DETERMINING END-OF-LIFE STRATEGIES AS A PART OF PRODUCT DEFINITION

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Abstract - This paper presents an approach for determining feasible end-of-life strategies from significant product characteristics. Previous surveys of a broad range of products led to a classification scheme that helps designers incorporate suitable end-of-life strategies in their product definition. The development of the end-of-life categorization results from statistical analysis applied to twelve characteristics across twenty products from the electronics and appliances industries. Further, the paper describes in detail the development of a web-based application, End-of-Life Design Advisor (ELDA). ELDA guides designers, recycling technology developers and policy makers to specify end-of-life strategies and improve decisions related to end-of-life strategies.

I. INTRODUCTION

Graedel and Allenby [1] cite design as the stage that has the strongest influence on environmental impact. Design for Environment should occur early in a product's design phase to ensure that the environmental consequences of a product's life cycle are taken into account before any manufacturing decisions are committed. Design for Environment, an integral component of the "design for X" paradigm, covers a wide range of activities including material extraction, manufacturing, transportation and usage phases. Increased environmental awareness and legislative developments implore manufacturers to address the product end-of-life phase. The European Union's proposed legislation established targets for collection and recycling for various consumer products [2]. The draft legislation for requiring take back and recycling of products addresses current societal concerns about resource, landfill or incineration and the impact of hazardous substances at the end-of-life phase. Producers must determine on a product level if an intended end-of-life system is technically and economically feasible [3]. Current product designs, recycling technologies and legislative decisions heavily influence the feasible end-of-life strategies.

II. PRODUCT DEFINITION AND DESIGN FOR RECYCLABILITY

Product definition encompasses the upfront product development activities that consider user needs' understanding, competitive analysis, product positioning, strategic alignment and charter consistency, technical risk assessment, priority decision criteria list, regulation compliance, product channel issues, project endorsement and other organizational support issues [4]. Wilson cites that the most common causes of project failure is the lack of full understanding of these issues shared by the product development team and other stake holders. Frequently, failing to identify of world wide regulatory issues relevant to project cause shortfalls in product marketing. During the product definition phase of product development, companies decide strategic issues associated with supply chain, life cycle support and manufacturing management. Many companies do not address product end-of-life issues until most of the design parameters are fixed.

Recent research activity in recyclability design includes methodologies that consider the following end-of-life scenarios: reuse, remanufacturing, and recycling. Recent research reveals that designers must accurately define the end-of-life strategy before considering recyclability or remanufacturability or designs will be optimized incorrectly. Design for recyclability requires knowledge, rather than assumptions, about how recyclers will treat various subassemblies, components, and materials to recover the residual value. Current researchers rely on designers to input end-of-life strategy information, ignore valuable knowledge from recyclers, recycling technology developers and other inverse supply chain members and focus excessively on disassembly.

Researchers are developing tools to help product designers create more environmentally friendly products. However, the research does not address the need to educate designers about end-of-life options or the impact of their decisions. Harper and Rosen [5] are developing a Computer Aided Design tool to link qualitative measures of remanufacturability to engineering information embodied in CAD systems. While their objective is to seamlessly integrate environmental concerns, they depend on the experience and knowledge of designers for critical input values relating to end of life strategies. For example, the designer must input the post-life intent whether they anticipate the product will be refurbished, recycled or landfilled. Similarly, Coulter et al [6]state that 'designers must use his/her experience and knowledge to evaluate the appropriateness of the material changes indicated.'

In addition to depending on the designers to provide end-of-life information, many tools ignore the valuable knowledge from recyclers, recycling technology developers and other inverse supply chain members. This has inhibited recyclability design improvements. Some companies have enhanced their products through improved communication with external and internal demanufacturing programs. IBM has a demanufacturing facility in Endicott, NY and with the Engineering Center for Environmentally Conscious Products integrate design activities with demanufacturing learnings [7]. The Hewlett Packard and Micro Metallics partnership between an original equipment manufacturer and a recycling company recovers service parts and recycles useful materials from end-of-life products [8]. Xerox concurrently design manufacturing and remanufacturing facilities for new models and, in steady state, most of their products are "newly remanufactured" copiers. Kodak has developed an extensive remanufacturing organization for the "single use cameras," remanufacturing 60% of the product world wide. However, given the number of manufacturing companies in the United States, this practice is not yet wide-spread as necessary.

Even when considering the end-of-life scenarios, research focuses heavily on disassembly. 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. Boothroyd and Dewhurst, Inc., a pioneer in DFA methodology, has been integrating disassembly analysis tools in their software[9]. Navin-Chandra [10] generate an optimal disassembly sequence for a given design, and to improve the design to enhance disassemblability. New Jersey Institute of Technology has also developed methods for disassembly planning using Petri Nets [11].

This paper describes n detail the development and application of a web-based tool, End-of-Life Design Advisor (ELDA). Unlike other tools, ELDA guides product designers, recycling technology developers and policy makers to coordinate to specify end-of-life strategies as a part of product definition and improve decisions influenced by end-of-life strategies.

III. Overview of End-of-Life Design Advisor

The End-of-Life Design Advisor (ELDA) is a web-based tool for product end-of-life strategy assessment. Case studies have shown that there is a preferred end-of-life strategy that depends on product characteristics [12, 13]. The goals of the End-of-Life Design Advisor are to increase designers' environmental awareness, to determine end-of-life strategies, and to assist in decision making.

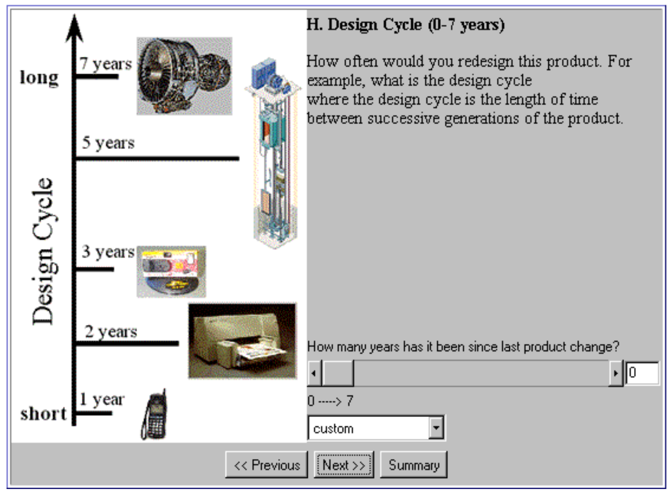


Fig. 1. Example of Product Characteristics Input Screen

ELDA asks designers to evaluate product characteristics and gives examples to guide the designer. The interactive nature of ELDA, along with direct focus on designer and specific products, provides an excellent medium to educate designers on environmental implications of their decisions. New improvements in supply chain management utilize the internet to synchronize efforts globally. Similarly, ELDA facilitates communication between globally separated design teams regarding environmental concerns. ELDA coordinates training and education of product designers while simultaneously aiding product definition.

ELDA currently displays the output in a spider graph with each axis representing a different characteristic. The spider graph displays a comparison between the inputted product characteristics and other products' characteristics. On the output screen, the user can compare and contrast the product with other products.

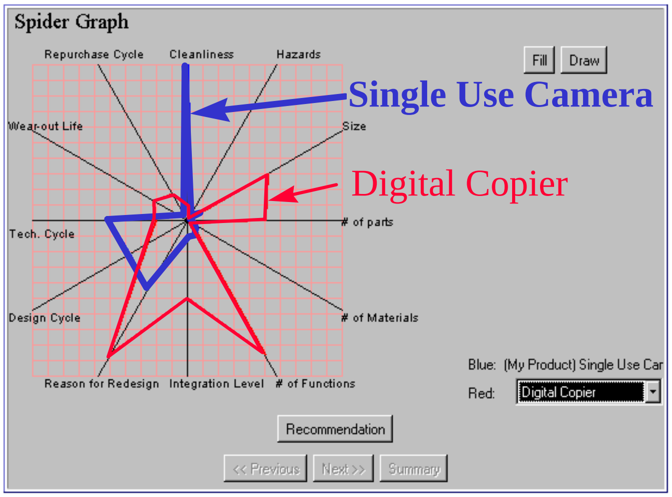


Fig. 2. Spider Graph for Single Use Camera and Digital Copier

Stanford's graduate course on Design for Manufacturability (ME217) used the first version ELDA during the 1998 course. This trial involved case studies on aircraft engines, portable phones, lead battery, bubblejet printer, line-matrix printer, portable projector, car, computer, automobile and server. The original product characteristics include size, number of parts, number of materials, number of modules, cleanliness level, hazards, wear out life, design cycle, technology cycle, repurchase cycle, reason for obsolescence and functional complexity.

Table 1. Summary of ME217 Project Teams from ELDA

Projects	Number of Parts	Technology Cycle	Functional Complexity	Cleanliness Level	Number of Materials	Wear-out Life	Repurchase Cycle	Hazards	Design Cycle	Size	Reason for Obsolescence
Cell Structure	high	med	high	low	low	med	med	high	low	med	worn-out
Computer	med	low	high	med	high	med	low	low	low	med	out-dated
Automobile	high	high	high	high	high	med	low	high	med	high	worn-out
Digital Copier	med	low	high	med	low	low	low	low	low	med	out-dated
Port. Projector	low	low	high	low	high	med	low	high	low	med	out-dated
Klystrons	high	high	med	high	high	high	high	low	high	high	out-dated
Shipping Container	high	high	low	med	low	low	med	low	high	med	worn-out
Elevator	high	high	med	high	low	high	high	low	med	high	worn-out
Aircraft Engine	high	med	high	med	high	high	med	high	high	high	out-dated
Inkjet Printer	med	low	med	low	low	low	low	low	low	med	out-dated
Single Use Camera	low	med	low	low	low	low	low	low	med	low	worn-out
TV	med	med	med	med	low	high	high	low	low	med	out-dated
Lead Battery	low	high	low	low	low	high	high	high	high	med	out-dated
BubbleJet Printer	med	low	med	low	low	med	low	low	low	med	out-dated
Line Matrix Printer	low	med	med	med	low	low	med	low	low	med	out-dated
Telephone	low	low	med	med	low	low	low	low	low	low	out-dated
Server	med	low	low	med	high	med	low	high	low	med	out-dated
Vacuum Cleaner	low	med	low	high	low	med	med	low	low	low	worn-out
Washing Machine	low	med	med	high	low	med	med	low	low	med	worn-out

Table 1 summarizes the responses from the ME217 project teams. While ELDA case studies only represent complete products, designers can apply ELDA to subassembly recyclability design as well.

The first phase of data collection through ELDA revealed that some characteristics required exceedingly specific information (number of parts), information not available to designers (reason for obsolescence) and additional interpretation (functional complexity). To address the confusion about functional complexity, we added two characteristics: number of functions and level of integration.

IV. Determination of Product End-of-Life Strategies

Our current research seeks deterministic models for the end-of-life strategies based on the product characteristics. The method seeks to overcome challenges in determining the product characteristics posed by a small sample size in comparison to the number of characteristics. We made few assumptions to proceed with the methodology, Classification and Regression Trees (CART). While the characteristics describe the actual product characteristics, the end-of-life strategy used in the methodology is the potential end-of-life strategy. For example, most portable phones are not currently shredded to reclaim material although the potential end-of-life strategy is to recycle the product by shredding.

In addition to the variety of methods to consider end-of-life strategies, there is also substantial disagreement in the definition of end-of-life scenarios or strategies [14]. Based on work in [15], [16], [17], [18] and [19], we outline the following end-of-life strategies.

1 – Reuse: Reuse is the second hand trading of product for use as originally designed.

2 – Service: Servicing the product is another way of extending the life of a durable product or component parts by repairing or rebuilding the product using service parts at the location where the product is being used.

3 – Remanufacture: Remanufacturing is a process in which reasonably large quantities of similar products are brought into a central facility and disassembled. Parts from a specific product are not kept with that product but instead they are collected by part type, cleaned, inspected for possible repair and reuse. Remanufactured products are then reassembled on an assembly line using those recovered parts and new parts where necessary.

4 – Recycle (separate first): Separation of material fractions increases the value of the materials recycled by removing material contaminants, hazardous materials, or high value components.

5 – Recycle (shred first): Shredding reduces the size of the products to approximately fist-size. The shredded material is

separated using methods based on magnetic, density or other properties of the materials.
6 – Disposal

Using product information gathered through case studies and the optimal end-of-life strategy, we implement a methodology commonly found marketing and medical data analysis. The CART, a statistical method, maps the characteristics to decision trees that categorize products into different end-of-life strategies. Classification analysis produces an accurate classifier or uncovers predictive structure of data to predict medical conditions, consumer behaviors and other complex patterns [20]. In most cases, researchers use CART to analyze sample sizes in the thousands. Our research examined approximately sixty runs of different combinations of the twelve characteristics. Sixteen combinations of the characteristics showed decreasing cross validated errors and small residual errors. The cross validated error is the best estimate for the reliability of the decision tree and the decision nodes. Table 2 displays the sixteen different decision trees and characteristics we examined in the Classification and Regression Tree analysis. Thus, for decision tree 10, the CART analysis included the following product characteristics: number of materials, level of cleanliness, wear-out life and technology cycle.

Table 2. Product characteristics used in CART Analysis.

Decision Tree	Size	Number of functions	Level of integration	Number of parts	Number of materials	Number of modules	Level of Cleanliness	Hazards	Wear-out Life	Design Cycle	Technology Cycle	Repurchase Cycle	Reason for Obsolescence	Functional Complexity
1	x			x			x	x	x	x	x			
2	x	x	x	x	x	x								
3	x	x	x	x	x									
4	x	x	x	x										
5	x	x		x		x		x		x		x		x
6	x	x	x	x	x	x	x	x	x		x		x	
7	x	x	x	x	x	x	x		x		x		x	
8	x	x	x	x	x		x		x		x		x	
9	x	x	x		x		x		x		x		x	
10					x		x		x		x		x	
11											x		x	
12											x			
13				x	x	x	x	x	x	x	x	x		
14				x	x	x	x	x	x	x	x			
15					x	x	x	x	x	x	x			
16			x	x						x	x	x		

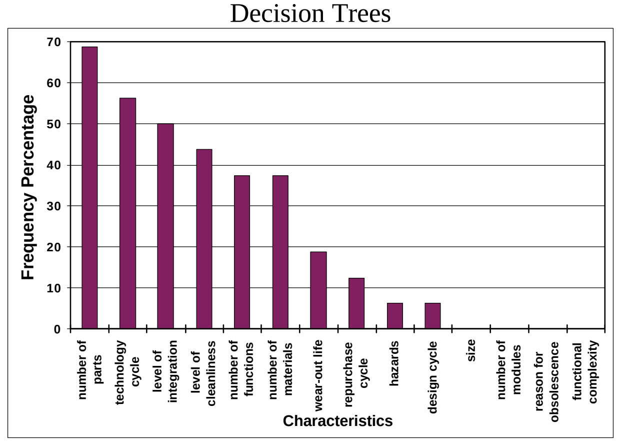
We examined the expected loss for an additional comparison of the 'best' of the trees developed by the Classification and Regression Trees. The expected loss is the ratio of items inappropriately assigned to all items assigned to categories. For this analysis, the expected loss is the ratio of products classified into incorrect end-of-life strategies over the total products classified. Table 3 summarizes the expected loss values. For example, an average of 21% of the products assigned through the decision tree 9 are incorrectly assigned. The current trees are preliminary and the expected loss values are higher than normal due to small sample size in comparison to the number of characteristics.

Table 3. Expected loss values.

Run Number	Average Expected Loss	Run Number	Average Expected Loss
1	27%	9	21%
2	30%	10	30%
3	30%	11	40%
4	33%	12	40%
5	30%	13	28%
6	21%	14	28%
7	21%	15	25%
8	21%	16	36%

We investigated the frequency of which characteristics are used as nodes in the decision tree. Fig. 3 shows the frequency with which characteristics are node elements in the decision trees. Decision trees most frequently include number of parts and technology cycle as decision nodes, being used in 69% and 56% of the trees, respectively. Size, number of modules, reason for obsolescence and functional complexity are not nodes in any of the sixteen decision trees under consideration.

Fig. 3. Frequency with which Characteristics are used in Decision Trees



Currently, no method exists to identify directly or quantitatively the characteristics that have the most influence for classification problems. Increasing the number of products and decreasing the number of characteristics will improve the classification of the end-of-life strategies.

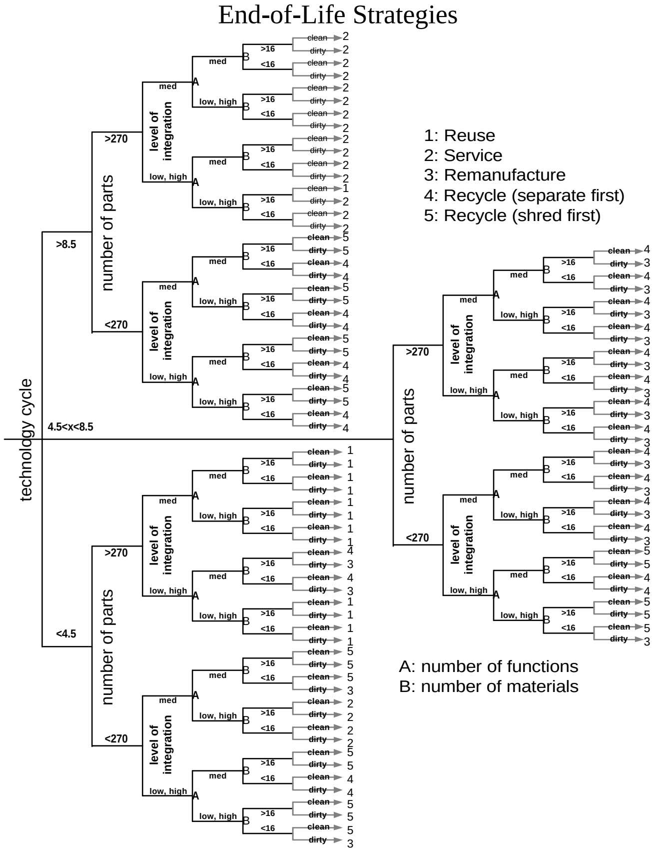
Table 4 summarizes the common decision nodes and splitting criteria for the sixteen decision trees. Number of functions, level of integration, number of parts, level of cleanliness, technology cycle and number of materials influence strongly the end-of-life strategy according to our analysis.

Table 4. Summarized Splitting Criteria

End-of-Life Strategy	Reuse	Service	Reman-ufacture	Recycle (sep 1st)	Recycle (shred 1st)
Number of functions				medium	low, high
Level of integration		medium	low, high	low, high	low, high
Number of parts		>270	>270	<270	>270
Level of cleanliness	medium, high		medium, high		
Technology cycle	<4.5 yrs	>8.5 yrs	4.5<x <8.5 yrs		<8.5 yrs
Number of materials				<16	>16

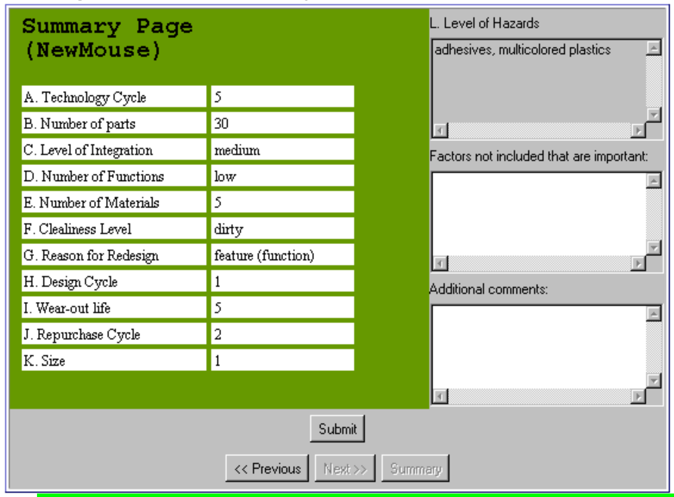
We formed a comprehensive decision tree for the product characteristics by combining the trees to minimize the expected loss.

Fig. 4 Finalized Decision Tree for Determination of Product End-of-Life Strategies



From the determined end-of-life strategy, ELDA provides design recommendations and guidelines based on the end-of-life strategy. Fig. 5 shows the ELDA summary screen for an example product, a fictitious new mouse for the United States market. ELDA then predicts the end-of-life strategy to be Recycle, by separating components first. Individual web pages outline recommendations for improvements to designs and also give best case examples for the designer with which to compare his/her product.

Fig. 5. ELDA Summary Screen for Fictitious Mouse



Requesting more generic information, information accessible by designers and clarifying characteristics will improve ELDA. Additionally, we find that some product characteristics are not used in determining the end-of-life strategy such as size and number of modules.

V. Conclusion

This paper describes the development of the end-of-life strategy categorization based on statistical analysis applied to twelve characteristics across twenty products from the electronics and appliances industries.

Future activities are:

- validation of the end-of-life strategy decision tree
- continued interaction with industrial and academic partners
- incorporation of product characteristics from international regions

Stanford's team is developing ELDA not only for educational purposes, but as a template for each industry and company to adapt the methodology to aid in end-of-life planning and Design for Environment during product definition.

VI. Acknowledgments

Funding for the research comes from the National Science Foundation and the Lucent Foundation. The authors would like to thank other members of the Manufacturing Modeling

Laboratory, especially Venetia Lee. Many thanks to our international collaborators including Prof. Ab Stevels and Casper Boks of Technical University of Delft in the Netherlands and K.J. Masui of MITI Mechanical Engineering Laboratory in Japan.

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