A New Approach to End-of-Life Design Advisor (ELDA)

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Abstract - The End-of-Life Design Advisor (ELDA) guides product developers to specify appropriate end-of-life strategies. Previous work led to a classification scheme for identifying suitable product end-of-life strategies early in the design cycle of a broad range of products. The product end-of-life strategies include Reuse, Service, Remanufacture, Recycle (disassembly first) and Recycle (shred first). ELDA succeeded in prediction of end-of-life strategies in agreement with industry best practices for 89% of the products. This ability to predict strategies enables designers to redesign products that move towards higher levels of reuse. A 'new ELDA' focuses primarily on technical product characteristics with eco-efficiency as a yardstick. Market developments are included through the functionality-time diagrams. This paper presents results from in depth case studies performed in cooperation with various global companies.

I. Introduction

Improving product impact at all life cycles is an important topic for manufacturers of electronic and electrical products. The end-of-life is one stage of the life cycle gaining attention in the market. Companies must understand how to improve their products so that the environmental impact will be lower at the end-of-life, while still being economically feasible. Knowledge of end-of-life strategies early in product design is necessary to develop new products with the highest possible eco-efficiency.

Researchers have attempted to incorporate end-of-life concerns into their design tools. These tools frequently fall short by delaying assessments until detail design stage, requiring too detailed information from the user and requiring the user to input critical end-of-life information [1-4].

However, Stanford's End-of-Life Design Advisor (ELDA) focuses on the designer perspective and seeks to recommend a best practice end-of-life strategy. Since 1997, ELDA has been under development to:

- Determine product end-of-life strategies early in design
- Provide technical basis for decisions made by product planners and end-of-life treatment technology developers and communicate with third parties (e.g. authorities, NGOs)
- Position environmental design in life cycle as well as business perspective

The definition of end-of-life used throughout this work is the point in time when the product no longer satisfies the ***initial purchaser***. This allows for reuse in addition to recycle as possible end-of-life strategies. Other definitions exist but do not include high eco-efficient end-of-life strategies such as reuse and service. The author chooses this definition because sometimes consumer preferences change more rapidly than the product wears out. Based on

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work in [5-9], 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 the 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): Recycling reclaims material streams useful for application in products. Separation of material fractions increases the value of the materials recycled by removing material contaminants, hazardous materials, or high value components. The components are separated by manual disassembly methods.
5– Recycle (shred first): The purpose of shredding is to reduce material size to facilitate sorting. The shredded material is separated using methods based on magnetic, density or other properties of the materials.
6– Disposal: This end-of-life strategy is to landfill or incinerate the product with or without energy recovery.

There are benefits from operating at different levels of the end-of-life strategy hierarchy at different stages during a product's life cycle [10]. There may be potential conflicts between these different end-of-life strategies. Depending on the end-of-life strategy, the design of the product may prohibit other end-of-life strategies, for example, by using materials challenging to recycle. Products with a reuse strategy at the end-of-life may use ceramics or composites to improve durability, which limit the recycling efficiency. Likewise, the use of metal screws in plastic instead of snap fits may facilitate repair work, but shredding the product at the end-of-life will result in a mix between metal and plastic. Therefore, product designers take into consideration the end-of-life strategy the product will experience when designing the product.

II. Case Studies

Stanford's graduate course on Design for Manufacturability provided case studies collect information on end-of-life treatment and product characteristics.

Table 1 shows the products, their characteristics, best practice end-of-life treatment, ELDA's predicted end-of-life strategy and the currently observed end-of-life treatment in practice (on average). Out of the possible end-of-life strategies, the best practice end-of-life is the strategy highest on the end-of-life hierarchy. The (average) practice is the end-of-life most frequently observed in industry. ELDA's predicted end-of-life strategy is based on the research on product characteristics at Stanford University.

The thirty-seven case studies come from a wide-range of product sectors. Products include a one-time use camera, lead acid batteries, a computer, printers, a computer video projector, a washing machine and vacuum cleaners. Additional case studies have been collected from fellow environmental design researchers from Canada, Croatia, Finland, France, Japan, Korea, the Netherlands, Norway, Spain, Sweden, the United Kingdom and the United States.

Table 1. Case Studies for Stanford's End-of-Life Design Advisor (ELDA)

Product	Computer-Video Projector	Cell Structure	Automobile	NLC Support Structure	Generators	Elevator	Klystrons	Aircraft Engine	Automatic Transfer Switch	Digital Copier	Hand Held Vacuum	Air Bag	Computer	Laserjet Printer	Electric Power Steering Motor	Miniature Robot	High Speed Line Printer Floor cabinet	BubbleJet Printer	Printer Hammerbank
Wear-out Life / Technology Cycle	2.5	2.8	1.9	2.1	1.4	2.0	2.0	2.9	2.0	2.5	0.7	1.5	4.0	1.6	0.5	1.0	2.0	1.6	1.0
Wear-out Life	5	11	13	19	14	20	20	20	20	5	4	12	6	8	5	5	20	8	5
Technology Cycle	2	4	7	9	10	10	10	7	10	2	6	8	1.5	5	10	5	10	5	5
Level of Integration	2	2	2	2	2	2	2	3	2	2	1	2	2	2	2	3	1	1	1
Number of Parts	25	1000	1000	20	718	1000	1000	1000	116	533	15	31	200	26	20	201	20	25	25
Reason for Redesign	2	1	3	1	2	3	2	2	2	3	2	1	2	2	5	2	2	2	4
Design Cycle	1	2	4	6	7	4	7	7	7	2	2	4	1.5	3	3	3	5	1	2
Hazards	2.5	3	5.5	0	1	1	2	3.5	1.5	0	2.5	0	3	1	1	1	0.5	0	2
Number of Materials	20	10	100	5	20	35	50	100	20	3	10	6	20	20	15	7	15	12	8
Size	4	5	10	9	10	9	10	10	7	6	2	3	5	8	1	3	7	5	7
Best Practice End-of-Life	1	1	1	1	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
ELDA Prediction	3	1	1	3	2	3	2	2	2	3	3	3	3	3	3	3	3	3	3
Current End-of-Life (average)	1	1	1	1	2	2	2	2	3	3	5	6	1	3	3	5	5	3	5

Product	Network Routers	Telephone	Network Server	Photocopier	Inkjet Printer	One Time Use Camera	Portable Radio	Television	Washing Machine Electric Motor	Lead Acid Batteries	Washing Machine	Connections	Shipping Container	Fiberoptic Transceiver	Computer Mouse	Filter	Typewriter	Vacuum Cleaner
Wear-out Life / Technology Cycle	10.0	2.5	9.0	1.0	2.7	0.5	5.0	5.0	2.4	2.0	2.0	2.0	0.5	3.3	1.5	1.2	1.7	1.1
Wear-out Life	10	5	9	5	4	2	10	15	12	20	10	20	5	10	6	12	15	8
Technology Cycle	1	2	1	5	1.5	4	2	3	5	10	5	10	10	3	4	10	9	7
Level of Integration	1	3	3	3	1	1	2	2	1	1	1	1	1	1	1	2	2	2
Number of Parts	10	22	135	100	100	25	20	100	27	8	101	2	100	11	5	30	55	75
Reason for Redesign	2	2	2	5	3	3	3	2	3	3	3	2	5	2	5	4	2	3
Design Cycle	2	1	1	2	1.5	3	2	3	4	6	2	7	7	1	3	1	1	3
Hazards	6.5	0.5	2	3	1	2	3	4	0	2	0	1.5	0.5	1.5	1	4	4.5	2
Number of Materials	25	30	52	20	17	7	8	20	4	4	7	2	13	20	4	100	20	19
Size	3	1	7	7	4	1	3	6	4	6	7	2	5	0	1	10	2	6
Best Practice End-of-Life	3	3	3	3	3	3	4	4	4	4	5	5	5	5	5	5	5	5
ELDA Prediction	3	3	3	3	3	3	4	4	4	4	5	5	3	5	5	5	5	5
Current End-of-Life (average)	5	6	5	3	5	3	6	4	4	4	5	5	6	5	6	6	6	6

III. Technical Product Characteristics

Traditionally, Design for Environment has made progress on technical solutions. Environmental issues must be examined from a value perspective, through Environmental Value Chain [11]. Technical approaches are limited to factors the company can control. Stanford's ELDA uses *technical* product characteristics to determine end-of-life strategies. Designers and product managers are able to influence technical aspects of the product.

Rose et al have defined various characteristics affecting product end-of-life treatment, categorized by external, material, disassembly, and inverse supply chain [12]. Originally, there were twenty-four characteristics, although research revealed that six key characteristics predicted the end-of-life strategy. Although not used in prediction, another six were included in the implementation of ELDA, for a total of twelve product characteristics. Further research, described in this paper, shows seven of the twelve characteristics are useful in predicting end-of-life strategies. Table 2 lists the product characteristics, the data ranges for ELDA input and whether the product characteristic is used in the ELDA prediction.

Table 2. Technical Product Characteristics

Product Characteristics	**Input Ranges**	**Used in ELDA?**
Wear-out life	0-20 years	Yes, used in ELDA prediction
Technology cycle	0-10 years	
Level of integration	High, medium, low	
Number of parts	0-1000	
Design cycle	0-7 years	
Reason for redesign	Minor/major and function/aesthetic	
Hazardous materials	0-14.5, weighted scale	
Number of materials	0-100	Not used in prediction
Size	0-10	
Level of cleanliness	n/a	Eliminated from ELDA
Number of functions	n/a	
Repurchase cycle	n/a	

These final product characteristics are used because they provide general information, describe the physical properties and describe the technology and design changes of the product. These product characteristics are generic and definable over a wide range of products, having quite diverse functions. The characteristics also describe the product's physical composition and the technology development.

Some product characteristics were eliminated to preserve the purely technical intent of ELDA, as follows:

Cleanliness level: This characteristic described the amount of dirt or filth in the product after use. Designers can not generally control the use conditions of a product.

Number of functions: Defining number of functions for a wide variety of products is challenging. Also, the number of functions may deteriorate over time. This product characteristic is incorporated into the functionality versus time diagram, as described in Section V.

Repurchase cycle: This characteristic is not a technical product characteristic but rather depends on new product functionality, consumer disposable income and consumer preferences.

The new ELDA uses relative numbers in the prediction of end-of-life strategies. The ratio of wear-out life to technology cycle is described in more detail in Section IV. Further improvements to ELDA combine other relative numbers into the prediction. A possible redefintion of number of parts is to include the weight of the product (i.e., number of parts divided by weight (parts/kg)). The possible redefinition of number of materials uses weight percentages of materials (i.e., metals, precious metals, glass, and plastics).

IV. New Classification Tree For ELDA

The case studies described in section II were used to predict the end-of-life strategy of products having similar characteristics. Using a statistical technique, CART, it was found that the product characteristics that influence the end-of-life strategies most are: product wear-out life, frequency of change in technology, level of product integration, number of parts, time between product redesigns and hazards. CART is one of many cluster analysis techniques and is a methodology commonly found marketing data or medical data analysis. Classification analysis uncovers structure of data to predict medical conditions, consumer behaviors and other complex patterns [13].

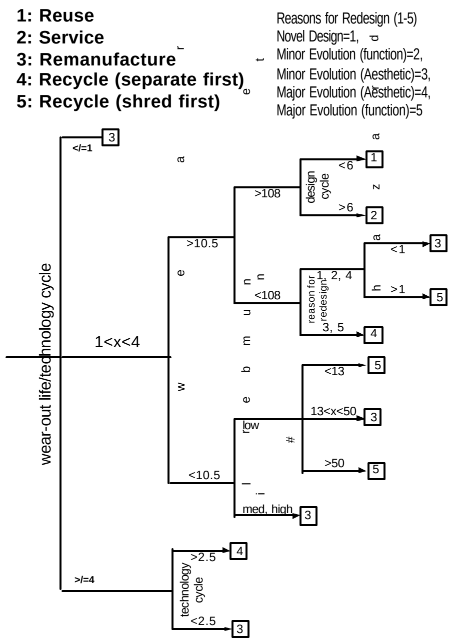

Fig. 1. Prediction Methodology for End-of-Life Strategies (classification tree used in ELDA)

The new prediction uses the ratio between product wear-out and technology cycle. In Rose et al [14], the mapping of wear-out life to technology cycle is used to make recommendations for end-of-life treatment. Fig. 2 shows graphically the first two levels of the prediction tree in Fig. 1. The diagonal lines divide the graph into three main groups. Group 1, in the upper left corner, is the products with wear-out life at least four times the technology cycle. Group 2, in the middle, consist of products whose ratio of wear-out life to technology cycle is between 1 and 4. Group 3 products have wear-out life less than or equal to the technology cycle and are located in the lower right corner.

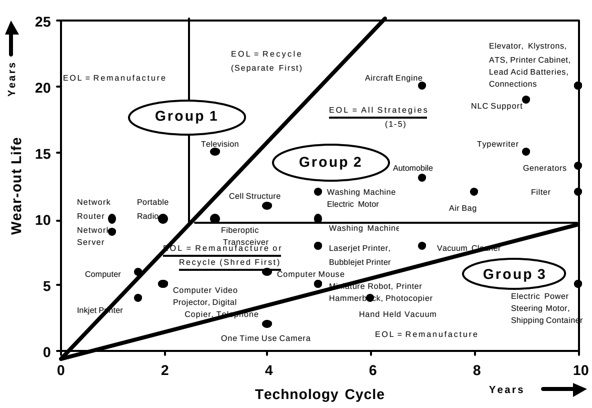

Fig. 2. Wear-out Life and Technology Cycle for Variety of Electronic Products

The products in Group 1 are a network router, a network server, a computer and a television. According to the prediction methodology, products within this category should be remanufactured or recycled, with separation first. The products with technology cycle less than 2.5 years should be remanufactured. Twenty-six of thirty-seven products fall into Group 2. They include inkjet printers, a digital copier, a computer mouse, a washing machine, a generator and an aircraft engine. Products with wear-out life less than 10 years should be remanufactured or recycled without separation. On the other hand, products with wear-out life greater than 10 years have a diverse set of product characteristics and experience the complete range of end-of-life treatment options – from reuse to recycle (shred first). Examples in Group 3 include a one time use camera, a photocopier, a hand held vacuum, an electric power steering motor and a shipping container. According to the prediction methodology, products in this category should be remanufactured at their end-of-life phase to replace worn-out parts and return to use in the market before the technology changes.

ELDA succeeds in prediction of product end-of-life strategies in agreement with current best practices in end-of-life treatment. The new prediction method yields 89% agreement with current best practices. This ability to predict strategies enables companies to design future products that move towards a higher level on the end-of-life hierarchy. The ELDA prediction matches the current average practice in 41% of the products. Out of current practice, the best and average end-of-life strategies are in agreement for 46% of the products. Out of the possible end-of-life strategies, the best practice end-of-life is the strategy highest on the end-of-life hierarchy. The (average) practice is the end-of-life most frequently observed in industry.

Table 3. Percentage agreement between different end-of-life treatments.

Comparison between:		**Score**
Predicted end-of-life strategy	Current best practice	89%
Current best practice	Current practice (average)	46%
Current practice (average)	Predicted end-of-life strategy	41%

Circumstances outside technical domain are hampering the goal of achieving the industry best practice for products. In some instances, factors, such as product cost, repair cost, functionality changes, recycled material prices, environmental regulations, availability of recycling facilities and feasibility of recycling technologies are limiting the wide-spread application of industry best practices. In depth examination of these factors will help achieve eco-efficient end-of-life strategies.

V. Functionality Changes Over Time

The feasibility of an end-of-life strategy is limited by product functionality changes over time. The challenge is to understand how changes in functionality over time affect users' desires to replace their products, which in turn means the products have reached their 'end-of-life.' Different reasons account for a product reaching the end-of-life, including technical, economic, ecological, aesthetic, 'feature', and psychological obsolescence [15].

The affect of market developments and consumer preferences on product end-of-life can be demonstrated with functionality versus time diagrams. Increases in functionality are pushed by consumer desires or pulled by advances in technology. Generally, as technology becomes more developed, it moves into lower-end models, becomes an industry standard, and becomes a minimum level of expectation for consumers.

The comparison of functionality of a variety of products (competitors or even levels within a company) at two different times is necessary to understand the situation. Figure 3 shows the low, medium and high end products at a given year t_1. The lines on this graph represent the range of consumer of expectations. This graph assumes products with additional functionality are available and the functionality of the original product does not deteriorate over the time period. After t_2-t_1 years:

(1) the high-end product now has the equivalent functionality of a new medium level product,
(2) the medium level product is now just sufficient,
(3) the low-end product drops out and can be discarded.

For the case of the high-end product, the reuse of the product is possible because the functionality falls into the range of the currently offered functionality. However, the low-end product, will not fall into the desired functionality at the time instance t_2. For this product, the end-of-life strategy is more appropriately recycling, either separating or shredding first.

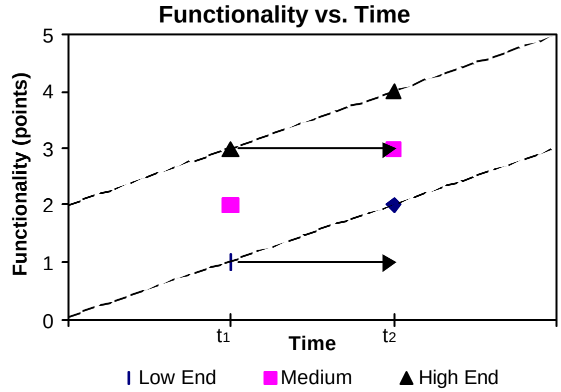

Fig. 3. Functionality mapping showing low, medium, and high end products.

Fig. 4 shows an example when the high-end product is broken, losing all functionality. The high-end product needs to be repaired or serviced to return a range acceptable by consumers. For a broken low-end product, even after repairing or servicing to its original functionality, it still would not satisfy consumer demands. Therefore, this product should be recycled for materials.

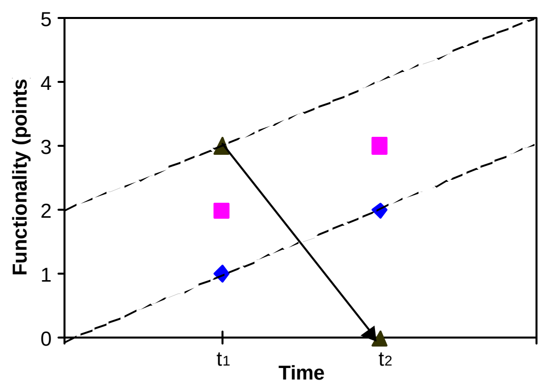

Fig. 4. Functionality versus time – high-end product needs repair or servicing.

VI. Conclusion

ELDA, with the new prediction methodology, is able to predict accurately end-of-life strategies based on technical product characteristics. ELDA is an excellent tool for use in early stages of design because the required information is general and easy to determine. ELDA provides the designers with the end-of-life strategy, enabling the designer to create products with a higher level of eco-efficiency for the given set of product characteristics. However, ELDA is intended to be a 0th order recommendation. Continuing work in developing a 1st order tool, Environmental Value Chain Analysis, will examine the feasibility and applicability of the recommended end-of-life strategy. Market developments are shown in the functionality and time diagrams. As functionality increases over time, the possible end-of-life strategy has to be changed.

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