Incorporating End-of-Life Strategy in Product Definition

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Abstract

This paper presents the critical importance of integrating end-of-life strategies in the early states of design, i.e., product definition. We begin with an overview of research and practice on Design for Environment (DFE) in the United States. DFE has been receiving increasing attention in U.S. academia and industry, but the level of implementation remains low compared to Europe or Japan. The survey starts with a broad perspective on Industrial Ecology and proceeds to recyclability. The paper concludes with our recent research on incorporating end-of-life strategies into the product definition..

1. Introduction

Over the past decade, Design for Environment (DFE) has attracted steadily increasing attention in the US. The copier manufacturers have aggressively integrated eco-friendliness as part of their design requirements. The single-use camera is another example of a successful product with a high level of recycling. However, the US still lags behind Europe and Japan in addressing environmental issues in product design. While energy efficiency has improved dramatically in the past decade, large appliances continue to pose serious challenges in minimizing solid waste. The automotive industry has enjoyed high levels of component reuse and material recycling in the past, but the recent customer preference for large "gas guzzling" sport utility vehicles result in not only energy inefficiency, but again, solid waste challenges. Recyclability is particularly an acute concern for electronics and electromechanical products due to their short technology cycle. The author believes that the U.S. still has a long way to go in catching up with the Europeans and the Japanese, particularly in systematically integrating environmental issues at the early stages of product development.

This paper describes the current state of DFE research and practice in the United States. Whereas it is by no means an exhaustive survey and may not include every group pursuing DFE, the author tried to cover a broad range of activities publicized in venues such as IEEE and ASME. The paper starts with a survey of activities with broad perspectives such as Industrial Ecology and later focuses on the author's area of expertise, design for recyclability. A section on advanced planning for end of life (EOL) strategies illustrates our group's recent research efforts. Figure 1 indicates the nature of DFE research and practice in the U.S., categorized by different viewpoints of product development.

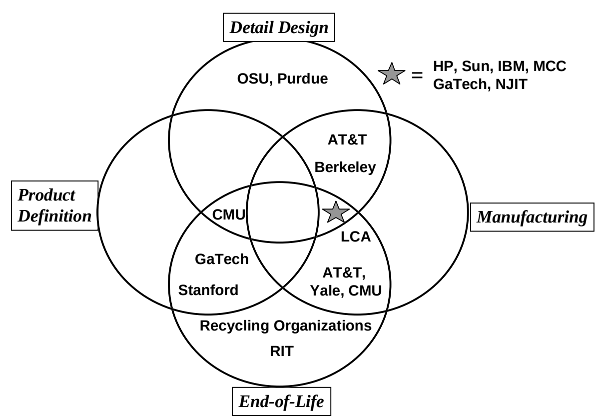

Figure 1: DFE Activities in the United States

2. Design for Environment: Research and Practice in the United States

2.1 Industrial Ecology

Industrial Ecology (IE) is a broad activity that links industry activities and environment towards sustainable development. From the designers' viewpoint, IE examines the products' life-cycle interaction with the environment. Graedel and

Allenby (1995) in their book "Industrial Ecology," state "the systems oriented vision accepts the premise that industrial design and manufacturing processes are not performed in isolation from their surroundings, but rather influenced by them, in turn, have influence on them." A significant aspect of IE is to link industrial activities to environmental policy. The American Electronics Association (AEA) provides representation in international policy decisions (AEA Technology, 1997). MIT is also conducting environmental policy research with specific emphasis on ISO 14000 (Norberg-Bohm, 1998). Allenby (1999) criticized current policy, citing "policy is ineffectual, even harmful, unless it hears a reasonable resemblance to the underlying phenomena it is intended to address."

Whereas there are many researchers tackling **Life Cycle Analysis (LCA)**, they are struggling due to LCA's need for standard metrics and vast amounts of data. A group at the University of California Berkeley claims that "defining resource consumption as exergy removal provides a basis for developing a 'thermodynamic interpretation' of ecosystem evolution" (Creyts and Carey, 1997). A group at Princeton is focusing on material life-cycle, looking at the complex flows of materials through the entire ecosphere (Socolow, 1998). A group at Carnegie Mellon University (CMU) has proposed an economic input-output LCA (EIO-LCA, Hendrickson, 1998). Resource inputs include electricity consumption, fuels use, ores consumption, fertilizer use, and water consumption. Environmental outputs include toxic emissions and hazardous waste, global warming potential, and conventional pollutant emissions. Michigan Technological University (Olson et al., 1998) is developing an analysis and decision making tool to permit the use of SETAC LCA as a method to optimize manufacturing processes and products.

A relatively new IE activity is addressing environmental impact along with supply chain management. AT&T is developing relationships with suppliers to manage products at end-of-life in addition to providing normal services during product "useful" life (Blazek, et al., 1998). Other electronics companies such as Sun, Hewlett Packard (HP), and Motorola have similar activities related to what HP calls "Product Stewardship." Purdue University is conducting ongoing research that seeks to develop supply chain models that include recovery of returned products and remanufacturing (Uzsoy, 1998). In the long run, they seek to provide companies with insight into the viability of product recovery and remanufacturing.

2.2 Design for Environment

Within the field of IE, Design for the Environment (DFE) has been the area receiving the most emphasis by engineers. Graedel and Allenby (1995) cite design as the stage that has the strongest influence on environmental impact. DFE covers a wide range of product development activities such as choosing materials, examining the product usage phase to reduce environmental impact, designing for energy efficiency, minimizing industrial residues during manufacturing, designing for recycling, etc.

Many groups are adapting LCA so that it can contribute to design and manufacturing decisions. CMU (Espinosa et al., 1997) seeks to adapt product focused life-cycle assessment to aid in design decisions. Princeton and New Jersey Institute of Technology (NJIT) proposed an "Abridged LCA," a shortened LCA (Thomas et al., 1998). These studies include a preliminary LCA inventory with material, energy and environmental balances, and an assessment of the life-cycle energy use.

A major design decision that impacts the environment is *process selection*. A group at the University of California Berkeley has an extensive research program on this subject, e.g., printed circuit board processes, machining operations (Siddhaye et al. 1998; Sheng et al., 1998). Michigan State University focuses on broader process issues such as product design and scheduling process (Melnyk, 1998). A group at University of Illinois addresses process optimization using pollution models through decision analysis approach (Thurston et al., 1998).

Within DFE, *recyclability* has received the most attention by engineers in the USA. Wide acceptance of design for assembly (DFA) methods provide a strong basis for including disassembly and recycling issues along with manufacturability evaluation. A product effectively designed for recyclability leads to extended use of resources and net reduction in energy used to manufacture the product. The author also believes that recyclability is an issue to which design engineers can contribute environmental compatibility most readily as long as they have an appropriate end-of-life strategy. The remainder of this paper focuses on recyclability as well as our own work on advanced planning for end-of-life strategies.

2.3 Design for Recyclability

Since the late 1980's, designing products for *ease of disassembly* has been an active area of research primarily due to the popularity of design for assembly methodology amongst various industries.

Boothroyd and Dewhurst, Inc., a pioneer in DFA methodology, has been integrating disassembly analysis tools in their software (ASME, 1998).

Navin-Chandra and others (1993) at CMU have applied Artificial Intelligence techniques to generate an optimal disassembly sequence for a given design, and to optimize the design for disassembly. NJIT has also developed methods for disassembly planning using Petri Nets (Zussman, 1998). A group at Georgia Institute of Technology (Emblemsvåg, 1997) has been pursuing disassembly modeling using activity based costing approaches.

Whereas disassembly is an important aspect of recyclability, designers must also consider the "fate" of disassembled subassemblies, components, or materials. One needs to minimize the level of disassembly necessary at the product's *end-of-life* and yet extract the most value out of the recovered components or material. A group at The Ohio State University (Ishii et al, 1994) acknowledged this fact and developed a computer tool "LASeR," that assists in identifying the best levels of disassembly and recovery of subassemblies, components, or materials for reuse or recycle. Another group at Ohio State is continuing this effort with emphasis on material selection (Stuart, 1998).

U.S. industries have been active in seeking higher levels of recyclability in their products. Anticipating some form of "product take back regulations," U.S. companies are extending their responsibility to product end-of-life. IBM has a demanufacturing facility in Endicott, NY, that integrates design activities with demanufacturing leanings (Grenchus, et al., 1998). MCC has similar activities (Murphy et al., 1998). HP/Micrometallics, a partnership between an OEM and a recycling company, reclaims useful materials from end-of-life products (St Denis et al., 1998).

Design for *Remanufacturing* is another focus of recyclability that seeks to reuse a significant portion of their value into similar products. Georgia Tech's group has studied key issues in remanufacturability and modularity (Amezquita et al., 1995). Further, Bras (1998) developed a tool whose objective is to link qualitative measures of remanufacturability to engineering information embodied in CAD systems. Products that lend themselves well to remanufacture are those with a defined "return path" to the manufacturer. Xerox has been a leader in extensive remanufacturing of their copiers. They concurrently design manufacturing and remanufacturing facilities for new models and, in steady state, most of their products are "newly remanufactured" copiers.

3. Advanced Planning for End-of-Life

3.1 The Importance of End-of-Life Strategies

Our recent research has revealed that designers must clearly define the end-of-life strategy before considering recyclability or remanufacturability. Design for recyclability requires knowledge about how recyclers will treat various subassemblies, components, and materials to take advantage of their residual value. Based on product characteristics such as product life, take-back regulations, and material value, appropriate end-of-life strategies can differ among various products. End-of-life strategies are particularly important for electronics products whose product lives depend on technological obsolescence rather than wear-out. Work on end-of-life strategies is relatively new in the United States.

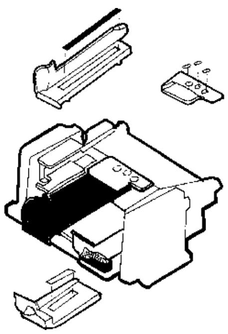

Fig. 2 HP Inkjet Printer Paper Tray

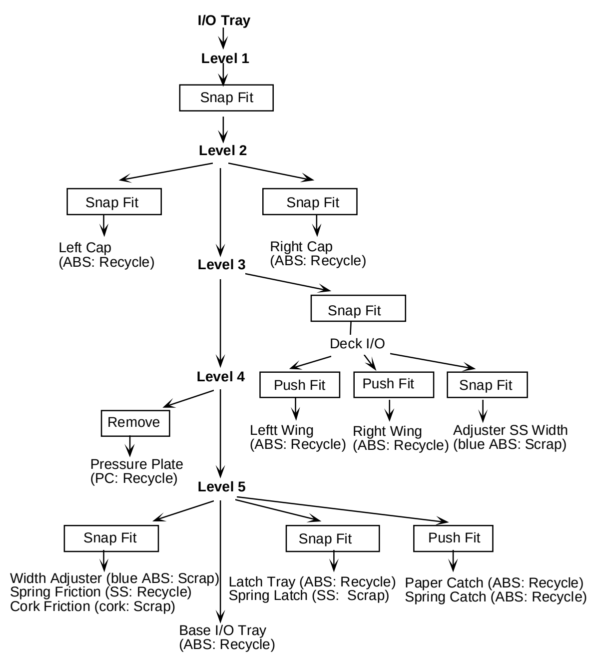

Figure 3: Reverse Fishbone Diagram

Georgia Tech (Pope et al., 1998) analyzed and evaluated three generations of audio video home electronic products: the VHS VCR, Laser Disc Player, and Digital Video/Versatile Disc Player. They investigated potential environmental improvements to the DVD player through design strategies for upgradability and end-of-life impact. evaluated three generations of audio video home electronic products: the VHS VCR, Laser Disc Player, and Digital Video/Versatile Disc Player. They investigated potential environmental improvements to the DVD player through design strategies for upgradability and end-of-life impact.

Our group at Stanford became acutely aware of the importance of end-of-life strategies when HP provided us an opportunity to improve the recyclability of their inkjet printers (Ishii et al., 1996; Lee et al., 1997). As mentioned in the previous section, HP/Micrometallics has a recycling center at which they retrieve a significant portion of subassemblies and parts to be used by HP's service group. Our initial effort was to envision optimal disassembly steps in "clumps" that could be reused or recycled for highest value. The graph shown in figure 3 specifies the disassembly and recovery process for inkjet printer tray (figure 2). The graph obtained the name "reverse fishbone diagram," in relation to the assembly fishbone diagram used to enhance assemblability (Ishii et al., 1996). However, our team quickly realized that considering one particular model of the printer was inadequate. This recycling facility must accommodate not only one type of their inkjet printer, but multiple models in their product line over several generations. Hence, designing for "ease of recycling" must address a variety of models as well as evolution of the design over time. Stanford now encourages its students to construct a reverse fishbone diagram that applies to product families and generations, i.e., envision a recycling facility that must accommodate variety (Lee et al., 1997).

3.2 End of Life (EOL) Strategy Case Studies

In addition to the HP inkjet printer example, Stanford's ME217 Design for Manufacturability course provided us with case studies to investigate what product characteristics affect end-of-life strategies. Table 1 shows the comparison of five projects with a recyclability focus under characteristics identified as the most important. This research continues today with more input from engineers who take the course over the Stanford Instructional TV Network. One notable finding from this study (Rose, 1998a) is that "product life" is a key factor influencing end-of-life strategy. Yet, "product life" is not simple to define and depends heavily on why people repurchase new products.

Table 1. Recyclability Map Case Studies (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	High
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

3.3 End of Life Design Advisor (ELDA)

Stanford's current work focuses on a web-based tool that guides product designers to the most appropriate EOL strategy and thus aids in design for recyclability as well as specification of the reverse supply chain and recycling facilities.

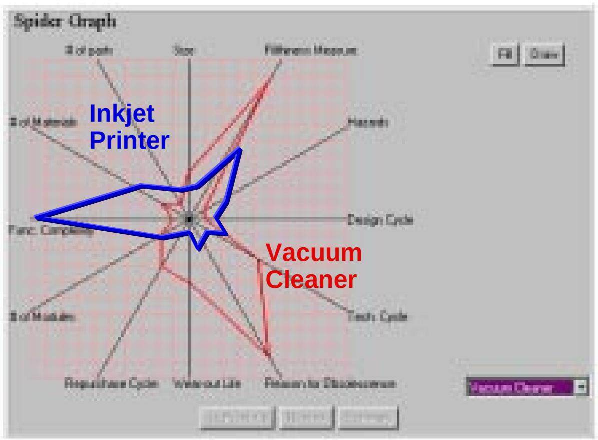

Figure 4: Spider Chart of EOL Factors

The EOL strategies should also help them in making a longer term plan for a product platform that enhances upgradability and leveraging/reuse of designs across multiple generations and accelerate the product development cycle. The current implementation of the tool, EOL Design Advisor (ELDA; Rose, 1998b) asks the user to respond to questions regarding the product characteristics mentioned in section 3.2, plots the results in a "spider chart" as shown in figure 4, and allows them to compare the end-of-life characteristics with other products, including inkjet printers and vacuum cleaners. Our current effort seeks to apply multivariate decision analysis and case-based reasoning to link the chart to suggested EOL strategies for the product and its components.

4. Conclusions and Future Perspectives

This paper gave an overview of current DFE research and practice in the United States, with emphasis on design for recyclability and advanced planning for end-of-life strategies that cover not only one product model but across product families and over multiple generations. The author firmly believes product development teams must address in the early stages of design not only product design but also forward and reverse supply chain as well as recycling facilities. Stanford's team is developing ELDA not only for educational purposes, but as a template for each company to adapt the methodology to aid in end-of-life planning and DFE.

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