly planning time by 13.2 min. Such an improvement could well make efficient the separation of plastic that would otherwise be destined for waste-to-energy or landfill. The symbolic methodology presented may also improve Design for Recycling and Design for Maintenance and Support.

Introduction

Worldwide markets for billions of electronics require global product transport over a product's life cycle. As a result, disassembly for recycling often occurs in locations far from the original manufacturing. The costs associated with data collection and recycling optimization for a given product model should not exceed its net recycling revenues, and product model proliferation prohibits recycling optimization in specific terms for each of many thousand particular models. Thus, recyclers must seek process designs that broadly balance processing energy and time, product complexity, embedded entropy, and material value for variable materials in an input stream. In a recycling center, disassembly presents a significant challenge since heterogeneous electronics differ by types, brands, manufacturing date, material composition, fasteners, model design, and production condition (*2*). Disassembly processing time must be reduced to lower disassembly costs to separate materials, especially plastics.

TABLE 1. Pre-disassembly Process Steps without Proposed Disassembly Symbols

activity	objective
exploration	operator turns the product in different directions in order to locate: "back" side of the equipment types of fasteners
familiarization	operator carefully examines three sides of the product to determine: no. of pieces that conform the case type and no. of each fastener type of tools required to release fasteners sequence to disassemble external housing
tool setup	operator locates special tools and grasps the first tool

Reviews of disassembly research summarize methods to determine the disassembly level and the disassembly sequence necessary to remanufacture products optimally (*3*, *4*). Typical disassembly optimization models, which require extensive product design information, may be applicable for the remanufacturing of large quantities of the same products but are not practical for treating the separation of materials derived from many different products. Green engineering principles call for reducing the number of materials to separate and the number of fasteners (*1*, *5*). Disassembly productivity and process time place critical constraints on the economics of product refurbishment and recycling (*6*). For example, previous work has shown that assembly and disassembly time and tooling cost savings can be achieved when designers switch some conventional fasteners to snap-fit assemblies in plastic parts (*7*, *8*).

Published studies on the disassembly time for vehicles (*9*), telephones (*10*), computers (*11*), and televisions (*12*) begin their disassembly analysis with the removal of the first component. Likewise, disassembly cost models specify the cost to remove a part (*13*). Although learning curves for each product may be included in the parameters for disassembly time (*14*), they do not completely account for the activities that preclude the disassembly of thousands of different models in a typical recycling center. As introduced in ref *15*, an important gap in disassembly research is the analysis of pre-disassembly evaluation and setup for the variety of electronics disassembled and the development of reasonably fast and simple methods to reduce the time to perform pre-disassembly steps.

To decrease disassembly time and expense, common product design and process characteristics need to be identified across electronic products. The present work focuses on the electronics housing as a design characteristic common to computing, media, and kitchen electronics as well as appliances and other equipment. Stuart et al. (*16*) show that removal of the whole housing on computers and printers and removal of the back cover on monitors are prudent choices that result in average plastic recovery rates of 1.376 kg/min for plastics disassembly for a sample of 71 different products.

The disassembly operator performs each of the pre-disassembly planning steps summarized in Table 1 on every

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TABLE 2. Assembly/Disassembly Methods and Tools

assembly method	disassembly method	set of tools for disassembly
screw	unscrew	flathead screwdriver, Phillips screwdriver
pressure clip/ snap-fit assembly	release	hands
join with other fastener	unfasten	Allen wrench, nutdriver, socket with ratchet, wire cutter, shears, drill, saw, hammer, chisel, prybar, other

TABLE 3. Tool Categories and Symbols for Disassembly

Category	Symbol #: No. of original fasteners P: Direction to first disassembly position	Tools
Frequent	#⊖P	Flathead screwdriver and/or Phillips screwdriver
No tools	☛P	Hands
Other	#🛠P	Allen wrench, pliers, nutdriver, socket with ratchet, wire cutter, shears, drill, saw, hammer, chisel, prybar, other.
Special	#ⓈP	Manufacturer specific tool

product. Table 1 includes not only tool setup but also product evaluation to select tools. The analysis presented in Table 1 assumes that the "back" side of the product contains connectors and product information. Disassembly operators may study four to six sides during the familiarization stage. For present purposes, we assume here that without the disassembly symbols proposed here, disassembly operators must carefully examine four sides of computers and monitors and six sides of printers during familiarization.

In this paper, we seek to answer the question: How can the extended supply chain label design attributes for disassembly on a large variety of products reduce the exploration and familiarization activity time? The activities to familiarize the operator with the product require different types of

TABLE 4. First Disassembly Position Assuming Back of Equipment Faces Operator

scenario	arrow symbol(s)	first disassembly position
1	—	back side, facing operator (no movement)
2	↑	top
3	↓	underside
4	←	left
5	→	right
6	↓↓	front

TABLE 5. Examples for Disassembly Symbols at Level 1

Example	Level 1	Description
1	3⊖—	3 fasteners using "frequent" tools and first disassembly position of back side
2	2🛠↓	2 fasteners using "other" tools and first disassembly position of underside
3	4⊖☛←	4 fasteners using "frequent" tools, "no tools" and first disassembly position of left side
4	1Ⓢ↑	1 fastener using "special" tools and first disassembly position of top side
5	4⊖2🛠→→	4 fasteners using "frequent" tools, 2 fasteners using "other" tools and first disassembly position of front side
6	☛←	Clips using "no tools" (hands) and first disassembly position of left side

movements and times. The most common disassembly and assembly methods as well as disassembly tools used in electronics are summarized in Table 2.

Experimental Section

Our experimental study adopts a symbolic methodology that reduces pre-disassembly processing time by quickly providing disassembly initialization information. The proposed symbols provide the disassembly operator with design information about the number of fasteners and the tooling to release the fasteners. We focus on disassembly of the housing because it is a common component across products.

In our sample of 71 different electronics, the most common tools used to disassemble the housing are the flathead screwdriver, the Philips screwdriver, and/or simply hands. To provide more information to the operator, the flathead

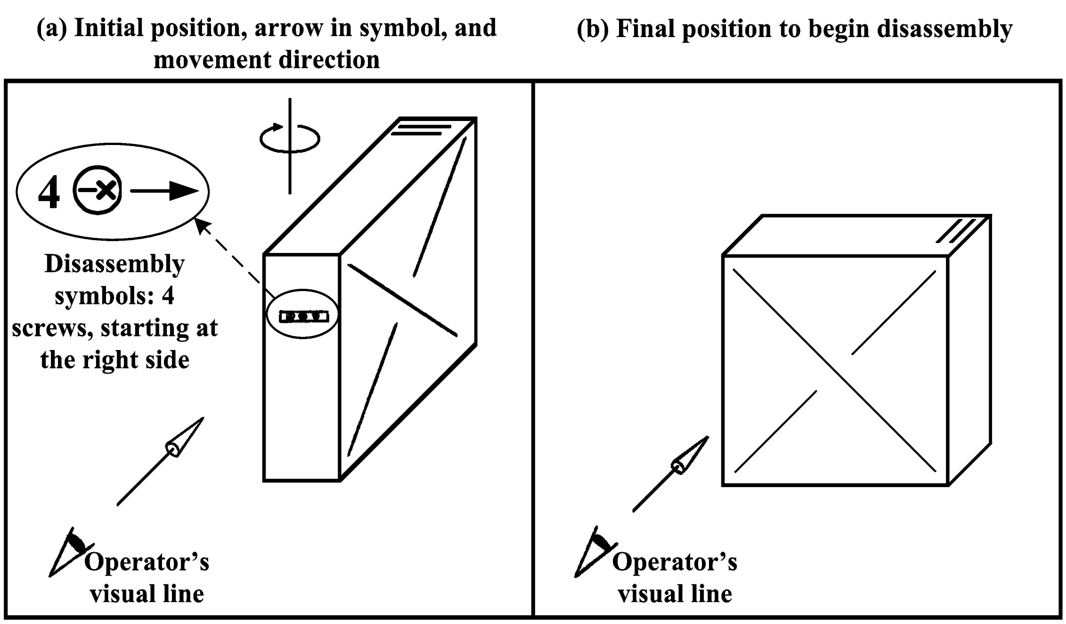
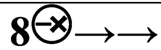
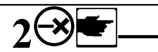
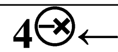
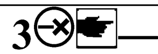
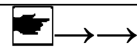
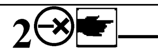
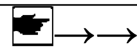
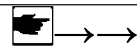
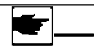
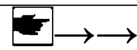
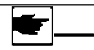
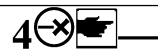
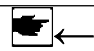
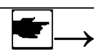


FIGURE 1. Definition of arrow in symbol for initial disassembly position.

TABLE 6. Symbolic Methodology Evaluation for Computers

				Pre-disassembly MTM time (seconds)		
No.	Computer	Year	Level 1 symbol	Without Symbols	With Symbols	Improvement
1	Epson Equity II +	1986*		20	5	76%
2	Macintosh II si	1990*		18	2	88%
3	Northgate SlimLine 333	June 1991		17	3	79%
4	Compaq Deskpro 3/33i	1992*		20	3	86%
5	Power Macintosh 7200/90	1994*		19	4	77%
6	Macintosh Perfoma 631CD	1995*		18	2	89%
7	Hewlett Packard Vectra XU	1996*		18	4	75%
8	Hewlett Packard Vectra VE	1996*		19	5	72%
9	IBM Power PC	Feb. 1996		19	2	90%
10	IBM Personal Computer 750	July 1996		18	2	91%
11	Gateway Tower 2000	Dec. 1996		20	3	87%
12	IBM Personal Computer 365	Jan. 1997		19	5	74%
13	Micron Millenia LXA	May 1997		18	2	89%
14	Gateway Tower E3100	June 1997		18	3	85%
15	Gateway Desktop E3000	Jan. 1998		19	2	88%
16	IBM Personal Computer 300 PL	Sep. 1998		18	3	82%
17	Dell OptiPlex GX1	Oct. 1998		18	4	79%

and Philips screwdriver are grouped under the "Frequent" category; "hands" as a tool is designated by the "No Tools" category. Other known tools, such as an Allen wrench, pliers, nutdriver, socket with ratchet, wire cutter, shears, drill, saw, hammer, chisel, prybar, or others are grouped under the "Other" category. The tools in the Other category are less frequently used for assembly and disassembly. Finally, when a specially designed tool is needed to disassemble a part, it should be specified by the "Special" category. For example, Kodak designed a special snap-fit and tool to discourage disassembly of their cameras by non-Kodak entities (*17*).

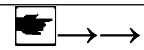
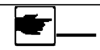
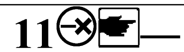
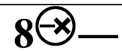
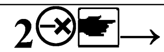
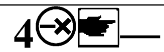
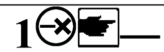
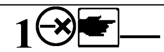
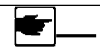
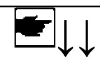
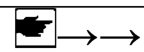
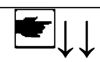
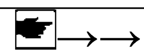
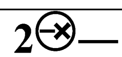
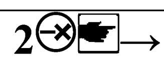
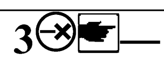
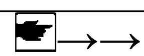
Table 3 categorizes tools by tool popularity: Frequent, No Tools, Other, and Special. Each category has a unique symbol and represents a specific set of tools.

The original number of external fasteners precedes the tooling symbol to provide a maximum number of screws for the operator to locate to remove the housing. The symbol also provides information for design-for-disassembly comparisons that seek to minimize the number of fasteners (*18*). The maximum number of fasteners indicator also helps operators when a screw is hidden by stickers, a common practice of manufacturers for warranty considerations. The No Tools symbol does not use the original number of fasteners indicator because pressing all the clips may not be required to release the housing. Following the tooling symbol is a dash or an arrow(s) to indicate where the disassembly operator should begin disassembly operations with respect to the unit sitting upright with the back facing the operator as shown in Figure 1. The set of arrows and first disassembly positions are summarized in Table 4. A dash indicates to the disassembly operator that no further movement is required.

Table 5 describes six examples of the symbolic methodology. In example 1, the symbol indicates that the equipment requires a flathead screwdriver to remove 3 screws and the operator may initiate disassembly on the back panel, the same side as the symbol. For example 2, the symbol indicates that the operator will begin disassembly on the underside with tools in the Other category. In example 3, the symbols illustrate that the operator begins disassembly on the left side with a screwdriver to remove up to four screws and clips to release the housing. The symbol for example 4 indicates that the operator will use a special tool to remove one fastener from the top of the product. The symbols in example 5 indicate that the operator will need both a screwdriver and another tool to remove 4 screws and 2 other fasteners beginning with the front side. Example 6 illustrates a symbol that represents housing removal with no tools starting on the left side panel.

The most important factors to be considered about the symbol's physical characteristics are height and distance.

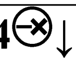
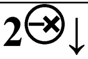
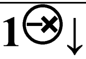
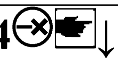
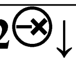
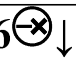
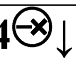
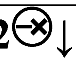
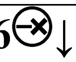
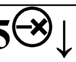
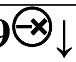
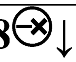
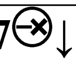
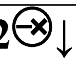
TABLE 7. Symbolic Methodology Evaluation for Printers

				Pre-disassembly MTM time (seconds)		
No.	Printer	Year	Level 1 symbol	Without Symbols	With Symbols	Improve-ment
1	IBM Proprinter II	1985		19	5	76%
2	Okidata Microline 320	1987*		17	4	78%
3	OKI Microline 395	1988*		17	3	81%
4	OKIDATA Microline 591	1988*		18	4	80%
5	DEC laser 2100	1990*		20	5	77%
6	HP LaserJet III	1990*		19	4	79%
7	HP LaserJet IIP	March 1990		18	3	86%
8	IBM PPS 2 2830	1991		20	4	77%
9	HP LaserJet IIIP	October 1992		16	2	87%
10	HP Laser Jet 4P	October 1993		20	5	76%
11	HP DeskJet 1200C	1994*		18	2	86%
12	Lexmark Color Jet 2050	1994*		18	4	77%
13	Cannon BJ-100 Bubble Jet	1995*		17	4	79%
14	HP Deskjet 600	June 1995		20	4	80%
15	Canon BJC-80 Color BubbleJet	1996*		14	3	77%
16	HP DeskJet 1600C	1996*		18	4	80%
17	Eltron International (UPS label printer)	September 1996		13	2	86%
18	HP DeskJet 870Cse	May 1997		16	2	87%
19	HP LaserJet 6L	July 1997		18	3	83%
20	HP Deskjet 890C	October 1997		20	4	80%
21	Lexmark 5700	1998*		15	2	86%
22	HP Deskjet 695 C	August 1998		21	3	84%

Sanders and McCormick detail the standards used for a reading distance of 28 in. (71 cm); a minimum symbol height of 0.20 in. (5.08 mm) is recommended (*19*). Contrasting colors are also recommended. The position suggested for the symbols on the electronic equipment is the back side of the electronic with other specifications such as voltages, compliances and restrictions. The new standard proposed in this paper introduces only four new symbols for operators to learn, which should not require a long learning process time.

To represent the variety of end-of-life electronics, we collected 71 different equipment models in our sample, as indicated in Tables 6−9. If a date sticker was not available on the housing, an "*" indicates that the year of manufacture was based on the oldest electronic chip year of manufacture. The pre-disassembly planning times in Tables 6−9 are based on work measurement studies using the Methods Time Measurement (MTM) technique (*20*). The disassembly operator begins each disassembly planning process with the product's back side facing them. Without symbols, the disassembly operator turns computers and monitors to focus their eyes on four sides to estimate the types of fasteners, tools, and upon which side to begin disassembly as described in Table 1. Since printer covers were frequently composed of more pieces than computer or monitor covers, the operator turns printers to focus eyes on six sides when they evaluate printers without symbols. The MTM pre-disassembly time

TABLE 8. Symbolic Methodology Evaluation for Monitors 1−16

				Pre-disassembly MTM time (seconds)		
No.	Monitor	Year	Level 1 symbol	Without Symbols	With Symbols	Improvement
1	IBM 5894000	October 1984	4 	10	3	71%
2	Atari	July 1985	5 	8	2	79%
3	HP	October 1985	2 	8	2	71%
4	Datapoint 1500	1985*	1 	10	3	73%
5	Macintosh SE	1986	1 	8	2	72%
6	Telex	April 1988	4 	7	2	69%
7	Infowindow	October 1989	2 	8	2	74%
8	Commodore	January 1990	6 	9	3	68%
9	Apple Color High Resolution RGB	January 1990	4 	8	2	71%
10	IBM Infowindow	May 1990	2 	10	2	78%
11	Packard Bell	November 1990	6 	10	2	78%
12	NEC	January 1991	5 	10	3	74%
13	NEC Multi Sync 5FG	November 1991	9 	11	2	80%
14	IBM 8512	July 1992	8 	10	3	71%
15	Memorex Telex	December 1992	7 	8	2	79%
16	IBM	May 1993	2 	10	2	77%

without symbols for Computer 16 (IBM personal computer (PC) 300 PL) in Table 6 is calculated to be 16 s according to eq 1.

Disassembly planning time without symbols = Eye travel around the perimeter of the back cover
+ turn computer 90 degrees so that the right side panel of the computer faces worker
+ eye travel around the perimeter of the right side panel
+ turn computer 90 degrees so that the front cover of the computer faces worker
+ eye travel around the perimeter of the front cover
+ stop to focus eyes once
+ turn computer 90 degrees so that the left side panel of the computer faces worker
+ eye travel around the perimeter of the left side panel
+ turn computer 90 degrees so that the back cover of the computer faces worker (1)

When symbols are added to the product, the familiarization step no longer requires a survey of the product to determine the types of fasteners. Instead, the operator immediately seeks the "back" side of the equipment. In the exploration step, the operator no longer studies four sides of the product to estimate the number of pieces and the number of fasteners. With the disassembly symbols, the operator focuses his/her eyes on the symbol, turns the product if necessary, focuses on the fastener, and grasps a tool if necessary to begin disassembly. The MTM pre-disassembly time with symbols for computer 16 (IBM PC 300 PL) in Table 6 is calculated to be 3 s according to eq 2.

Disassembly planning time with symbols = Eye travel around the perimeter of the back cover
+ stop to focus eyes once (2)

The computer sample in Table 6 includes models from the top three global computer manufacturers in the mid-

TABLE 9. Symbolic Methodology Evaluation for Monitors 17−32

				Pre-disassembly MTM time (seconds)		
No.	Monitor	Year	Level 1 symbol	Without Symbols	With Symbols	Improve-ment
17	IBM	November 1993	3⊗↓	9	3	72%
18	Gateway 2000 1776LE	April 1994	5⊗↓	11	3	70%
19	Memorex Telex	August 1994	5⊗↓	7	3	63%
20	Sun	November 1994	4⊗⚒↓	10	2	74%
21	NEC Multi Sync XE15	December 1994	2⊗↓	9	2	75%
22	Samsung Sync Master 17GL	January 1995	6⊗↓	10	3	73%
23	WYSE	September 1995	10⊗↓	10	3	71%
24	HP ErgoUltra UGA	December 1995	5⊗↓	8	2	77%
25	IBM InfoWindow II 3153	March 1996	4⊗↓	9	2	75%
26	CSV 1500PS	May 1996	2⊗⚒↓	11	3	73%
27	IBM 6543-301	July 1996	3⊗↓	9	2	79%
28	IBM	April 1998	4⊗↓	12	3	73%
29	Miracle 14” Mono	September 1998	5⊗⚒↓	9	3	70%
30	Elo ETC1706	November 1999	4⊗↓	10	3	70%
31	M20DAP1KO	December 1999	8⊗⚒↓	10	3	73%
32	Miracle 9” SVGA	March 2001	3⊗↓	6	2	69%

TABLE 10. Summary of Comparison of Pre-disassembly Planning with and without Symbols

		improvement per machine (s)		total pre-disassembly time (s)		reduction in total pre-disassembly time (%)		
sample size	equipment	min	max	with symbols	without symbols	min	max	total pre-disassembly time improvement (s)
17	computers	13	17	54	313	72	91	259
22	printers	11	18	75	391	76	87	316
32	monitors	4	9	78	295	63	80	217

1990s (*21*) as well as the top four manufacturers who captured 40% of the global computer market by the end of the 1990s (*22*). Tables 6−9 compare pre-disassembly process steps with and without symbols for equipment from 27 different manufacturers. Tables 6−9 contribute a sample size, diversity of equipment, and pre-disassembly time evaluation that is unique.

Results and Discussion

Table 10 summarizes the total improvement statistics for computers, printers, and monitors. The high minimum pre-disassembly time improvements per computers, printers, and monitors of 13, 11, and 4 s, respectively, demonstrate significant savings. In our sample in Tables 6−9, the improvement for pre-disassembly time varied from 63% to 91%. The improvement in pre-disassembly planning time is dramatic even for monitors, which have a more consistent housing design that frequently begins disassembly with back side facing up toward the operator. These savings promise a significant reduction in the cost to recover the engineering plastic in housings from approximately three billion end-of-life electronics each decade (*23*). To be truly effective, very broad industry acceptance and regulatory recognition of the proposed symbols are needed.

Moreover, the symbols proposed here also provide useful disassembly planning information for designers, service technicians, and disassembly operators. The generic symbols as exemplified in Table 5 contain no proprietary information, apply to any company's electronic product cover, and are easy to implement. The final form should be screened to ensure multi-cultural acceptability.

Designers could compare design alternatives using the symbols as illustrated in Tables 6−9 to quickly distinguish between significant pre-disassembly time differences. Although our tests focused on a wide variety of computers, printers, and monitors, the symbols we have devised may also be used to advantage on appliances and other equipment.

Among the major beneficiaries of our research will be the technical support centers within the global supply chain. The proposed solution improves the disassembly familiarization process, which is useful not only for materials separation but also for worldwide technical support and maintenance (*24*).

In recycling facilities, the symbols will have a significant impact, both for experienced dismantlers as they are confronted by the need to explore and familiarize themselves with thousands of different models of equipment as well as for inexperienced workers disassembling their first machines. By reducing pre-disassembly time to remove housings that are frequently plastic, symbols will reduce the costs to acquire purer streams of high-value engineering plastics (*16*).

The purpose of this paper has been to present a symbolic methodology to improve the process design for disassembly. Our process design improvement applied to electronics disassembly points to a means to more efficiently separate and recover the plastic housings. Our symbolic methodology promises significant time reduction from the assistance that our label provides to operators disassembling many different product models.

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