Development of Products Embedded Disassembly Process Based on End-of-Life Strategies

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Abstract

This paper surveys end-of-life strategies currently used in the electronics and appliances industries and identifies product characteristics that define feasible end-of-life strategies. Our survey indicates that two key characteristics serve as factors to categorize appropriate products' end-of-life path: product life and technology cycle. The categorization leads to a methodology that guides product developers to specify end-of-life strategies, to seek environmentally friendly designs, and to identify opportunities for developing new recycling technologies. The goal of disassembly differs depending on each product category, however, efficient disassembly is a key to carry out the ideal end-of-life strategies for every product category. To enhance disassemblability, we propose the concept of Product Embedded Disassembly Process. The fundamental idea is to embeda separation feature inside a product during manufacturing and activate it at disassembly.

1. Introduction

Environmental consciousness is now a fundamental focus of product design in a variety of industries. Currently, companies are reducing emissions, conserving energy consumption, and eliminating hazardous materials. In addition to environmental effects during manufacturing and use of products, companies must also assume that they will be responsible for "retiring" the product at the end of its life. Take-back schemes proposed in Europe, Japan and other regions of the world directly are addressed to the end-of-life concerns. To avoid costly product retirement, designers must identify ideal end-of-life strategies before specifying the structural attributes of the product.

Over the past two years, Stanford's graduate level Design for Manufacturability course (ME217) included several projects that addressed recyclability design of various products, such as an inkjet printer, digital copier, vacuum cleaner and washing machine. These products have different end-of-life strategies depending on characteristics such as wear-out life, technology cycle, reason for obsolescence, number of materials, cleanliness of product, and number of modules. End-of-life strategies may include a combination of reuse, remanufacturing, primary and secondary recycling, incineration and disposal options. Using a survey of current products and associated end-of-life strategies, this study seeks to identify these relevant factors, focus on key significant product characteristics, and develop a methodology that guides product developers to an optimal end-of-life strategy.

Concerning design strategies to improve eco-efficiency, not only strategies to decrease the environmental impact and also strategies to increase the utility including upgradability are being investigated [1]. The key here is strong relationship between product developers and recyclers because product developers need the information about disposing ways of retired products as well as recyclers need the information about the products. The most important point on determining design strategies is the "simultaneous" planning for retirement in the early stages of design[2]. The guideline we propose is for both product developers and recycle technology developers having the aim of sharing the same strategy for each product.

To carry out the ideal end-of-life strategies and enhance the recyclability, efficient disassembly is essential for every product category. For the sake of its importance, researchers are getting more interested in the investigations on disassembly such as disassembly process planning, disassembly evaluation and design for disassembly[3, 4, 5]. To enhance disassemblability of the products, we propose the concept of *Product Embedded Disassembly Process*. The fundamental idea is to embed a separation feature inside a product during manufacturing and activate it at disassembly. Advantages of this concept include position insensitivity and simultaneous separation of plural connections, and thus, shortening disassembly time and enhancing automation potential. Chiodo et al.[6] investigated generic self disassembly using Shape Memory Alloy actuators for consumer electronic products. Our approach is to minimize currently used disassembly process and appropriate disassembly process for each product and then embed them into the products. Disassembly of CRT which consists of two different types of glass serves as an illustrative example of *Product Embedded Disassembly Process*. The results of preliminary experiments show that fastened two pieces of glass like CRT can be separated by heating the Nichrome wire embedded into the boundary.

2. Identification of appropriate end-of-life strategies

2.1 Analysis of characteristics for end-of-life strategies

Depending on a product's characteristics, a appropriate end-of-life strategy may be different. The survey of case studies have highlighted a set of product characteristics that has implications for the product end-of-life strategy. The preliminary results of the survey classified the characteristics as related to external, material, disassembly and inverse supply chain. The proposed factor categorization evolved as survey progressed. Table 1 shows the comparison of five products with a recyclability focus under characteristics identified as the most important.[7, 8]

The following characteristics, listed under key factors, are important for identification of end-of-life strategies. We define the characteristics as follows:

- *wear-out life:* the length of time from product purchase until the product no longer meets the original functions; e.g., 7–10 years for many automobiles.
- *design cycle:* the length of time between successive generations of a product; e.g., 2–4 years for automobiles.
- *technology cycle:* the length of time before mechanisms, supporting the main functions of the product, become outdated; e.g., 10–20 years for automobiles, 2–4 years for computers.
- *replacement life:* the length of time before users feel the need to purchase product based on increased functionality.
- *functional complexity:* perception of complex interactions between parts and functions the product performs.
- *obsolescence:* the reason a product is no longer able to perform its intended function; e.g., because of failure of key components, or because it is outmoded.
- *number of materials:* number of different materials; e.g., seven for single use camera; forty for inkjet printer.
- *number of parts:* approximate number of parts in the product, indicated by in bill of materials.
- *number of modules:* number of subassemblies that are physically detachable and preserve function.
- *hazards:* hazardous or unwanted materials that can contaminate components.
- *filthiness:* amount of dirt or grime that hinders reuse and recycling.
- *size*: approximate dimension of product; e.g., large for digital copier and washing machine and medium for inkjet printer.
- *ecodesign focus:* companies initiatives in environmental design, e.g., EcoLabel.
- *recycling value drivers:* the parts or materials with high profits that drive either recycling or reuse.

Each case study addressed the current end-of-life strategy used for the product, especially attempting to understand the inverse supply chain. The intended end-of-life strategy heavily influenced the proposed redesigns. The Xerox copier and Hewlett Packard printer are products with high value, short product life, and rapidly changing technology. The proposed redesigns incorporated methods for raising percentages of reuse and remanufacture. Since the Panasonic vacuum cleaner and Toshiba washing machine are typically used for extended periods and have slower technology cycles, the standard redesign only aimed at increasing material recycling.

The case studies also assume that recycling process technologies would be similar to what we have today at the product end-of-life. None of the case studies proposed suggestions for improved recycling technology. This research indicates that depending on the assumed end-of-life strategy distinct recyclability design will result. Thus, designers must accurately identify end-of-life strategies with the help of these characteristics.

Table 1 Case Study Summary (1996-97)

Case Source	**HP** Color Inkjet Printer	**Xerox** Digital Copier	**Panasonic** Vacuum Cleaner	**Toshiba** Washing Machine	**Philips** 21” Color TV
Product Features	· high-speed · long-life	· midrange · modular	· fuzzy control · quiet	· fast cycle · low power	· Standard
Wear-out Life (years)	5	5	8	10	15
Design Cycle (years)	1	2	1	2	3
Technology Cycle (yrs)	1	2	5	5	6
Replacement Life (yrs)	2	4	7	10	14
Functional Complexity	High	High	Low	Medium	Sharpness
Obsolescence	Outdated	Outdated	Worn-out	Worn-out	Worn/outdated
# of Materials	High	Medium	Low	Low	High
# of Parts	Medium	High	Low	Low	High
# of Modules	5	7	4	4	5
Hazards	ink	toner	PVC	motor oils	picture tube
Filthiness	Medium	High	High	High	Medium
Size	Medium	Large	Medium	Large	Medium
EcoDesign Focus	95 % recycle	50% Remfg	80% recycle	80 % recycle	Energy, Hazard
Recycling Value Drivers	Service Parts	Remfg. Parts	Metals, Plastics	Metals, Plastics	Glass, Metal, Plastics

Notes:
This information has been gathered from Stanford University ME 217 reports.
Special thanks to Casper Boks for providing information for Philips Television.

2.2 Product Categorization based on Wear-out life and Technology cycle

From the case studies and discussions with recycling organizations, two characteristics surfaced as being important in predicting end-of-life paths: wear-out life and technology cycle. As seen in table 1, the products which have short technology cycle regardless of the length of wear-out life include the components available for reuse and remanufacturing. Likewise, the long technology cycle invokes a more material recycling focus for the end-of-life products.

Further developing this relationship, we plotted various products with the horizontal axis as wear-out life and vertical axis as technology cycle (Figure 1). Several other products such as containers, automobiles, computers, refrigerators and manufacturing equipment are added to this graph for comparison. The arrow in the figure shows two fundamental design strategies depending on the length of wear-out life. One is the design strategy with aim of long-term use to reduce waste products. The other one is the design strategy accelerating short-term use for high efficiency value recovery.

This plot only displays wear-out life and technology cycle, two of many key characteristics. One can predict a more suitable end-of-life strategy by including in the decision other key product characteristics such as cleanliness, ease of access to components, replacement life, functional complexity, and number of parts. While this figure omits many key characteristics, it accurately displays the need to efficiently maximize value of resources. The following section will discuss in more detail how product designers and recycling technology developers can apply this categorization.

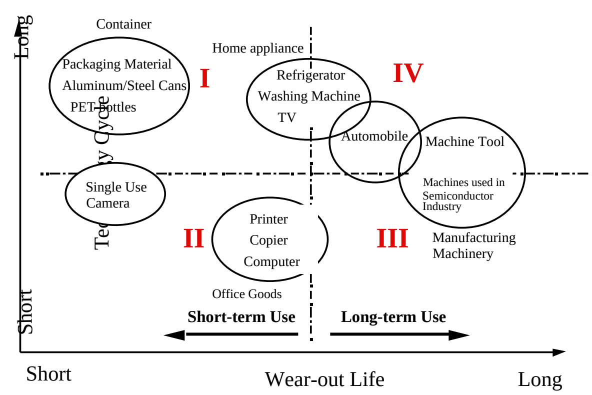


Fig. 1 End-of-life strategy plot

Table 2 Guidelines for Product Designers and Recycling Technology Developers

Product Category	End-of-life Scenario	Product Designers	Recycling Technology Developers
Type I	material recovery	ease separation of components for recycling high quality material	develop separation technologies accounting for different physical properties between materials that can not be sorted
Type II	remanufacturing	enhance reusability by using common parts and modular components in product family	develop efficient cleaning and inspection technologies to reduce remanufacturing cost
Type III	lengthen product life by upgrading	extend product life by modular design of key devices which define value of product	develop non-destructive techniques for removal of key components
Type IV	lengthen product life by maintenance	enhance disassemblability for facilitating maintenance	develop diagnostic technologies for maintenance

2.3 Application to recyclability design and recycling technology development

This categorization of products, in Figure 1, can shed light on basic guidelines for recycling technology developers and product designers. Many of the case studies discussed in previous section informally followed these guidelines, but addressed product designers. Table 2 depicts guidelines for improving recycling process technology development as well.

Type I products are characterized by short wear-out life and long technology cycle for recyclability design, designers can ease separation of components to increase material recycling. Likewise, recycling technology developers are able to alter separation technologies to account for novel products. The short wear-out life and technology cycle of Type II products encourages designers to enhance the recyclability of the product by using modular components and common parts across product families. The development of more efficient cleaning and inspection technologies reduces the remanufacturing costs for products of Type II. The products with long wear-out life and short technology cycle should have modularity to enhance upgradability as the focus in the design stages. Non-destructive disassembly techniques may be an ideal area of research for recycling technology developers of products with categorization, Type III. For Type IV products, with their long wear-out life and long technology cycle, designers have opportunities to lengthen the product life by facilitating maintenance. Recycling technology developers can focus efforts on non-destructive techniques and diagnostic technologies for easing maintenance.

3. Product embedded disassembly process

The goal of disassembly differs depending on each product category such as removing hard parts and hazardous materials, retrieving reusable parts and keeping quality of retrieved materials. However, efficient disassembly is a key to carry out the ideal end-of-life strategies for every product category. The fundamental idea of *Product Embedded Disassembly Process* we propose is to embed a separation feature inside a product during manufacturing and activate it at disassembly.

3.1 Advantages

Disassembly of products is very difficult due to variety of the products. For instance, the cutting position for disassembly and the position of screws are different depending on the each model even if they are the same kind of products. Recyclers must identify these positions for each different model.

We focus on identifying the essential part of currently used disassembly process and minimizing the mechanism for disassembly and then embedding them into the products. The advantage of this approach includes position insensitivity, and thus, shortening disassembly time and enhancing automation potential. Further, the same effect for disassembly can be obtained without special expensive equipments.

3.2 Case Study: Disassembly of CRT

Disassembly of CRT which consists of two different types of glass serves as an illustrative example of *Product Embedded Disassembly Process*. CRT consists of a panel made of high quality glass and a funnel including a lot of lead. At the retirement stage of TV sets and monitors, CRTs are removed and separated into two types of glasses. Although several methodologies to separate these glasses have been developed, it is still difficult to set up CRTs on disassembly equipment accurately and quickly due to variety of the products.

3.2.1 Methodology One of conventional methodologies to disassemble CRT is thermal stress cleaving method. Four Nichrome wires set along the boundary between a panel and a funnel as the line heat devices are heated. As the result, thermal stress induced by local temperature change exceeds the allowable level. In this case, setting Nichrome wires takes long time because the positions to set wires are different from each model depending on the screen size. If these wires were embedded along the boundary during manufacturing as shown in Figure 2, this operation would be much easier.

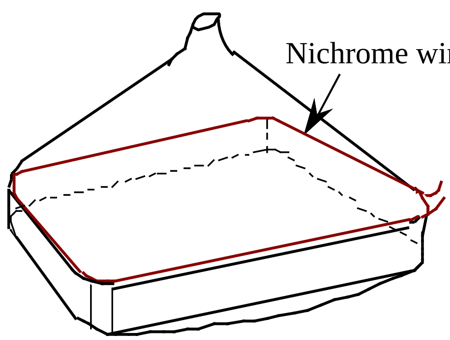
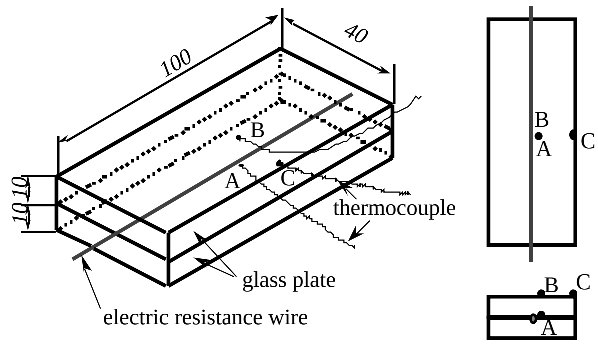
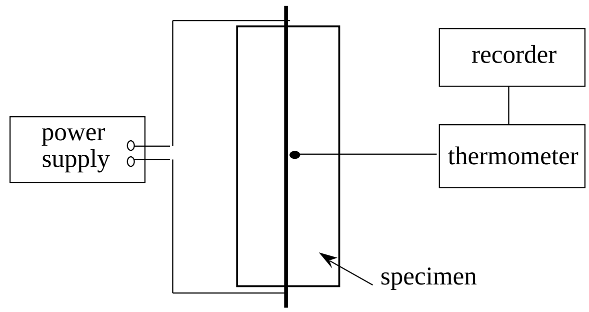


Fig. 2 An example of CRT Disassembly

3.2.2 Preliminary Experiment The following preliminary experiment here has been carried out in order to certificate the phenomenon when the line heat sources are embedded into glasses. Saimoto et al.[9] have analyzed transient thermal stress intensity factor of an edge crack and have explained the mechanism of thermal stress cleaving through the theory of linear fracture mechanics. The specimen shown in Figure 3(a) is made by heating, softening and combining two pieces of soda glass and embedding a Nichrome wire and the thermocouples located at A on the boundary. The thermocouples located at B and C(Figure 3(b)) on the surface are attached at measurement. Figure 3(c) shows the specimen subjected to the transient thermal stress induced by line heat source. To heat the electric resistance wire, the direct current of 10A is supplied. The resistance of the wire is 1.2 ohm, and the heat capacity of 120W is supplied to the specimen through the whole wire.



(a) Specimen geometry (b) Location of thermocouples



(c) Specimen subjected to the transient thermal stress induced by line heat source

Fig. 3 Experimental Setup

3.2.3 Results and Discussions Figure 4 shows the temperature change observed at the location of A, B and C. Thermal stress induced by local temperature change cleaved the specimen along the line heat source in about 36 seconds. To shorten the disassembly time, bigger current should be supplied so that gradient of temperature change becomes bigger.

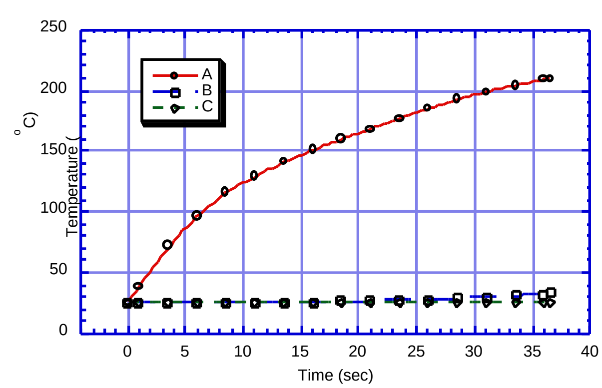


Fig. 4 Temperature change observed at the location of A, B and C

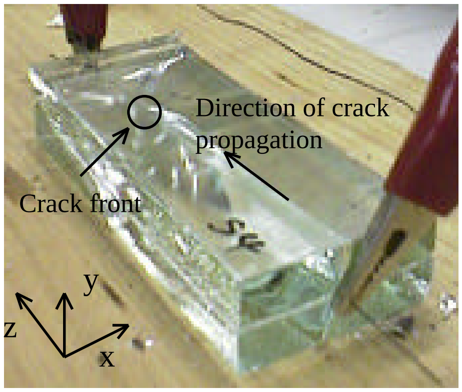


Fig. 5 Crack propagation along line heat source

Figure 5 shows the propagation of the crack generated at the edge of the glass. The crack surface is vertical to the x axis in the figure and the crack front is propagating to z direction. Currently, we are checking the effect of glass geometry on the direction of the crack surface.

4. Conclusions and future work

The product characteristics presented in the case studies can be used to categorize the products and identify their optimal end-of-life strategies. We propose guidelines based on categorization of the products by wear-out life and technology cycle. By proposing an end-of-life strategy, designers and recyclers are able to seek environmentally friendly designs, and to specify opportunities for developing new recycling technologies. The goal of disassembly differs depending on each product category, however, efficient disassembly is a key to carry out the ideal end-of-life strategies for every product category. We proposed the concept of *Product Embedded Disassembly Process*. This idea solves the problem that variety of products make disassembly difficult, because the products embedded disassembly process have functions of self-disassembly. We are investigating the case studies of products embedded disassembly process based on end-of-life strategies.

Acknowledgments

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