DESIGN FOR ENVIRONMENT: A METHOD FOR FORMULATING PRODUCT END-OF-LIFE STRATEGIES

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Abstract

The research seeks to develop methodologies that aid in formulating the end-of-life strategies across a wide range of products. The analysis of current end-of-life practices identifies improvements to product design that reduce the impact of manufactured goods on the environment. There are two core parts of this research. First, the methodology determines what end-of-life strategy is possible according to the products' technical characteristics. Second, the research validates the method by comparing the proposed end-of-life strategies with current industry practice. The resulting software, the End-of-Life Design Advisor (ELDA), guides product developers to specify appropriate end-of-life strategies. The product end-of-life strategies include reuse, service, remanufacture, recycle (with disassembly) and recycle (without disassembly). Case studies from various industries detail the outcome of a product's end-of-life (i.e., what happens to a cell phone when it no longer functions or is outdated?). These case studies came from Japan, Korea, United States, and Europe. The product characteristics that influence the end-of-life outcomes the most are product wear-out life, technology cycle, level of integration, number of parts, design cycle and reason for redesign. ELDA succeeded in classifying end-of-life strategies in agreement with industry best practices for 86% of the products. The research compares the strategies these companies have taken in implementing new environmental policies and to discover the most streamlined and cost-effective method for moving towards environmentally friendly product designs. By understanding better the end-of-life strategy appropriate for the product, the proposed method can help the company develop appropriate and profitable end-of-life strategies for their unique position, systematically.

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1 INTRODUCTION

This chapter gives a short description of the motivators for including environmental initiatives in business decision making and practices. It then introduces objectives, focus and methodology of this research on design for environment. Finally, an explanation of the dissertation structure concludes Chapter 1.

1.1 Motivators for Environmental Change

Concern for future generations and alarming rates of nonrenewable resource consumption provide the impetus for research on sustainability and improving our natural environment. Countries and companies are establishing goals for achieving sustainable development and reducing resource consumption in hopes of preserving the natural environment for future generations. The environmental problem is an extensive, complex problem, and some example areas of study are energy consumption, material/resources use, recycling, and environmentally relevant substance control. In the electronics industry, these are of particular concern because electronic products, by nature, consume energy. Waste management is crucial as landfills close and populations grow (Pohlen et al. 1992). Further, these products are being disposed of at higher rates than historically because of increasing speed of technology developments and changes in how consumers interact with products. Control of environmentally relevant substances for electronic products is critical because printed circuit boards are concentrating potentially toxic substances. Halogenated flame retardants are used in plastic housings as protection from the threat of electrical fires. However, incineration of these plastics can produce toxic dioxins (Taberman et al. 1995). All of these concerns combine to yield a crucial research subject – end-of-life treatment of electronic products.

Possible solutions to the challenge of end-of-life treatment of electronic products must balance the positives and negatives of three partly conflicting goals:

- reducing landfilled material,
- maximizing recycling, and
- controlling hazardous materials

From the environmental perspective, many industrial activities have been regulated since 1970s. The main focus of legislation has been on production processes and industry sectors involved in basic production (chemicals, materials like steel, paper, etc) (Stevels 2000b). The solutions to problems were sought through ‘end of pipe’ cleaning through investments in machinery and equipment. There has been extensive research into methods to reduce cost or environmental impact at processing or manufacturing stages. Recently, efforts have moved to eliminate the environmental problems in processes earlier by reducing environmentally relevant material use and processing steps, called cleaner production.

During this same time, little or no regulation existed for products or the design of products. The only slight hint at product regulation are bans on landfilling of certain products (appliances or televisions, lead acid batteries, for example), and only recently the take back or recycling targets for certain products. Currently, the research for product improvement is lagging far behind process improvement work. The present work shows improvements and methodologies to help leaders make more knowledgeable decisions regarding product design and the effect at end-of-life.

Learning from the past, end of pipe legislation had limited effect on improving environmental conditions. More successful solutions address the root causes or seek to address the causes instead of the effects, so for example taking them into account when the product is designed originally. End of pipe remediation was based on the ‘polluter pays’ principle. This was problematic because it is difficult to determine who was the polluter and many companies were incorrectly burdened with exorbitant costs. However, in recent developments, the ‘polluter pays’ principle has been altered to ‘producer pays’ principle, thus transferring the burden for many of the activities of modern society to manufacturers of products that may then be passed to consumers. In the long term, society has to bear the burden of environmental improvement and can help manage this through eco-efficiency concepts.

The concept of eco-efficiency has changed the approach of many forward-thinking companies. Eco-efficiency means not only ecological efficiency, but also economic efficiency, making a direct connection between environmental targets and market opportunities (Cramer et al. 2000). Using eco-efficiency involves a chain-oriented approach, which requires more communication and cooperation between partners in the product chain (for instance, between suppliers and / or customers). The eco-efficiency approach becoming a part of the strategic planning of the company is much more important than the more operational environmental management approach currently in place in most companies. Experiences gained in the application of eco-efficiency approach have shown that it is possible to create win-win situations. Eco-efficiency improvements can lead to cost reduction, strengthen the market position of existing products, extend products to new markets, avert criticism by external stakeholders, and increase the possibility of the company's surviving in the long-run (Cramer et al. 2000).

Instead of only relying on the 'producer pays principle,' a more realistic and appropriate option for future success is for joint responsibility by consumers, producers, governments, and recyclers. This joint responsibility should be distributed in such a way that those who are able to manage the most eco-efficiently take responsibility. It is important to understand the drivers behind the increase in research to increase eco-efficiency.

The following sections outline the reasons why a company should take steps to address environmental concerns, more specifically end-of-life concerns. The reason for incorporating design for environment depends on the strategy for each company. Some companies are defensive, proactive or cost driven in their reactions to external developments related to environment (i.e., social pressures, additional legislation or taxes). The following three sections will briefly outline these motivators so that the reader can gain insight into why companies and organizations are involved in these efforts. Reasons pushing the focus on product end-of-life are consumer attention leading to increased market advantages, reducing potential costs and risks and anticipating pending legislation.

1.1.1 Customer Pressure

Recent surveys have shown that when a private consumer is purchasing a product the environment is placed further up their list of purchasing criteria (Ottman 1998). Research has shown that both in Europe and the United States attitudes of the buying public towards environment can be subdivided as follows (Stevels 2000a):

- Approximately 25%- strong environmental motivation; will pay higher prices for 'demonstrated environmental improvement',

- Approximately 50%- positive for environment but are not prepared to pay higher price, and
- Approximately 25%- neutral or negative for environment; perceive products with same price as traditional products as products with lower performance.

Environment alone will not sell products but in combination with other improvements, at least 65% of consumers will be interested and chances to increase market share are good. Ottman expects that enhanced primary benefits in performance, convenience, price and safety, for example, that accompany environmental improvements to continue to propel the market for environmentally preferable products in the years and decades to come (Ottman 1998).

Where competing companies' products are closely matched, the fact that a particular company has included environmental criteria into the product's design may sway the customer to purchase that product over and above the product of competitors (Lucacher 1996). In this tough competitive climate, environmental compatibility breaks ties at the shelf, where pragmatic consumers purchase those products that can be recycled or otherwise safely disposed of in their communities (Ottman 1998).

A new situation occurs where an increasing number of companies see the environmental aspect as an issue that could improve the market position of their products (Nilsson 1998). With the pressures on companies to 'go green' and the associated research and implementation costs, companies are looking for some kind of financial pay-back (Clegg et al. 1994). Efforts and pressure from industrial customers can have a great effect in bringing environmental improvements to the marketplace (e.g. U.S. government energy requirements bringing 'Energy Star').

Environmental demands made by industrial customers are powerful drivers for the environmental improvement of the company approach and its products. Large companies cannot always make their suppliers liable for the environmental aspects of their products; therefore, companies increasingly request information from their suppliers. In general, an industrial customer is able to influence a company more than an end-user. Industrial customers want their suppliers to contribute to their environmental success (and image). On the other hand, boycotts of products organized by consumer organizations or environmental NGOs have considerable impact on company behavior.

Another important factor, relating to consumers and more broadly to stakeholders, is a concern for the company's image. Many existing end-of-life systems were pushed or motivated by negative publicity directed at the company. As consumers and other stakeholders press for continued environmental improvements, firms competing in the external marketplace are stepping up their efforts to provide 'environmental value' to their customers through new products, services, and organizational arrangements. It is possible to improve the image of the product and company by communicating environmental quality of a product, good reports in consumer testing or better behavior of the company. It is also good publicity to demonstrate the company's environmental goals and progress through publishing an annual environmental report (Stancyzk 1995).

1.1.2 Competitive Forces

Companies implement environmental initiatives that reduce operating costs or increase quality. Increasing its profitability is still a main driving force of a company. The increasing cost of materials, related to scarcity in natural ecosystem, means the manufacture of parts is more expensive and efforts to reduce part weights and size gives substantial reduction in manufacturing costs. As energy costs continue to rise, companies seek to eliminate product steps to reduce energy consumed. In addition, efficient management of water and other auxiliary materials during production can also achieve a considerable saving in costs. As a result of stricter legislation on disposal practices, the costs of disposal of hazardous and non-hazardous waste have risen over the last decade. A financial benefit can also be achieved in time by generating less waste and by reducing the fraction of hazardous waste. Business has opportunities to reduce cost by examining product end-of-life, by increasing market share and bringing insight to product usage and disposal.

The risks associated with introducing products have increased because of consumer product safety obligations and fear of possible lawsuits. Companies must make investments during product development to prove products do not pose threats to consumers during use, do not emit toxins after product disposal. The responsibility for hazardous material control and worker safety encourages companies to eliminate hazardous substances in their product and processes. Inappropriate management of these risks can prove costly for companies, causing them to lose to competitors who are better able to manage risks.

Failing to take steps forward in environmental initiatives may mean loss of competitiveness in the market place. Competitors that make progress in environmental issues will put more pressure on the ‘fence-sitters’ to take steps to improve environmental performance. Within the companies, management is developing environmental strategies, roadmaps and programs (Stevels 2000b). The competitive field is now using environmental issues in marketing, quite successfully. Even environmental management systems are moving quite rapidly from an element of quality to a standard (Stevels 2000b).

The development of new technology has allowed companies to reduce cost and improve environmental performance. The application of smart materials, with novel interlocking abilities, reduces manufacturing and disassembly costs. More powerful integrated circuits allow for smarter software and lower energy costs, reducing usage costs and environmental impact. The development of software has given designers more tools, such as Computer Aided Design (CAD), Finite Element Analysis (FEA), and Virtual Reality, to help expedite the detail design stage, reducing the development costs of products.

New technology development is crucial to producers because in all of the years of producing products, this is the first time producers will have to manage what happens to a product at the end-of-life. Companies have experience in producing and releasing new products and providing customer service, it is a new paradigm for them to be responsible for products at the end-of-life stage. As changes are made, new models to understand and analyze these changes are needed.

1.1.3 Legislation Initiatives

In the middle of the 1970s, stricter environmental legislation was spurred by precipitating environmental crises. Legislation has increased from this time to constrain further environmental effects (Welford et al. 1993). The end of pipe regulation restricted types of materials that can be discarded, as well as how and where they can be discarded. Examples of regulation include Clean Air Act, Clean Water Act, and the

Resource Conservation Recovery Act. Much of this legislation has targeted activities by industry, has high cost penalties, and thus encourages companies to respond. Legislation is forcing industry to find alternative environmentally preferred ways of dealing with these problems (Matthews 1993). The most recent developments in environmental regulation target electronic products.

Proposed legislation for extended producer responsibility, or product take back, would require producers to address the end-of-life stage of their products. The European Union's proposal (to European parliament and Council of member states) requires producers to 'take back' electrical and electronic equipment (EU-DG-XI 2000). Many other countries are discussing, preparing or have already enacted take back legislation. U.S. companies, selling products in many European markets, are now required to establish systems to take back products from consumers. The currently operating Dutch take back system for large electronic appliances started in January 1999 and smaller products started in April 2000. The consumers pay a take back deposit to the stores when they purchase new products. The products are collected at collection centers, managed by the municipalities. There is curbside pick-up for some products. Most products are recycled by local recycling companies, who the share the profits or deficits with producers' group.

The general consensus in Japan is that to tackle environmental problems, industry, administration and the general public have to act together to achieve breakthroughs. Coming into effect in 2001, legislation in Japan seeks to achieve proper disposal of products with a united effort from organizations related to the production, manufacturing, distribution, consumption and disposal of products. The legislation requires the recycling percentages (by weight) for the following products: refrigerator (50%), air conditioners (60%), televisions (55%) and washing machines (50%) (Yamamoto 2000).

The assumed logic is that if producers are financially responsible for end-of-life product management, producers will have a financial incentive to design their products with less hazardous and more recyclable materials. The logic does not always hold true. In many situations, the financial burden is passed on to the consumer. Many electronics companies are the global leaders in innovative design techniques that eliminate or minimize adverse environmental impacts throughout the product life cycle, or that make the product easier to recycle at the end-of-life stage. This industry sector has also been a leader in the development of voluntary recovery programs to reuse, refurbish and recycle electronic products (EIA 1999). In the UK, the Industry Council for Electronic Equipment Recycling (ICER 1993) has been set up to develop a national waste strategy for electronic goods. The recycling organizations are Cycle for Germany, Suico for Switzerland and NVMP for the Netherlands. Companies such as IBM, DEC, Hewlett Packard, Rank Xerox and Grundig are already taking back used equipment, while Toshiba and Hitachi have research programs to reduce disassembly times (Copper 1994). While these are positive movements with respect to environmental improvement, there are many untold negative stories.

Regulations are ‘leveling the playing field’ and offer therefore no opportunity for competitive advantage (Stevels 2000b). Competitors who can not comply with this sharpening government legislation are disadvantaged. Like earlier environmental regulations that prescribed technological responses, mandates on producer responsibility stifle innovative approaches and impose added costs on consumers (Scarlett 1999). It is necessary to understand the flow of tangibles (products and money) and intangibles in order to prevent unintended consequences of legislation and to develop regulation that is better adapted to the market forces.

1.2 Purpose of Current Research on End-of-Life Strategies

Initially, Environmental Design (Ecodesign or Design for Environment) has been seen as a set of technical issues. For this reason, Ecodesign activities were positioned in product development departments of companies. Over the past decade, Design for Environment (DFE) has attracted steadily increasing attention throughout the world and in the United States (Ishii et al. 2000).

Steps forward, in regards to environmental impact of products, are positive for the company. Inactivity is negative for the company, in terms of publicity and competitiveness. Inactivity or reluctance to change may result from lack of information about the future. Experience has shown that decisions must be made, even in the event of lacking information, in order to move forward. Companies do not realize that end-of-life scenario can vary over time, but it is just because they do not have enough information to predict changes and how to deal with them (Boks 2000). Several studies are now describing end-of-life scenarios that yield benefit to the company on the basis of product end-of-life value.

Companies should establish end-of-life systems out of self-interest. Managing product end-of-life treatment can be financially beneficial to a company, bring insight into product usage, and increase market share. Producers, such as Xerox, Kodak, Nike, Philips Medical Systems, are indeed making a profit on end-of-life systems. Collecting products at the end-of-life has given IBM an opportunity to examine usage and wear to improve product design. Kodak and Nike, not only make money through their end-of-life product programs, but also have improved company image and resulting market share for their contributions to the environment. As markets become more competitive, losing market share or stakeholder support can result from not establishing end-of-life treatment programs. Whether competitors move to set up programs earlier or only after it is required by legislation, starting a product end-of-life treatment program later could be more expensive.

There are many reasons given for companies not establishing end-of-life systems, because they cost money, the retained risk of the product is too high, the competition is not doing it, and it is not part of the core business interests. Indeed establishing a product end-of-life take back system will cost money, but results have shown that it is possible to make substantial profits through this activity. Managing the risk of collecting and recycling the end-of-life products is a barrier to entry for smaller companies. A company's reason for not implementing a program that a competitor is not doing it or it is not part of the core business interests are both contradicted when the program generates substantial revenues.

The following section will outline the issues faced by companies establishing end-of-life programs for their products. These issues are addressed through this research and the proposed methodology given in section 1.2.2.

1.2.1 Issues and Challenges

In many companies, a strategy for developing end-of-life systems is lacking or could be enhanced. A systematic approach to incorporating the end-of-life concerns into product development needs to be developed. There are no approaches currently available that enable a systematic integration of the end-of-life concerns into all relevant phases of product development, in a holistic way. Product end-of-life management encompasses not only technical details, but it also requires a unified business approach. Building a strategy for end-of-life treatment of products is necessary in order to gain market share, adhere to legislation and maintain competitive advantage.

1. While successes in the field of Design for Environment have been made based on technical solutions, for example eliminating CFCs in manufacturing and use, reducing car pollution through adding catalytic converters; there are aspects of products that will require more than technical fixes. Previous research, described in detail in Chapter 2, has placed excessive emphasis on the designer and places responsibility on designers' shoulders to fix items that are often out of their realm of responsibility. The research does not make recommendations to help product management determine appropriate incentives to move towards better environmental design. Most research, to this point, has been very fragmented. Depending on the particular researchers' background, their work has focused on particular issues within the end-of-life system: for example, economics of recycling (Boks 2000), recycling percentages weighted by hazardous material content (Huisman et al. 2000b), remanufacturing guidelines (Das et al. 1999), CAD tools for disassembly assessment (Harper et al. 1998), disassembly line balancing operations (Gungor et al. 1999), end-of-life supply chain analysis (Uzsoy 1998), tools for non-destructive disassembly (Feldmann et al. 1996, Chiodo et al. 1999), and even tools for destructive disassembly (Masui et al. 1999). However, to date, few researchers are have looked at the picture from a holistic perspective.

2. Reuse, Service and Remanufacturing, as end-of-life strategies, have addressed relatively little in the research community (in fewer tools). Discussions concerning end-of-life systems have been very disjointed. A wide variety of perspectives and positions have been in conflict. The number of companies and organizations

involved in the take back discussions is large. For example, within the European Union discussions about consumer electronics product take back, involve over 30 organizations and companies. Managing and understanding the relationships and interactions between these entities is crucial for positive outcomes to the discussions.

3. Tailored solutions are not possible because of the differences in product characteristics. Most end-of-life recycling quotes have been based on industry sectors. Identifying the ideal strategy is necessary before outlining actions. This does not take into account that within sectors product technical characteristics vary greatly (e.g. the telecommunications sector that includes cellular phones, switching equipment and backup power systems). Recycling percentages to be realized depend not only on product characteristics but also end-of-life technology, industrial infrastructure and outlets for secondary materials. To optimize environmental gains and minimize costs, efforts in take back and recycling should be tailored to product sectors and types. Existing practice of end-of-life treatment does not obey sector divisions, but rather is based on the characteristics of products. By making legislation per industry sector, recycling companies will have to revamp their entire system, leading to inefficiencies. Understanding what is possible by current standards in recycling based on product characteristics will improve legislation, processing technology and design.

4. Much of the previous work makes recommendations on what companies should do, but no one has taken the opportunity to observe current company practices and improve and learn from their successes and failures. Observations of how business actually operates would reveal what is possible, what business struggles with and what business needs help with, rather than stating what business should do without seeking to understand what they already do. By examining company programs, research is able to learn from mistakes, understand problem areas, examine objectively the issues and combine these items into a structured methodology.

5. Some companies have developed eco-efficient end-of-life systems, to reclaim value from their products. However, some of these programs were developed in a defensive manner, reacting to consumer demands (Nike, Kodak); still others fell into the programs (HP, Xerox); and a small percentage established their end-of-life

systems based on historical observations (GE). However, replicating these systems to other products in their companies has not proven successful. A systematic method to develop end-of-life systems, taking into consideration the relationships existing within the company and outside the company is needed. Also by systematically analyzing the existing end-of-life systems, improvements can be made to increase profits, take back percentages and consumer satisfaction.

6. Circumstances outside the 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 application of eco-efficient end-of-life strategies.

1.2.2 Key Research Questions

The research seeks to develop methodologies that aid in formulating the end-of-life strategies across a wide range of products. The analysis of current end-of-life practices identifies improvements to product design that reduce the impact of manufactured goods on the environment. There are two core parts of this research. First, the methodology determines what end-of-life strategy is possible according to the products' technical characteristics. Second, the research validates the method by comparing the proposed end-of-life strategies with current industry practice. By better understanding the end-of-life strategy appropriate for the product, the proposed method can help the company develop appropriate and profitable end-of-life strategies for their unique position, systematically. The research approach is to:

- use case studies to classify products' end-of-life strategies and develop a methodology
- evaluate the current implementation of end-of-life systems in industry.

The ultimate goal is to communicate these results to (a) producers, (b) recycling companies and (c) policy makers.

1.2.3 Contribution made by this work

This research contributes to engineering knowledge by providing a design tool for use in industry; this tool is called End-of-life Design Advisor (ELDA). ELDA's innovation focuses on using simple product characteristics to make end-of-life strategy decisions. ELDA succeeds in classifying products into end-of-life strategies in agreement with current best practices. ELDA links insights into product end-of-life based on recycling experiences with designers and product managers. This tool is applied in early stages of design when changes to the design are still possible. Product designers and managers might recognize that different products have different characteristics, but ELDA is the first to show that these differences control the possible end-of-life treatment of the product. ELDA considers the technical product characteristics controlled by product designers and managers, looking at the products as an issue conquered by technical solutions. Evaluation and validation of ELDA is through comparison between the classification method and the end-of-life treatment currently implemented by industry. The differences between the actual practice, both best and average, and the ELDA method shows that not all of the issues for end-of-life can be achieved by technical solutions, non-technical business items are also needed.

ELDA is powerful, revealing in a very early stage of design that the end-of-life strategy of the product based on characteristics. ELDA looks objectively at the possible end-of-life strategies and reduces subjectively associated with developing product end-of-life systems. ELDA removes the product sector approach by removing function and emotional attachment to product (from ELDA's perspective, electric generators are equivalent to cars; TVs are same as vacuum cleaners).

An extension to ELDA is the functionality-time diagram that shows the influence of consumer behavior and market developments' on product end-of-life strategies. A topic for future work in end-of-life treatment of products is through Environmental Value Chain Analysis (Rose et al. 2000c). Realizing that possible approaches for developing a product's end-of-life strategy are not dependent on technical considerations only, Environmental Value Chain Analysis addresses non-technical business considerations.

1.2.4 Research Approach

This section will describe the research methods that were used to develop ELDA. The research methods used include literature review, case studies and statistical analysis.

The literature review is a research method that involves searching through books, journals, conference proceedings, newspapers, dissertations and CD-ROMs for published information on the field of research. The ecodesign research field is rapidly evolving and therefore this method of research continued throughout the entire period of work. Even though the research field is new, a substantial amount of literature already exists. The literature has been found comprehensive in some respects while incomplete in others. For example, reports on how current products are being recycled have been found limited in scope and number.

Within design engineering, researchers prove hypotheses by extensive case studies. Most researchers examine product development teams before and after a change in design methodology to verify the efficacy of their approach. Typically this research is used for testing timesaving design methodologies or managing the creative design process.

One strong area of the intended case studies is the diversity of products that will prove the wide application of the techniques and methodologies. A substantial amount of information has been collected through indirect and direct case studies. Indirect case studies include the case studies collected through the ELDA web tool, such as from ME217 graduate student projects and other professional contacts. Several direct case studies were collected during six months at Philips Consumer Electronics.

Further information concerning product end-of-life treatment was gathered from reviewing corporate documents on the recycling of products, marketing and publicity documentation, organization documentation and others. The literature study has therefore been supplemented with interviews and discussions with people involved in the recycling business as well as through visits to recycling facilities around the world.

ELDA has been built using a statistical technique, Classification and Regression Trees, to map the technical product characteristics to the end-of-life strategies. Classification is a type of cluster analysis, used to group items with similar characteristics into classes.

1.3 Focus and Scope

The products studied in this work are mostly electronic products, whose functions include heating, cooling, lighting, generation of electricity, transmission of electricity, storage and treatment of information, transportation, motion, communication and ignition of flammable substances (Hedemalm et al. 1995). The research forming the basis for this thesis emphasizes consumer electronic products of a complex character. Products include small electric appliances, such as cellular phones, larger consumer products, e.g. cars and white goods, and large industrial or institutional products, such as medical systems or aircraft engines.

The baseline of this thesis is the product development process into which the end-of-life aspects are to be incorporated. The discussion on how this could take place is not limited to any particular working procedure of designing. The way product development is referred to in this thesis is very broad and general. Therefore the integration of the end-of-life aspect is also discussed from a broad and general perspective and not restricted to any specific type or structure of a company.

From a geographical point of view, this thesis will focus on the application of the methodology to the United States. The suggestions on how to integrate the knowledge are not limited, in principle, to a certain geographical area. Wherever the waste is generated, the approach should be similar, with minor differences in legislation and structure of existing end-of-life treatment systems to be kept in mind. There are some minor differences in the specifics of how a product is used and the reasons for disposing of the product.

A limitation of this research is that the end-of-life strategies were developed from observations of activities in the United States. This is mostly based on differences in legal systems and how politics are involved in this process. This challenge is most noticed by companies distributing products globally. There will always be differences in legislation and consumers will have different reactions to these regulations. However, it is encouraging that these systems are moving closer together rather than diverging in various aspects.

1.4 Outline of Dissertation

Chapter 2 discusses the research foundations of the work. The work is based on engineering and design, environmental improvements, and business strategy. Chapter 2 presents research initiatives in each of the fields that have been integrated and form the basis of this work.

Chapter 3 is devoted to describing Design for Environment, focusing solely on the end-of-life concerns in product design. This chapter examines the different definitions of possible end-of-life treatment. The justification of the end-of-life strategy hierarchy is derived from life cycle analysis data. It also presents current end-of-life research, based on product and process perspectives. Understanding the basis and the current research in this field provides background for the research contributions outlined in other chapters.

Chapter 4 focuses on the development of the End-of-Life Design Advisor (ELDA). The End-of-Life Design Advisor determines the appropriate end-of-life strategy based on technical product characteristics. This chapter describes the evolution of the technical product characteristics based on case studies and expert opinion. The statistical method of classifying products based on technical product characteristics is explained. This chapter describes the development of the end-of-life strategy categorization based on statistical analysis applied to six technical characteristics across thirty-seven products from the electronics and appliances industries. The dissertation presents the development of a web-based application, End-of-Life Design Advisor (ELDA).

Chapter 5 demonstrates the validation and evaluation of the ELDA method. The products' classified end-of-life strategy and industry practice are compared and analyzed. Agreement between ELDA and industry practice validates the method. It is shown that ELDA succeeded in classification of product end-of-life strategies in agreement with current industry practices. The mismatch between ELDA and current best practice identifies areas for improvement in design and business practices. The application of ELDA to the case studies provided by Philips Consumer Electronics yields interesting results that are relevant to the evaluation of the model and understanding the implications of the work.

Chapter 6 discusses other factors influencing ELDA's recommendation including the Environmental Value Chain and market developments. Work that examines environmental value relationships that are particular to a company (internal value chain) and business in general (external value chain) is presented. The market developments, or changes of product functionality over time, are discussed as well.

Chapter 7 describes the implications of this work on decision makers, including product designers, recyclers and policy makers. Chapter 7 explains the impact of these tools in application and the usefulness to decision makers. The focus is placed on product designers and managers, including a brief description of the impact of decisions made by recyclers and policy makers. Companies and other organizations, both governmental and non-governmental, seeking to establish product end-of-life treatment systems can learn from this research on product end-of-life strategies.

Chapter 8 summarizes the main research points of this dissertation. It summarizes the crucial lessons and observations resulting from the research. In addition, this chapter identifies opportunities for future research. Chapter 8 presents new avenues for research through creating minor ELDA changes, applying ELDA 'in reverse' and developing a methodology for Environmental Value Chain Analysis.

1.5 Conclusion

Motivation for this work was provided by pressure from consumers, competitiveness issues and legislation. Consumers typically target a particular company, whereas the legislation concerning end-of-life treatment targets entire sectors of products. The underlying common goals are to reduce landfilled material, maximize recycling and control environmentally relevant substances.

The goals of this research are to help designers and product managers understand possible end-of-life strategies and to identify the strategy appropriate for their product. This research develops a method that relies on designer knowledge about the product and also presents necessary analysis on the end-of-life strategy. Understanding possible end-of-life strategies as well as their implementation can help address the environmental impact of the a product's end-of-life.

This research is based on three distinct areas of knowledge – engineering, environment and strategy. To date, there has been a lack of research and methods that link these three together as well to focus on product end-of-life. Previous research on product end-of-life has been excessively aimed at design, losing sight of environmental engineering metrics and lacking an underlying strategy.

2 RESEARCH FOUNDATIONS

Chapter 2 discusses Design for Environment in general, with a specific focus on product end-of-life phase. The work is based on three fundamental areas of research – environment, design and strategy. These individual research areas are described in the first three sections of this chapter. Chapter 2 presents research initiatives in each of the fields that have been integrated and form the basis of this work.

2.1 Environmental Foundations

Design for Environment covers a wide range of product development activities including choosing appropriate materials, examining the product usage phase to reduce environmental impact, designing for energy efficiency, minimizing industrial residues during manufacturing, designing for end-of-life, improving packaging and reducing use of environmentally relevant substances. Design for Environment is a subset of the work done in Industrial Ecology as well as combining principles from Life Cycle Engineering. While Industrial Ecology supports efforts by scientists and researchers on such varied topics as global warming, nonrenewable resource depletion and Life Cycle Assessment, Design for Environment focuses on efforts by producers and manufacturers to reduce product or process impact on the environment. By incorporating more principles from Life Cycle Engineering, efforts can be made where and when they can have the most impact.

2.1.1 Industrial Ecology

Industrial Ecology is focused on management of resources. Industrial Ecology is a systems view of manmade environment in which activities are managed so as to optimize resource, energy, capital and use for sustainable development. Industrial Ecology examines all industrial processes as a system that interacts and influences the biological ecosystem. Graedel and Allenby (Graedel 1995) in their book state "this systems oriented vision accepts the premise that industrial design and manufacturing processes are not performed in isolation from their surroundings, but rather are influenced by them, and in turn have influence on them." Industrial Ecology applies both to processes and products and aids in the evaluation and minimization of environmental impact. Another research area is material flows or cycles, techniques for tracing material use and location over time. Topics at the latest Gordon Research Conference on Industrial Ecology include carbon cycle engineering, forestry management, product life cycle management, and moral, ethical, and cultural dimensions of earth systems engineering.

Managing potential toxicity is a more important issue in managing products and the environmental impacts of products. Increasingly circuit boards and computer chips are concentrating environmentally relevant materials, presenting challenges at the end-of-life. As computer chips and electronics move from current applications to wider applications (i.e., hand-held devices, control systems, sensors, etc), more and more products contain electronics that will need to be disposed of. Therefore, better management of end-of-life and managing resources consumed is necessary in order to reduce environmental impacts.

Biological studies have shown that increased industrial activity indeed impacts the natural ecosystem. Many chemicals have proven hazardous or toxic to animals and plants. Controlling these substances is essential to limiting further damage to the natural environment. There are chemicals that are banned by international treaties (i.e., CFCs). Metals frequently used in electronics or printed circuit boards have proven toxic when emitted to air, water or ground, finding their way to vegetation or animals. As companies take a more proactive role in providing a clean and safe environment, many have established lists of controlled substances, or substances that should not be used in products or processes. These initiatives have been well received by environmentalists, who continue to raise concerns for the protection of natural ecosystem.

2.1.2 Life Cycle Engineering

Life Cycle Engineering is the engineering and design of products and processes to minimize the cost and environmental impact for the life cycle phases of a product. The first stage in the life cycle of any process is the extraction of resources from their natural reservoirs (Graedel 1995). The extractive activities considered are those used to produce the consumable resources used throughout the life. Material extraction is the process of retrieving valuable materials from layers of the earth’s crust. Examples of materials with high extraction costs (environmentally and monetarily) are gold, aluminum and uranium. Recycled materials are nearly always preferable to virgin materials because the (1) avoid the environmental disruption that virgin material extraction involves, (2) generally require less energy in recycling than would be required for virgin material extraction, and (3) avoid landfilling or disposal of the material being recycled. Figure 2-1 provides a generic representation of the product life, flowing from material extraction to product end-of-life.

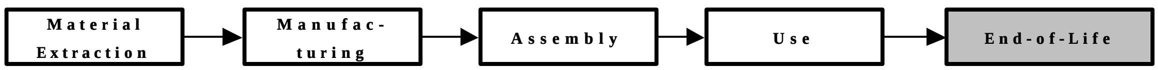


Figure 2-1. Generic representation of product life cycle

Manufacture of a product is the steps or processing of the materials into parts. These parts and processing techniques are quite diverse based on necessary performance characteristics. Assembly is the phase in which manual or automated processing is used to join or integrate the various product parts. Depending on the complexity of design, this phase varies from two steps to thousands of steps. The use of the product pertains primarily to the amount of time the consumer owns and operates the product. Obviously, energy consumption is included in usage of product. Packaging has a short lifetime although provides critical functions such as protecting product, providing information and simplifying storage, handling and transport. Lastly the end-of-life is the final processing of a product for disposal, incineration, recycling, remanufacturing or other end-of-life processing.

A product being designed can be optimized for individual life cycle phases. However, life cycle engineering, or the life cycle perspective aims to optimize these stages together, instead of separately. The process requires tradeoffs to develop the optimal product that balances the gains and losses in the following focal areas: energy usage, material usage, packaging, chemical content and end-of-life. Products, under development, can be specifically designed to accommodate a preferred end-of-life, only by understanding the possible ramifications to other life cycle phases. The life cycle approach is of crucial importance for ecodesign since it allows for environmental impact to be prevented in such a way that the best solution is chosen for the whole life cycle. A company can select those suppliers who generate the least pollution in each individual phase. This paves the way for a concerted effort to reduce the total environmental load of the product in cooperation with suppliers, distributors, users, recycling companies and waste-processing firms.

Televisions pose a unique challenge for balancing the product life cycle. Based on Life Cycle Assessment studies at Philips Consumer Electronics, the environmental impact of manufacturing is 396 millipoints and environmental impact of the usage based on energy consumption is 1611 millipoints (Reijnen 1999). The product is an ideal candidate for reductions in energy consumption during use and previous redesigns have achieved 39% reduction in energy consumption compared to previous models (Stevels 1999). The reductions in energy consumption affect the product end-of-life stage. For example, if a television is used for twenty years, the environmental impact is much greater than recycling the product after ten years and purchasing a new product.

The product end-of-life has increasing importance due to consumer interest and market activity. Market forces, especially in business-to-business activities, are encouraging companies to examine more closely the treatment of the product at end-of-life. There has been little investigation into the strategy of managing the product end-of-life. Frequently, decisions are made without strategy, resulting in higher costs and lower success. To date, there is little published research in this field.

The challenge for the OECD (Organisation for Economic Cooperation and Development) and other regulatory entities is to encourage the continuation and expansion of these current and future initiatives, while allowing for local governments, third party recyclers and other others to participate in recycling efforts. It should be emphasized, of course, that managing products at the end-of-life is just one stage in the product life cycle and may not even result in the greatest reduction of environmental impact (EIA 1999).

2.1.3 Life Cycle Analysis

Life Cycle Assessment (LCA), a validation technique, is a broad methodology for identifying environmental burdens that arise from products through the material suppliers, through manufacture, use and disposal (SETAC 1991, EPA 1993). LCA seeks to examine the complete environmental perspective, including in the analysis of, for example, electricity generation, infrastructure and other items which are not be directly influenced by the designer or industry. LCA is not very suitable for generating green design options, because ideas generated from the results go beyond the scope of influence of designers (Brezet et al. 1999). LCA has limited applicability because, as a holistic approach, it requires delineation of all environment effects irrespective of their position in the life or their origin (Stevels 2000b). LCA can not appropriately separate internal and external issues – which makes the application to industry near impossible. LCA unfortunately does not adequately describe product end-of-life issues, because of difficulties in defining boundaries, embedded toxicity, emissions and environmental impact of end-of-life treatment systems.

2.2 Engineering Design Foundations

2.2.1 Design

Design can be described as a set of decisions taken to solve a particular set of product requirements. Figure 2-2 shows generically how decisions made concerning manufacturing, distribution, marketing, consumer usage, servicing and end-of-life can be influenced by critical decisions made during product design. Within the product development process, the there are several phases: idea generation, product definition (also called product planning), conceptual design, detail design and embodiment design. Graedel and Allenby cite design as the stage that has the strongest influence on environmental impact (Graedel 1995). It is important to use product information available to design engineers and recycling technology developers *early in the development cycle*.

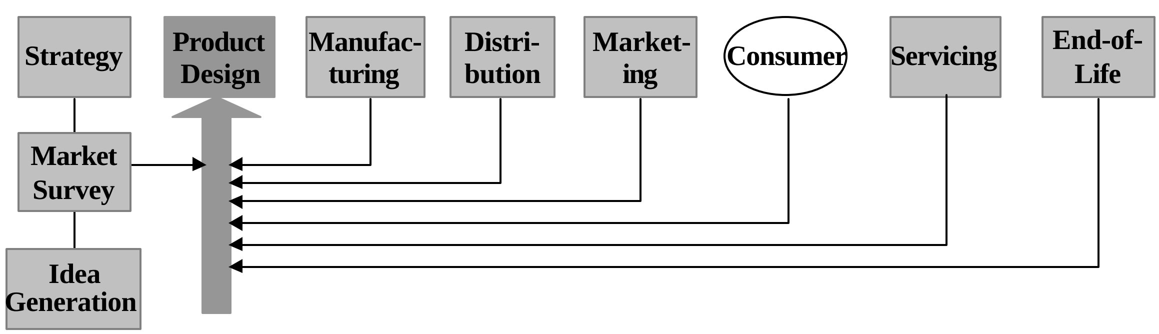


Figure 2-2. Representation of design process

Product definition is an initial and crucial stage in the product development process. It is at this stage where the environmental attributes of a product can be identified and built into the design. It is important to recognize that DFE will require some portion of the designer's effort, and that, like all other aspects of design, thoughtful choices made early in the design process are by far the most cost-effective. These tools are typically applied as early as possible to have the most influence. During the product definition phase of product development, companies decide strategic issues associated with supply chain, life cycle support and manufacturing management.

The conceptual design phase is the most important phase in concurrent engineering after the project planning phase or product definition. Approximately eighty percent of a product's life cycle costs are committed through design choices, such as materials and manufacturing process selections in this phase. Conceptual design comprises concept definition, exploration, evaluation and selection (Allen et al. 1998).

Detail design embarks on the actual physical design of the product using CAD models to determine the physical worthiness of the product. Often times, design problems found later on in the design process (embodiment or detailed design stages) cause costly and time consuming redesigns of the product extending the product's delivery or introduction to market.

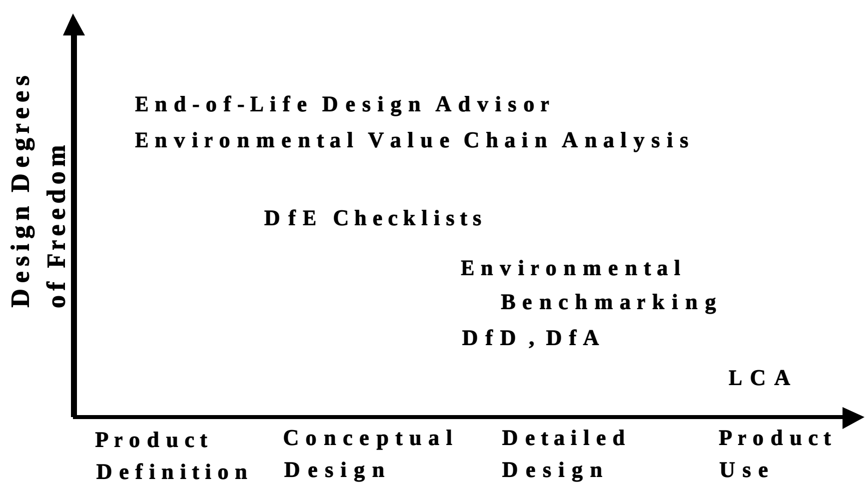


Figure 2-3. Degrees of freedom in various stages of design (Design for Environment)

Figure 2-3 shows the different design stages and the degrees of freedom to change design. Several Design for Environment tools are listed with their corresponding focus area in design. Tools that are useful at product definition stage include the End-of-Life Design Advisor and Environmental Value Chain Analysis. Design for Environment checklists guide aspects such as material selection and are appropriate at conceptual design. Design for assembly and disassembly are appropriate for the detailed design stage. Life Cycle Assessment (LCA) is only possible at the product use stage, after data regarding energy consumption can be collected. Interviews conducted at Cranfield University reveal the need for 'quick and dirty' tools to be used early in product design (Evans et al. 1999).

Environmental benchmarking is an effective engineering and environmental tool for comparing products of similar functions or in similar market segments (Jansen et al. 1998). There are five categories which the products are rated – energy usage, environmentally relevant materials, end-of-life, material composition, and packaging. This tool has proved effective in comparing and understanding products to gain insight into possible improvements. Environmental benchmarking is limited because it requires finalized products and competitors to compare against.

2.2.2 Design for X

The marketplace for manufactured products has become increasingly competitive with ever more discriminating customers. Along with those changes, the requirements of product design have steadily expanded. In order of their organizations to remain competitive, product developers are no longer able to optimize the design with respect to just the traditional functional (i.e. performance) requirements of the product. They must insure that the product excels in all other aspects that lead to customer satisfaction and product profitability such as cost, quality, reliability and environmental impact (Sarbacker 1998). Experience has shown that with challenges in process (either manufacturing or assembling products), it is best to address the core problem and take efforts to improve the product rather than reacting to the symptoms. Product improvements are more crucial in this case, and this logic follows to addressing environmental concerns. It is best to improve the source, or the product, and then examine the process.

Design for X is an integrated approach to designing products and processes for cost-effective, high quality life cycle management. Design for X, or DfX, tools help to shift the emphasis of the important design decisions to the start of the development process. To support the additional requirements of product developers, a variety of product development methodologies, collectively known as 'Design for Manufacturability' or 'Design for X', have been developed to help achieve the diverse product requirements. Some methodologies include:

- Design for Assembly (Boothroyd et al. 1994, Kmenta 2000)
- Design for Process / Design for Producibility (Bralla 1986)
- Design for Serviceability (Gershenson et al. 1991), Design for Ownership Quality (Kmenta et al. 1999)
- Design for Environment (Graedel 1995), Design for Product Retirement (Ishii et al. 1994), Design for Recyclability (Ishii et al. 1996), Design for End-of-Life (Rose et al. 2000d)
- Design for Product Variety (Martin 2000)
- Design for Supply Chain (Esterman et al. 1999)

As research continues in the field of Design for X, more techniques focus efforts on product definition phase of the product development process, where there is more impact on the product for the work expended.

Several tools developed at Stanford address needs of designers to have structured methodologies available to implement during early design stages. Value Feasibility Evaluation Method, Design for Variety, Design for Producibility, Advanced Failure Modes and Effects Analysis are all examples of DfX tools. These DfX tools request appropriate information or input from designers and provide relevant analysis to reduce risk, variety costs associated with excessive redesign, design costs for assessing plastics applications, product failure, respectively. Each of these tools is unique but all bring data from life cycle into the earlier stages of design. ELDA follows in the line of methodologies, providing crucial information concerning end-of-life planning early in the design process.

2.2.3 Design for Environment as part of Design for X

Design for Manufacture was seen as an operative paradigm, with the decades of research into Design For 'tools and methods' (DFX) providing an excellent base from which to develop Design For Environment (DFE) tools. Design for Environment means that 'the environment' helps to define the direction of design decisions. In other words, concern for the environment is co-pilot in product development. In this process, the environment is given the same status as the more traditional product values such as profit, functionality, aesthetics, ergonomics, image and overall quality. DFE considers the environmental aspects in each stage of the product development process, striving to achieve products that have the lowest possible environmental impact throughout their entire life cycle (van Hemel 1998).

Design for Environment is the systematic consideration of design performance with respect to environmental, health and safety objectives over the full product and process life cycle (Boks 2000). Design for Environment, an integral component of the Design for X paradigm, covers all life cycle stages including material extraction, manufacturing, transportation, usage and end-of-life phases.

Design for Environment seeks to understand the life cycle of the product and its impact on the environment at each of its life stages and to make better decisions during product design so that environmental attributes of the product are kept at a desired level. Design for Environment must occur early in the design phase to ensure that the environmental consequences of a product's life cycle are taken into account before any manufacturing decisions are committed. Functionality of the product also contributes to the environmental consequences, which is also committed very early in product design. A majority of possible product end-of-life costs (or yields) are committed during the conceptual design stage. The challenge is to provide as much relevant information as early as possible to proceed with design. Given both the internal and external impetus for environmentally responsible design, DFE should be a component of the product definition and creation cycle (Graedel 1995).

2.3 Business Strategy Foundations

The past decade has seen an increased awareness of environmental issues of products by manufacturing companies. The primary interest was through technical and technological approaches (Design for Environment or Ecodesign, as called in Europe). Subsequently, proactive companies have expanded this concept: environmental strategy, environmental validation from a scientific, compliance or customer perception perspective. Twenty-first century business practices will increasingly move toward product-design and manufacturing decisions that routinely blend in environmental considerations. Moving toward this industrial ecology involves experimentation in product development and new technologies as well as in organization strategy and institutional design (Scarlett 1999). Companies are learning the hard way how to develop appropriate environmental strategies, by trial and error.

Previous approaches do not adequately incorporate all variables associated with the product development and are lacking a strategic point of view, or the ability to prioritize environmental improvements based on impact reduction and investment required. In order to prioritize, it is necessary to understand the products, the product development process, the company and the company's stakeholders. A company has to make sure it is putting effort and making investments in the 'right' environmental aspects. If a company has chosen a direction that turns out to be less rewarding in terms of environmental and business aspects compared to other options it will result in inefficiency. Such a business risk can be reduced when the appropriate direction is chosen.

A critical phase for deciding the product strategy is product definition. Product definition encompasses the up-front 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 (Wilson 1990). These notions of product positioning, strategic alignment, regulation compliance are critical to the development of the company's environmental strategy. Designers typically have strong influence over these factors during product definition. Wilson cites that the most common causes of project failure are the incomplete understanding of these issues shared by the product development team and other stakeholders. Frequently, failing to identify the world-wide regulatory issues relevant to the project can cause shortfalls.

An example tool available to aid in development of design strategy is the Ecodesign strategy tool. Van Hemel's Ecodesign Strategy wheel visualizes ecodesign strategies, which can be compared to previous or future target areas. Her work identifies over thirty generic ecodesign strategies for improving the life cycle impact of electronic products (van Hemel 1998). The ecodesign strategy wheel is used as a general framework, provoking new improvement options. While the Ecodesign Strategy wheel includes environmental prioritizing, relevant drawbacks are the lack of feasibility assessment and business conditions.

STRETCH, acronym for the Selection of sTRategic EnvironmenTal CHallenges (Cramer et al. 1997) includes business and managerial aspects into their environmental strategy model. Taking into account the Business Groups' strategy, future demands of stakeholders, including suppliers and customers, gives the tool a stronger position to be applied in business. Through application at Philips Consumer Electronics, Akzo Nobel, and various other businesses, STRETCH proves integral to general business planning, especially when embedded in the organization and adapted to related activities.

The Ecodesign matrix, used at Philips Consumer Electronics, is similar to a Pugh Concept Selection Method (Stevels 1999). The Ecodesign matrix, shown below, analyzes the benefits of implementing a new design option to the stakeholders first. Only after the benefits to the environment, business, customer and society have been assessed is the technical and financial feasibility analyzed. Proceeding in this order allows for more idea generation before options are limited by monetary or technological concerns. Many times the environmental benefits perceived by the customers and other stakeholders are more important than scientific calculations of environmental gains. The Ecodesign Matrix guides designers to prioritize their efforts, choosing the options that yield the highest environmental impact reduction for the expenditure or effort. It also allows designers to categorize the benefits and decide which benefits are crucial to the business.

Table 2-1.Ecodesign Matrix

GREEN OPTIONS	ENVIRON-MENTAL BENEFIT	BUSINESS BENEFIT	CUSTOMER BENEFIT	SOCIETAL BENEFIT	FEASIBILITY	
					Tech-nical	Finan-cial
Option A						
Option B						
.						

Within the field of engineering, especially in industrial engineering, and at many leading business schools, supply chain management is an important research area. Supply chain management seeks to optimize the supply of services and products to customers. Improvements to flow and supply of products and services to consumers have proved quite beneficial, financially and image-wise to companies. Unfortunately, to date, the techniques have only been used to streamline the relationships among producers of a product and the consumer of the product. In managing supply chains, the chain is normally divergent with products being produced in several locations but then delivered throughout the world. The opposite is true for inverse supply chains where the products must be collected from diverse sources. Work in so-called inverse supply chain is slowly gaining speed in the research field. Ideally, integration of forward supply chain with inverse supply chain flows would be more desirable, but much more complicated. Purdue University is conducting ongoing research that seeks to develop supply chain models that include recovery of returned products, disassembly and remanufacturing (Uzsoy 1998). AT&T is developing relationships with suppliers to manage products at end-of-life in addition to providing normal services during product use (Blazek et al. 1998).

As consumers and businesses move towards more environmental initiatives, an environmental strategy is crucial for formulating all the actions to be taken to realize the vision in a given period of time; the results of the external and internal analysis are taken into account. Strategy formulation starts with a thorough analysis of the current environmental position of the product line, both in technical, industrial and commercial terms. The most successful tools aid in concept generation while giving designers and managers the freedom and guidance to make decisions.

2.4 Conclusion

Competitive pressure, consumers and policy makers push for better management of the product end-of-life. Producers and recyclers need tools and methods to help assess the end-of-life strategies appropriate for the product. The method must draw from engineering, strategy and environment.

Environmental issues combined with engineering and strategy research addresses the complex problems of determining end-of-life strategies appropriate for products. Many other methods are useful to draw results from but are not directly applicable. Pulling together these diverse fields is complicated but must be accomplished to reach a solution.

As applied together to address the concerns of product end-of-life stage, the method developed is powerful. There is some clarification needed for the end-of-life point as well as how end-of-life strategies are defined in this work. Previous work in this field of product end-of-life is helpful to understand the context into which ELDA fits.

3 PRODUCT END-OF-LIFE STAGE

Chapter 3 is devoted to describing Design for Environment, focusing solely on the end-of-life stage. This chapter provides the justification of the end-of-life strategy hierarchy. It also presents current end-of-life research, divided by focus on product and process improvements. Understanding prior and current research in this field provides background for the research contributions outlined in subsequent chapters.

3.1 Product End-of-Life Considerations

Reducing product environmental impact at all life cycles is an important topic for manufacturers of electronic and electrical products. As mentioned in Chapter 1, product end-of-life is only one aspect of product life that is 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 and understanding of the product end-of-life is crucial to moving towards reduction of the environmental impact and reducing hazardous materials remaining in the environment.

3.1.1 End-of-life Definition and End-of-Life Strategies

The definition of end-of-life used throughout this work is the point in time when the product no longer satisfies the initial purchaser or first user. This allows for reuse in addition to recycle as possible end-of-life strategies. The definition adopted in the current research is chosen because user preferences change more rapidly than the product wears out in several product categories. Other definitions start from the last user, but do not include high eco-efficient end-of-life strategies such as reuse and service as strategies to improve product end-of-life performance. Others define end-of-life as the point at which the product no longer performs the intended functions due to failure or wear-out. Other definitions do not appropriately account for changes in customer preferences.

End-of-life strategies describe the approach or method associated with dealing with the product at the end-of-life. End-of-life treatment includes the activities associated with recovering value from the product, through manual labor and/or machinery. The end-of-life system includes the activities associated with strategic planning and implementation ranging from the collection of products, treatment of those products and the associated impacts to society and environment.

Based on work in (Overby 1979, Ishii et al. 1994, Luttrop 1997, Mackenzie 1997, Nilsson 1998), table 3-1 outlines the following end-of-life strategies.

Table 3-1. Definitions of End-of-Life Strategies

NAME	DEFINITION
Reuse	Reuse is the second hand trading of product for use as originally designed.
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.
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.
Recycling with disassembly	Recycling reclaims material streams useful for application in products. Disassembly into material fractions increases the value of the materials recycled by removing material contaminants, hazardous materials, or high value components. The components are separated mostly by manual disassembly methods.
Recycling without disassembly	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.
Disposal	This end-of-life strategy is to landfill or incinerate the product with or without energy recovery

Figure 3-1 shows these end-of-life strategies as part of the hierarchy, including closed and open loop strategies and is based on Ricoh's comet diagram (Tani 1999). Closed loops are preferable from an environmental perspective because they make use of resources and value already added to the natural resources, rather than open loop which landfills or incinerates the materials. The smaller loops represent a more efficient end-of-life strategy with less reprocessing of the materials for reapplication in products. The user is the focal point on the diagram. The products are finished being used by the consumer, there are a variety of strategies the product can take – reuse, service, remanufacture, recycle with separation, or recycle without separation and disposal either in landfill or through incineration.

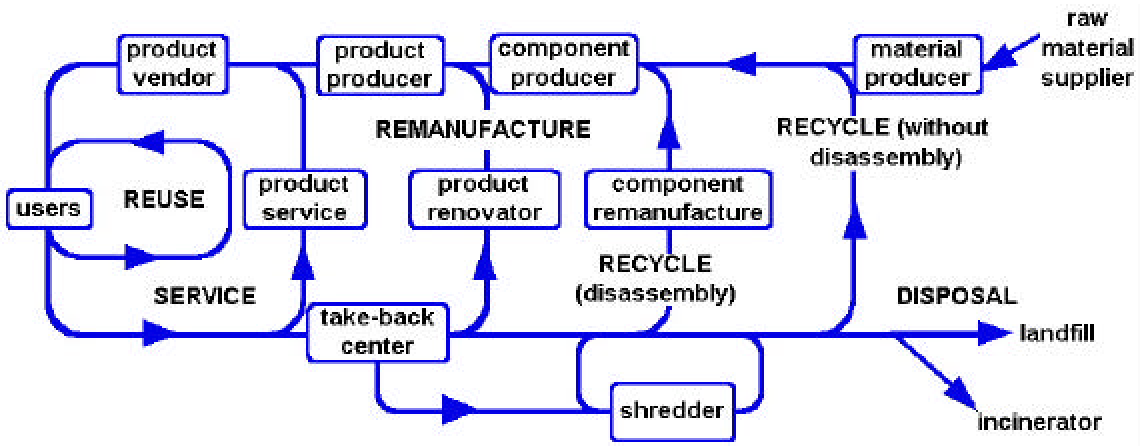


Figure 3-1. Modified Ricoh Comet Diagram depicting product end-of-life strategies

Along the top line are the material producers, manufacturers, assemblers and original equipment manufacturers. The bottom line includes collection facilities and recycling companies. The middle group provides service to move the products from the recycling infrastructure back to the manufacturers and include such activities such as service, product renovation and component remanufacturing (Tani 1999).

Disposal is not a focus area of the current research because of increasing costs associated with landfilling or incinerating products at the end-of-life. Landfill closure and escalating landfill costs make 'classic' landfilling of products cost prohibitive.

For comparison, other definitions of end-of-life options are presented. End-of-life definitions, given in the Dutch Promise Manual (Stevels 1997), are:

- Reuse the product as a whole, either for the same or a new application
- Reuse sub-assemblies and components by remanufacturing and refurbishing
- Recycling the materials involved by 1) recycling in the original application (primary recycling); 2) recycling in a lower-grade application (secondary recycling); 3) recycling of plastics by decomposing their long plastic molecules into elementary raw materials which are subsequently reused in refineries or for the production of petrochemicals (tertiary recycling, also known as feedstock recycling);
- Safe incineration with energy recovery and waste disposal 1) incinerate non-reusable materials by using energy generation technology and good flue gas purification (quaternary recycling, also called thermal recycling); 2) incinerate non-reusable materials without energy generation technology but with flue gas purification; 3) dispose of the residual material in a controlled fashion as solid waste

- Incineration without flue gas purification and uncontrolled dumping fall under the category of prohibited options.

Ishii and others describe the following end-of-life strategies (Ishii et al. 1994):

- remanufacturing / reuse: the use of parts “as-is” or after minor repairs or overhauls;
- primary recycling: processing of materials into another “high-value” application;
- secondary recycling: processing of material into a “low-value” application ;
- disposal: landfilling or incineration)

Still others give the following definitions for the possible end-of-life strategies (Ijomah et al. 1999):

- Reuse: process of using a functional component from a retired assembly
- Repair: process of bringing damaged components back to a functional condition
- Reconditioning: process of restoring components to a functional and / or satisfactory state but not above original specification using such methods as resurfacing, repainting, sleeving, etc.
- Remanufacture: process of bringing an assembly to like-new condition through replacing and rebuilding component parts at least to current specification
- Recycling: process of taking component material and processing them to make the same material or useful degraded material

3.1.2 Justification of Hierarchy of End-of-Life Strategies

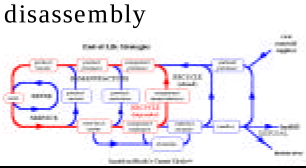
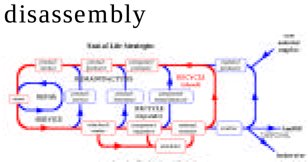
The highest on the hierarchy according to calculated environmental impact analysis is reuse, then service, remanufacture, recycling and last disposal either through incineration or landfilling. Ranking highest is product life extension through reuse of the product. Moving towards reuse of the product as a whole is an ideal solution for the product end-of-life to minimize environmental impact. As well, extending the product through servicing is second on the hierarchy. The next strategy is reuse of subassemblies and components through remanufacturing. Recycling with and without some disassembly first leads to two applications - into the original application (frequently called primary recycling) and recycling in a lower-grade application (called secondary recycling). In the case of secondary recycling, the material quality does not meet the original specifications, but still can be used in applications such as plastic park benches and garbage cans. Lowest on the hierarchy of end-of-life strategies is disposal of the product through either incineration or disposal. The aim of this calculation is to identify the environmental impact of each end-of-life strategy and verify that the end-of-life strategy hierarchy given in Table 3-1 is correct (details of calculation included in this section).

Philips Consumer Electronics Environmental Competence Centre performs extensive case studies that examine energy usage, environmentally relevant materials, end-of-life, material composition, and packaging. In order to quantify the product's environmental performance, the products are disassembled and the material content, manufacturing process and weight are identified. Philips researchers have performed this environmental benchmarking on approximately seventy consumer electronic products.

Philips' Environmental Competence Centre then uses this information to perform a life cycle analysis on the product using Ecoscan (Goedkoop et al. 1996, ten Houten 2000). Ecoscan, like most Life Cycle Assessment (LCA) tools, examines the entire life cycle of the product, from extraction, manufacture, packaging, usage to end-of-life. While there are certain limitations in applying LCA, the analysis of environmental impact of end-of-life strategies can be derived from such results. The Ecoscan results are given in millipoints, quantifying the environmental impact of the product. Higher values denote greater environmental impact.

The environmental impact of a product's end-of-life can be modeled using data from these case studies. The environmental impact analysis results are crucial for determining the environmental impact of different product end-of-life strategies. The manufacturing environmental impact includes extraction and manufacturing processes. For some materials the extraction environmental impact is much higher than the manufacturing processing. The environmental impact quantifies the impact of usage conditions (batteries or grid electricity), as well. Packaging environmental impact accounts for the impact of plastic, cardboard and paper used in packing materials. In the current calculation, the end-of-life impact is only accounted for by the disposal through incineration. The previous table shows the impacts and bonuses for the environmental impact calculation. The percentages shown for recycling material retrieval are reasonable assumptions based on observations of current recycling processes (Mattos 1999).

Table 3-2. Impacts and bonuses identified by environmental impact analysis

END-OF-LIFE STRATEGY	ENVIRONMENTAL IMPACT	ENVIRONMENTAL BONUS
Reuse 	Only original manufacture needed.	
Service 	On average, 10% of parts needed for repair, therefore these parts must be manufactured.	
Remanufacture 	On average 40% parts replaced during remanufacturing of product, therefore these parts must be manufactured	
Recycling with disassembly 	Replacement product is manufactured from virgin materials.	Recycled Material: Electronics-100%; Glass-80%; Metals-100%; Plastics-100%; Wood-0%
Recycling without disassembly 	Replacement product is manufactured from virgin materials.	Recycled Material: Electronics-90%; Glass-0%; Metals-90%; Plastics-20%; Wood-0%
Disposal (either landfill or incinerate)	Replacement product is manufactured from virgin materials.	

To consistently perform an environmental impact analysis across all possible end-of-life strategies it is necessary to determine a reference point. Assuming that a product is introduced to the market, used for 10 years and then reaches 'end-of-life', how much environmental impact is there to deliver the product in 'resellable' condition? For example, a product that will be reused, does not need any new manufacturing or end-of-life processing before it is ready for resell. On the other hand, if the product has the end-of-life strategy of recycling – this requires materials to manufacture a new product. Since the original product is being recycled, there will be a reduction in the overall environmental impact based on the percentages of recovered material. The environmental impacts include some or all of the following manufacturing and extraction, energy, transportation, disposal, and packaging, depending on the end-of-life strategy. The environmental bonus is based on percentages of materials recovered from recycling. The resulting units of the equations are millipoints. EI stands for environmental impact and LCA represents the values directly derived from the Ecoscan values.

$$EI_{life-cycle} = EI_{manufacture} + EI_{transportation} + EI_{packaging} + EI_{usage} + EI_{disposal} + EB_{bonus} \quad (3.1)$$

$$EI_{manufacture} = (1+x)LCA_{manufacture} \quad (3.2)$$

The value x in equation 3.2 is the percentage of the product that must be manufactured for the second life. The values range from 0% (for reuse), 10% (for service), 40% (for remanufacture), 100% (for recycle and disposal).

$$EI_{transportation} = 1.131 \bullet y \bullet w \quad (3.3)$$

In Equation (3), the transportation required is the distance (y) between the end-user and the recycling or recovery facility and ranges from 20 miles for reuse and 100 miles for disposal. The variable w is the weight of the product in kilograms. The value, 1.131, has units millipoints per mile-kilogram (derived from the Philips Eco-indicator database).

$$EI_{packaging} = LCA_{packaging} \quad (3.4)$$

$$EI_{energy} = LCA_{energy(1st-life)} + LCA_{energy(2nd-life)} \quad (3.5)$$

$$EI_{disposal} = 2.1 \bullet w_{electronics} + 2.0 \bullet w_{metals} + 1.8 \bullet w_{plastics} + 0.8 \bullet w_{misc/glass} + 0.1 \bullet w_{wood} \quad (3.6)$$

Equation 3.6 assesses the environmental impact of the product disposal, as a weighted sum of the weights of the materials. The multipliers are determined with the help of the Philips database (based on Life Cycle Assessment studies) and are given in units of millipoints per kilogram. The variable, w, is the weight in kilograms of the material fraction.

$$EB_{bonus} = -(0.8 \bullet LCA_{electronics} + 1.0 \bullet LCA_{metals} + 0.8 \bullet LCA_{plastics} + 0.8 \bullet LCA_{misc/glass}) \quad (3.7)$$

Recycling of the product yields an environmental bonus rather than impact. The recovered material is reapplied, preventing the need to extract more raw materials from the environment. The values are given as the recycling yields, assumed from a disassembly operation. The recycling yields are highest for metals, close to 100%, whereas for wood is 0%.

These assumptions combined with the life cycle analysis data collected on the Philips products, yield environmental impact estimates for various end-of-life strategies. The following table displays the values from the analysis on televisions.

Table 3-3. Environmental Impact Reults for Television

ENVIRON-MENTAL IMPACT (MILLIPOINTS)	REUSE	SERVICE	REMANU-FACTURE	RECYCLE WITH DISASSEMBLY	RECYCLE WITHOUT DISASSEMBLY	DISPOSAL
Manufacturing	396	435.6	554.4	792	792	792
Transportation	0	0.4	2.2	2.2	2.2	2.2
Energy (first life)	1611	1611	1611	1611	1611	1611
Energy (second life)	1611	1611	1611	1611	1611	1611
Packaging	0	0	12	12	12	12
Disposal	0	0	0	2.9	2.9	17
Bonus	0	0	-116.5	-291.3	-76.9	0
Total	3618	3658	3674	3740	3954	4045

The calculations presented in Table 3-3 were performed for each of the products. The following table presents the results of the environmental impact calculation for several Philips Consumer Electronics products.

Table 3-4. Environmental Impact Results for Philips Products

PRODUCTS	REUSE	SERVICE	REMANU-FACTURE	RECYCLE WITH DISASSEMBLY	RECYCLE WITHOUT DISASSEMBLY	DISPOSAL
Cell Phone	88 (63)	93 (66)	95 (68)	105 (75)	122 (87)	140 (100)
VCR	613 (76)	631 (78)	639 (79)	666 (82)	698 (86)	812 (100)
CRT Monitor	1877 (70)	1950 (73)	2035 (76)	2186 (82)	2463 (92)	2679 (100)
LCD Monitor	1942 (57)	2083 (62)	2473 (73)	3223 (95)	3260 (96)	3384 (100)
Portable CD Player	2590 (98)	2596 (98)	2609 (98)	2632 (99)	2636 (99)	2652 (100)
Audio Product	3321 (85)	3375 (87)	3357 (86)	3393 (87)	3474 (89)	3892 (100)
Mainstream Television	3618 (89)	3658 (90)	3674 (91)	3740 (92)	3954 (98)	4045 (100)

*Numbers given in parenthesis are percentage of disposal
**Disposal numbers averaged between incineration and landfill

As Table 3-4 shows, the cellular phone has low environmental impact for the end-of-life strategies, ranging from 88 millipoints to 140 millipoints on average. The VCR impacts the environment at 76% for reuse, compared to 82% for recycling with disassembly as a percentage of disposal value. The audio products considered have end-of-life strategies ranging from 3321 millipoints for reuse, 3357 millipoints for remanufacture and 3892 millipoints for disposal. Televisions have environmental impact for the reuse strategy of 3618 millipoints, whereas disposal of televisions has environmental impact of 4045 millipoints. Monitors had higher environmental impact of reuse, 1942 millipoints, compared to the other products. The monitors examined had greater environmental impact during their original manufacture. Appendix II contains more information.

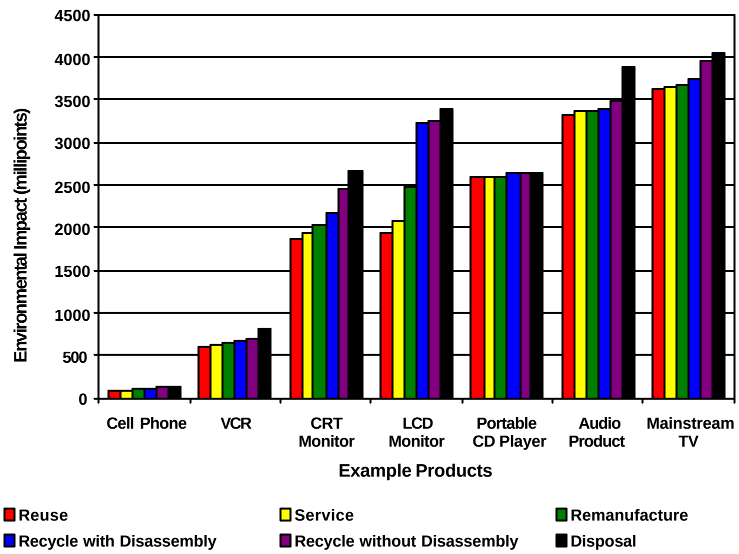


Figure 3-2. Environmental impact of End-of-Life Strategies

The main result from this analysis, as shown in Figure 3-2, is the environmental impact of products does increase from reuse to disposal. This calculation confirms the ranking of the end-of-life strategies in the hierarchy.

However, it is to be noted that in consumer electronics, energy consumption dominates. This makes that between the best (reuse) and the worst (disposal) strategies, difference may be less than commonly perceived. The environmental impact of reuse compared to disposal for televisions is 89%, for VCRs 76%, for cell phone 63% and the highest for portable CD player -- 98%. The following chart shows the environmental impact data for all end-of-life strategies as percentages of disposal environmental impact. For example, if the environmental impact of disposing of a cellular phone is 100%, then reusing the cellular phone has environmental impact of 63% (a 37% reduction).

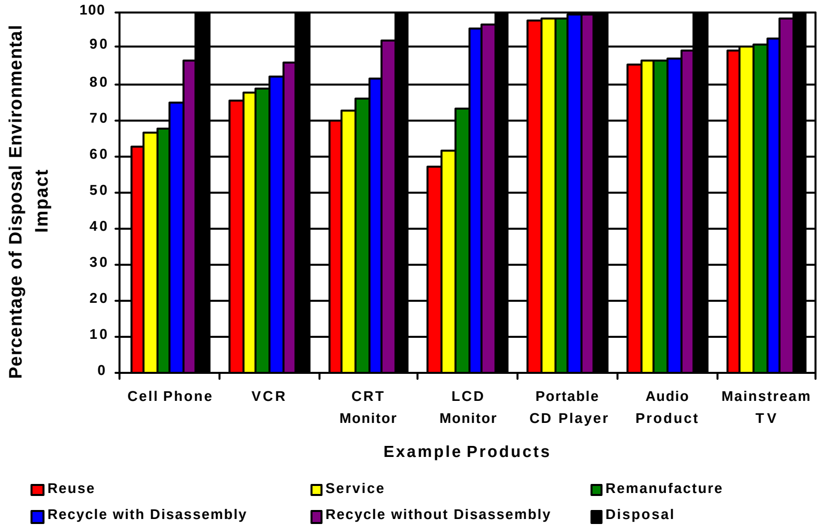


Figure 3-3. Environmental impact of End-of-Life Strategies compared to disposal

The end-of-life strategy hierarchy represents a ranking of the possible end-of-life strategies from least to greatest impact on the environment. The calculation of the environmental impact of end-of-life strategies is an original contribution in this work.

3.1.3 Knowledge of End-of-Life Strategies

There are benefits from operating at different levels of the end-of-life strategy hierarchy (Copper 1994). Products have different characteristics that determine the end-of-life strategy possible. Determining the end-of-life strategy is necessary in order to improve the product. The end-of-life strategy allowable depends on product characteristics. Inappropriately applying design rules or a design strategy for a product's end-of-life can lead to inefficiency. The design rules for life extension, product reuse, component reuse and material reuse are not the same: they can sometimes counteract one another.

Knowledge of the product characteristics allows designers to determine the end-of-life strategy early in the product design. The fact that different end-of-life strategies have varying environmental impact (as illustrated in Table 3-4) identifies opportunities to move to higher levels on the end-of-life hierarchy. For example, through use of technical product characteristics, it is possible understand why plastic or metal dominated products differ in their end-of-life treatment.

Being aware of the strategic issues associated with different end-of-life strategies is necessary to improve the product design. Some examples from Appendix B of the Dutch Promise manual (Stevels 1997) of issues relevant for different end-of-life strategies are, as follows:

- Reuse: In the event of product reuse it is important that the manufacturer knows how much expert knowledge is available in the (repairs) firm; the product will bear the manufacturer's name in its second life too, not the name of the firm that has repaired it.
- Remanufacturing/refurbishing: If it is a case of remanufacturing or refurbishing, then it is important that the processing firm guarantees quality and volume. Access to secondary markets – often on other continents – also plays a significant role.
- Recycling: Processing material reuse poses entirely different requirements. The main concerns are the technology available and sufficient economy of scale. For instance, the effective processing of old cars requires a shredder plan with a capacity of 50,000-100,000 tons/year. The high-end engineering plastics used for television cabinets can be recycled profitably on a line that has a capacity of 2,000 tons per year (corresponding to 300,000 televisions a year). Ecologically sound and cost-neutral processing of printed circuit boards calls for a processing line with capacity of 2,500 kilograms per day.
- Incineration: If the products will end up (as whole or in pieces) in incineration plants, then it is important to know what are the restrictions for acceptance: will it be accepted for incineration as household waste or classified under a special category of waste (involving a higher incineration charge)?

Once a designer has identified the end-of-life strategy appropriate for the product, the detailed issues including tradeoffs between different life cycle stage improvements is necessary. For example, a particular end-of-life strategy, such as automated disassembly, may increase service costs. Furthermore, by focusing on service as the assumed end-of-life strategy, the product could have higher shredding costs. For example, a frequently failing part, one that needs to serviced frequently may be made of a more durable material in a following design. This change in material for service needs could then affect the mechanical shredding of the product and may indeed require that the part be removed prior to shredding, adding time and cost.

Knowing the end-of-life strategy of the product also reduces the tedium of calculating environmental impact results for products before making improvements. An advantage with the ELDA classification is the detailed information required by LCA is no longer needed to assess the end-of-life strategy appropriate for the product.

3.2 Product Focused End-of-Life Research

The life cycle perspective includes the take back and reprocessing of the product at its end-of-life – from cradle to cradle. The product being developed can then be specifically designed to accommodate a preferred end-of-life route (Poyner 1997). Environmental impact analysis tools consider specific aspects of the design of a product and are being used at the detailed design stage where it was difficult to employ any of the suggested design improvements (Poyner 1997).

The research areas for improvements to products are diverse. Researchers have attempted to incorporate product 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 data. Other research seeks to improve product modularity. Sosale (Sosale et al. 1997) reports on a study that helps designers form modules and make decisions to enhance modularity. Product modularity can also provide designers with easily detachable subassemblies and components that facilitate remanufacturing, reuse, material recycling and disposal. This research does not provide a mechanism to balance tradeoffs between creating modules appropriate for different end-of-life strategies. The method sub-optimizes because it ignores other life cycle phases such as manufacturing and assembly, that are strongly affected by modularity.

Harper and Rosen (Harper et al. 1998) describe a tool being developed to link qualitative measures of remanufacturability to engineering information embedded in CAD systems. The tool is designed for implementation during detailed design and the user must indicate if the parts will be refurbished, recycled or landfilled. Harper and Rosen suggest, that “the designer typically knows with some degree of certainty the post-life intent of the individual components.” The post-life intent, or end-of-life strategy, can not be determined without extensive knowledge of end-of-life treatment techniques. While uniting CAD and product recyclability information is helpful, it is difficult to make changes in design at these late stages. Furthermore, the research results in specific information concerning the end-of-life of parts, which (1) ignores possible reuse of the product as a whole and (2) assumes the product will undergo some disassembly at the end-of-life.

Other end-of-life product focused improvements demonstrate the use of product embedded sensors. CMU and Bosch have investigated embedded sensors to monitor the conditions of possible reused components (Klausner et al. 1998, Klausner et al. 1999). The use of embedded sensors shows promise in reuse of motors and other parts that are difficult to manufacture, costly to purchase, taxing to the environment, and have remaining use in the market. However at present, adding more electronics to products to sense the wear and record it in memory is not cost effective for all products and may cause greater environmental impact over the product life. This is a promising area of continuing work.

Researchers, through guidelines and manuals, identify principles that should be taken into consideration to facilitate end-of-life treatment. Most of these manuals assume an end-of-life treatment of recycling, mostly through manual disassembly. Contributions from a wide variety of European sources lead the way in this effort (Jovane et al. 1993, Bergendahl et al. 1995).

Unfortunately, these improvements exclusively focus on redesign of existing products and the improvements rely too much on designer perceptions. 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. Other efforts do not address product end-of-life issues until most of the design parameters are set.

An example of industry initiatives associated with improving products is Philips Consumer Electronics' EcoVision Program. The cornerstone of the EcoVision Program is the communication of top achievements as embodied in Green Flagship products to customers and other stakeholders. These achievements come primarily from management of the cross-functional processes around creation, production and marketing and sales of these products (Wilson 1993). The EcoVision Program was introduced top-down in the organization, through initiative and commitment of the president and chief executive officer of the company. Its implementation is now well underway; the Consumer Electronics Division has already achieved impressive results in Green Flagship products such as a television, videocassette recorder, audio systems and telephones (Ishii et al. 2000). EcoVision includes end-of-life as one of the five focal areas and shows good life cycle integration overall. However, it works on a comparative basis, 'better than the competition', and because it is essentially based on current design practices is not likely to generate real innovative improvements.

3.3 Process and Technology Focused End-of-Life Research

This section describes process improvements that address the end-of-life phase of the life cycle. Boks et al (Boks et al. 1998a) have identified various factors influencing differences in end-of-life treatments in Europe, Japan and United States. The study compared various materials recycling techniques as well as remanufacturing of appliances and electronic products in different regions of the world. Their findings included recommendations to legislators, designers and recycling organizers for improved communication and increased research into end-of-life treatment processes.

3.3.1 Remanufacturing

Remanufacturing is the process in which quantities of similar products are brought into a central facility and disassembled. Parts can be reused when the wear-out life is longer than the technology cycle. In most cases, there are important market opportunities for these parts. Lund reports on remanufacturing operations in the United States by product – automobile (46%), electrical apparatus (23%), toner (14%), tires (12%) and other (5%) (Lund 1996). Williams and Shu research areas of remanufacturing including an analysis on the waste streams of a printer cartridge remanufacturing facility to remove obstacles (Williams et al. 2000). Their work explores differences between products and industries in remanufacturing operations. Researchers at Rochester Institute of Technology look at remanufacturing operations including evaluating remanufacturing of printer cartridges (RIT 2000). NJIT is working with automobile demanufacturers to transform the industry from a single station, single worker setting with an output rate of 1 vehicle per 6 hours to a 12 station setting with a rate of 24 vehicles per 6 hours (NJIT 1999). The project focus will be first to develop analytical tools to support this design and modeling process, and second to build testbed prototypes for automotive and electronic industry applications.

3.3.2 Disassembly

Disassembly is motivated by two goals – to obtain pure secondary materials and to isolate environmentally relevant materials from other materials. Disassembly of products into separate materials is just one of many possible end-of-life treatment options. Even though complete disassembly may seem to provide a way of minimizing the damage to the environment, some studies conclude that with the current recycling technology and market prices for recycled materials, complete disassembly is not profitable since the cost of disassembly is more than the market and environmental benefits. Thus, it is important to find a balance between the resources invested in the disassembly process and the return realized from it (Bhamra 1997).

Many researchers are seeking optimal disassembly orders to retrieve highest material value in lowest time and steps. Boks et al. (Boks et al. 1996) address the reuse and material recycling of televisions by comparing assembly times calculated using different methods of disassembly.

Design for Disassembly software tools generally calculate potential disassembly pathways, identify the fastest pathway, and reveal obstacles to disassembly that can be ‘designed out.’ 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, have been integrating disassembly analysis tools in their software (ASME 1998). The software simulates a disassembly process as it would likely take place when the product reaches its end-of-life phase (Knight et al. 1999). Ishii et al (Ishii et al. 1994, Ishii 1995) developed a software tool, LASeR that concentrated on advanced planning for product retirement and addressing the level to which a product should be disassembled. LASeR allows the user to evaluate a design at various stages of the life cycle. After entering the required data into the software’s input stream, the tool displays the disassembly times for components and fasteners, the compatibility index and the retirement cost breakdown for each clump, including reprocessing and disassembly cost.

Other work has also developed methods for disassembly planning using Petri Nets (Feldmann et al. 1997, Moore et al. 1998, Zussman et al. 1998). Moyer and others survey of recycling and the complexity of disassembly (Moyer et al. 1999). These approaches are limited in their modeling of real life situations such as disassembly cost, paths to commercial recycling streams, and fragmentation of parts (Das et al. 1999). Indeed reducing the disassembly time makes separating materials easier at the end of the product's life, but it is only one of six possible end-of-life strategies.

These models may result in optimal disassembly for a product, but it overlooks that it might not be optimal to disassemble the product from a life cycle perspective. This misses the key to the life cycle perspective that optimizing one area may overlook possible improvements elsewhere. For example, optimizing the time to remove a battery overlooks the solution of creating a product that does not rely on battery power. As with other tools such as Life Cycle Assessment, the results from these analyses are not directly applicable to product designers. However, on general terms, lower disassembly times often results in lower assembly times.

Recently researchers seek to improve the actual disassembly of products by novel fastening techniques and automating the disassembly process. Automated disassembly of keyboards and other electronic equipment shows limited application (Feldmann et al. 1996). Products are more diverse and collected products have characteristics too difficult to distinguish through databases and computer control. The demonstration automated disassembly facility in Japan, funded by MITI, relied on extensive databases of product information to control the separation of components (Yoshida et al. 1999). Manual disassembly techniques using innovative disassembly tools show substantial improvement in disassembly times and preserve the intended product use (Eisenreich et al. 1996). NJIT concentrates on development of new types of fasteners that meet design specifications and are quick to assemble and disassemble (NJIT 1999). While the development of special tools for disassembly may be non-destructive, this further complicates the disassembly of the product because the recycler must have the tools unique to the product. These techniques seek to fix the process rather than the product, and will have limited success. Reversibility of locking mechanisms is of special interest, leading to fasteners activated by the insertion of a special purpose tool or an external trigger that will initiate disassembly (Das et al. 1999). Because using adhesives complicates disassembly and recovery of pure material, NJIT hopes to develop new and economical fastener technologies to supplant some uses of adhesives (Das et al. 1999). Other research into disassembly uses smart materials, such as shape memory alloys or shape memory polymers, for releasable fastener devices. Active Disassembly using smart materials demonstrates disassembly of sub-assemblies, unbonded components and constituent assemblies including components such as housing, PCB, LCD, antenna, shielding, transformer, mechanical components, hard and disk drives, and many other fastened components (Chiodo et al. 1999). Masui reports on the investigation of separation using imbedded hotwires for separating cathode-ray tube glass used in televisions and computer monitors (Masui et al. 1999).

3.3.3 Recycling through mechanical methods

Material not disassembled, manually or automatically, can be recycled through mechanical processing lines. A full recovery value from these waste streams requires utilization of a sequence of different steps, for example, shredding, electromagnetic separation, and further size sorting and electrostatic separation. Shredding is the chopping of the different materials to achieve size reduction using hammer, cutting and cryogenic mills.

Micrometallics provides recovery and recycling services for electronic products and components to original equipment manufacturers (Mattos 1999). They perform disassembly, component recovery and testing, shredding, material separation and recovery operations in Roseville, California. The end-of-life materials management facility does not landfill any material, does not use water in the processes and even the filters the exhaust air to remove any dust. They handle a wide variety of products including mainframes, computers, workstations, printers, military equipment, copiers, plotters, telecommunications equipment, and prototype electronic equipment. Since 1996, they have partnered with Hewlett Packard to manage their waste stream and recover value from their used products (St. Denis et al. 1998).

Separation, as the name implies, separates the material fractions based on weight, magnetic and density properties. Ferrous metals are separated by magnets, non-ferrous metals are separated by eddy-current process, plastics are separated by wind sifting, for some examples. While these are the dry processing techniques, there are wet processing techniques such as hydro-cyclone separation, flotation and sink/flow separation. European and Japanese research efforts have made improvements to recycling technology. Outlets for metals already exist on a large scale, especially precious metals where the value is retained and the recovered purity from smelting operations is equivalent to newly extracted metals.

Compared to metal outlets the plastic recycling industry is still in its infancy. The desired quality, which is of the virgin material, of the plastic fraction is not easily obtained. Economically viewed recycling of plastics is not feasible at the moment. This is caused by not being able to know what kind of different plastics are mixed in the recycling process, resulting in unknown chemical properties. MBA polymers, in conjunction with the American Plastics Council, reports that their efforts into identifying plastics on a whole part basis using automated spectroscopic units and manual or automated sorting is not as economically promising as plastic flake sorting (Arola et al. 1999). Their findings indicate that whole part sorting would require extensive particle-by-particle sorting for further enrichment to meet purities exceeding 99% such that the plastic could be used in new durable goods, or for the plastic to have any considerable resale value.

Recycling of toxic wastes can avoid dissipation of the materials into the environment and avoid new production. For example, rechargeable nickel-cadmium batteries can be recycled to recover both cadmium and nickel for other uses. Inmetco Corporation in Pennsylvania and Accurec in West Germany are routinely recycling such batteries using pyrometallurgical distillation.

3.4 Conclusion

Increasing concern for product end-of-life is pushing companies to establish programs to take back their products. Currently, these companies rely on ad hoc approaches to build their end-of-life systems. Without a unified perspective of strategic, environmental and design issues, many of these programs fail to achieve the necessary targets to be profitable.

The end-of-life is the point in which the product no longer meets the needs of the original owner. The hierarchy of end-of-life strategies is reuse, service, remanufacture, recycle with disassembly, recycle without disassembly and disposal. There has been substantial research into the processing of products at end-of-life but little research into improving products so that higher levels on the end-of-life hierarchy are achieved. The research field is fragmented and disorganized, making it difficult for companies to find quick, simple solutions they can implement for a wide variety of products.

ELDA guides product designers to identify end-of-life activities appropriate for their product. Relying on technical characteristics of the product, the classification methodology identifies the end-of-life strategy. The research approach is based on case studies as well as statistical analysis to determine the appropriate classification.

4 END-OF-LIFE DESIGN ADVISOR

Chapter 4 focuses on the development of the End-of-Life Design Advisor. The End-of-Life Design Advisor classifies the product into the appropriate end-of-life strategy based on technical product characteristics. This chapter describes the evolution of the technical product characteristics resulting from case studies and expert opinion. The statistical method for classifying products according to technical product characteristics is explained. This chapter describes the development of the end-of-life strategy categorization based on statistical analysis applied to six technical characteristics across thirty-seven products from the electronics and appliances industries. Based on this classification, chapter 4 describes the development of a web-based application, End-of-Life Design Advisor (ELDA).

4.1 Basis for End-of-Life Design Advisor

The acronym, ELDA, stands for End-of-Life Design Advisor. End-of-Life because it is focused on this stage of product life cycle. Design because it is focused on the contributors of technical characteristics in product design, including product managers and designers. Advisor because it is intended to support decisions with technical basis, in order to improve decisions made by companies.

Traditionally, Design for Environment has focused on technical solutions, limited to factors the company can control. Product designers and managers are able to influence technical aspects of the product. ELDA uses technical product characteristics to determine end-of-life strategies. ELDA objectively examines the technical characteristics that control the product's possible end-of-life treatment. By using data available in early stages of product design, ELDA brings in the environmental perspective without the usual subjectivity. Although the technical product characteristics influence the product end-of-life strategy, the strategy chosen depends on intangible business and legislative aspects, frequently out of the control of designers.

The ELDA classification is equivalent to the best end-of-life treatment observed in industrial practice. From a technical and environmental perspective, ELDA is based on the observations of current end- of-life treatment. In order to determine the preferred end-of-life treatment accurately, the product end-of-life strategies, it is necessary to have meaningful parameters for the classification analysis. It is also necessary to consider only those product characteristics that are known and controllable in the early design stages allowing for improvements. The rationale for choosing technical product characteristics is that they are available to designers, valid for a wide variety of products, and are easy to collect based on knowledge of the product. It is crucial to look first at what is possible from a technical perspective, through ELDA, and then assess the reasons affecting the implementation of end-of-life strategies. Differences in the classified end-of-life strategy and what is done in industry are discussed in Chapter 5. The possible actions, with knowledge of the end-of-life strategy, are design improvements to the product and enhancements to the value chain, by either providing design incentives internally or additional external organization of the product end-of-life.

ELDA is particularly useful for products across a wide variety of product sectors. ELDA is appropriate for application in design of new and existing products. While designers are able to use benchmark techniques to compare existing products, it is not possible when designing new products. With ELDA, it is possible to build an end-of-life strategy for both new and existing products. Not only does ELDA develop the strategy effectively, ELDA enables the designers to see similarities in products that otherwise they might miss because of the focus on product function. Current benchmarking techniques examine products within product categories, aimed at the same market segment or provide similar function. These benchmarking techniques overlook products that may have very similar characteristics but have different functions. By only looking at product function, the similarities between a network router and portable radio are overlooked, for example. Looking at a wider range of products, the advances in environmental performance of a product category can transfer to products in other market segments. Taking advantage of these similarities can reduce work by transferring knowledge and reapplying proven tools.

ELDA’s focus on the entire product is unique; other tools examine products on a per part basis. Apart from examining the entire product, the analysis includes all end-of-life strategies such as reuse and service as well. ELDA is intended to provide determination of the end-of-life strategies early in product development process and is not meant to require or provide detailed level information known at other design stages. The End-of-Life Design Advisor also takes advantage of the cross-functional nature of design, pulling together a variety of disciplines and looking at environment aspects with technical perspective. Implementing and using ELDA during design stages can help management improve cross-functional processes associated with product creation, production, marketing and sales. Environmental improvements provide motivation for creativity, pushing design teams to think outside of the box. Cross-functional teams have been able to look at the product with fresh eyes from the environmental perspective to answer and solve problems. ELDA enables the designers to lay out the roadmap or the clear avenue for further work.

ELDA does not address other characteristics such as legislation, infrastructure, supplier and secondary material recycling, since design and manufacturing engineers have limited control over these issues. Whether the classified end-of-life strategy materializes in practice depends on internal and external factors. External factors include cost structures, industrial infrastructures of different countries, and labor costs of the country the products are being disposed of in. Internal factors are such items as overall company strategy, company organization, incentive systems, etc. However, more in depth discussion about the legislation, producers, consumers and recyclers' relationships is given in Chapter 6.

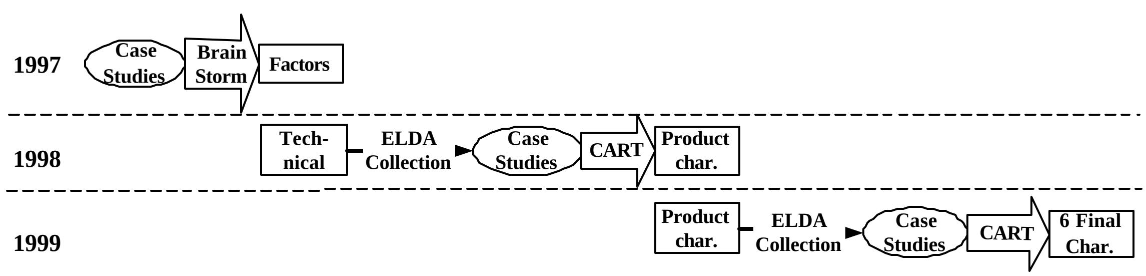


Figure 4-1. Timeline of Research

The timeline for the research is shown in Figure 4-1. It shows the method of gathering case studies and analyzing the data using statistical technique. The case studies were collected in 1997, 1998 and 1999. The characteristics were narrowed down from 24 to 6 during the three years of research. The following sections describe these steps in more detail.

4.1.1 Case Studies

This research includes case studies ranging from generic to very specific. The generic case studies come from Stanford University's graduate level Design for Manufacturability course (ME217). Examples have been collected each year from 1996 to 1999, with approximately ten case studies a year as shown in Figure 4-2.

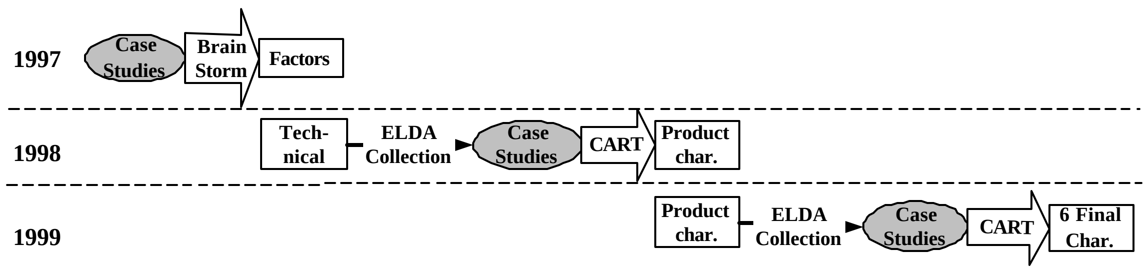


Figure 4-2. Timeline of Research – Case Studies

Stanford University's graduate level Design for Manufacturability course is a six month long course covers design topics such as Quality Function Deployment, Cost-worth, Design for Environment, Product Definition, Robust design, Advanced Failure Modes Effects and Analysis, Design for Variety and Design for Producibility. Project teams of four students apply these concepts to projects provided by a wide variety of companies. Off-campus students, participating through Stanford's Instructional Television Network, have projects sponsored by their companies. Over the last three years, some of the over 100 projects have focused specifically on environmental improvements. Two of the thirty-five lectures describe environmental activities with guest lecture from leaders in implementing environment and business. Other case studies have been collected through the internet with ELDA, from countries including: Japan, Korea, United States, Canada, Croatia, Finland, France, The Netherlands, Norway, Spain, Sweden and the United Kingdom and are listed in Table 4-1.

Using course projects from 1996 and 1997, the initial case studies addressed a vacuum cleaner, a digital copier, a washing machine, an inkjet printer, a single use camera and a television. The digital copier project focused specifically on improving end-of-life treatment of the product. In 1998, the case studies included an aircraft engine, a portable phone, a lead acid battery, a bubblejet printer, a line-matrix printer, a portable projector, a car, a computer and a server. The 1999 case studies included a generator, an automatic transfer switch, a handheld vacuum, a miniature robot, a network router and a fiberoptic transceiver.

Table 4-1. Types of products studied (by year)

YEAR	IT PRODUCTS	CONSUMER DURABLE PRODUCTS	COMMERCIAL PRODUCTS	OTHER PRODUCTS
1997	Digital copier, inkjet printer	Vacuum cleaner, washing machine, television	Shipping container	Single use camera
1998	Portable phones, bubblejet printer, line-matrix printer, portable projector, network server		Aircraft engine, lead batteries, elevator	Car, door panel
1999	Network routers, fiberoptic transceivers, laserjet printer	Handheld vacuum	Generators, automatic transfer switch, miniature robot	
Other	Computer	Audio product		Typewriter

Additional case studies, courtesy of Philips Consumer Electronics, are used to validate and draw implications from the application of ELDA. These case studies, results and conclusions are presented in Chapter 5.

4.1.2 Application of CART to build backbone for ELDA

Cluster analysis is a subset of techniques used to classify objects or cases into relatively homogeneous groups called clusters. Objects in each cluster tend to be similar to each other and dissimilar to objects in other clusters. Cluster analysis is also called classification analysis or numerical taxonomy. Cluster analysis can be useful for:

- investigating useful conceptual schemes for grouping entities,
- generating hypothesis through data exploration and hypothesis testing, and
- attempting to determine if types defined through other procedures are present in a data set.

Cluster analysis can be viewed as a set of techniques designed to identify objects, people or variables that are similar with respect to some criteria or characteristics. Cluster analysis has been used in marketing for a variety of purposes, including the following:

- segmenting the market,
- understanding buyer behaviors,
- identifying new product opportunities,
- selecting test markets, and
- reducing data.

Classification and Regression Trees (CART) is one of many cluster analysis techniques and is a methodology commonly found marketing data or medical data analysis. Classification analysis produces an accurate classifier or uncovers predictive structure of data to predict medical conditions, consumer behaviors and other complex patterns (Breiman et al. 1984). In most cases, researchers use CART to analyze sample sizes in the thousands. Currently, no method exists to identify directly or quantitatively the characteristics that have the most influence for classification problems. It is advantageous to use CART over other classification tree programs because the method is transparent, the user is able to change the parameters easily and the tool performs analysis quickly.

CART can also be used to determine behaviors including air travel frequency, pet ownership, AM radio preferences and TV watching duration, for example. A classification tree fits categorical data given by 9185 individuals and their demographic information. For example, the most important classifiers to determine pet ownership are type of domicile, home ownership, ethnicity, number of people in the family and years of residence in Bay Area (Ellis et al. 1998).

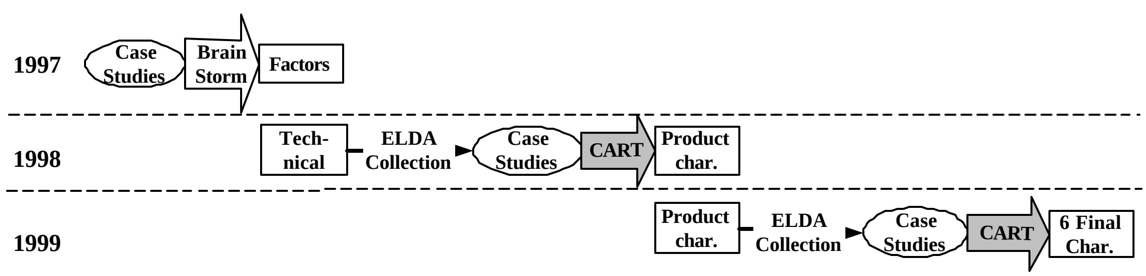


Figure 4-3. Timeline of Research – CART Analysis

In depth CART analysis was performed on the data at two separate points in the present research. Both times, an iterative process was used to find the most accurate classification of the end-of-life strategies. The data is entered into CART (C program stored on a Leland server) and the data is classified according to the best classifiers. The results of CART, applied to the data, are included in sections 4.2.2 and 4.3.3.

4.1.3 ELDA Internet Tool

Ishii and Hornberger (Ishii et al. 1992) have reported that designers required the following characteristics for a computer-based tool to have long term value:

- simple inputs (easy to learn, short execution time, small amount of input),
- objective output (quantitative values, cost estimates and sensitivities), and
- focused subject matter (designer's responsibility).

Environment is only one of the many issues facing designers and therefore, any tool must be simple and quick. The ELDA tool takes approximately ten minutes to use and receive a meaningful result. It does not rely on existing knowledge of the designer, provides examples for the designers to use, and only requires six inputs. ELDA recommends an end-of-life strategy with examples, presented in an objective manner.

The End of Life Design Advisor (ELDA) is a web-based tool for evaluating and improving product end-of-life strategies, available at http://dfe.stanford.edu. The full structure of ELDA is given in Appendix IV. The user inputs are reported back to Stanford using a Java applet and compiled into a database for further follow-up and analysis.

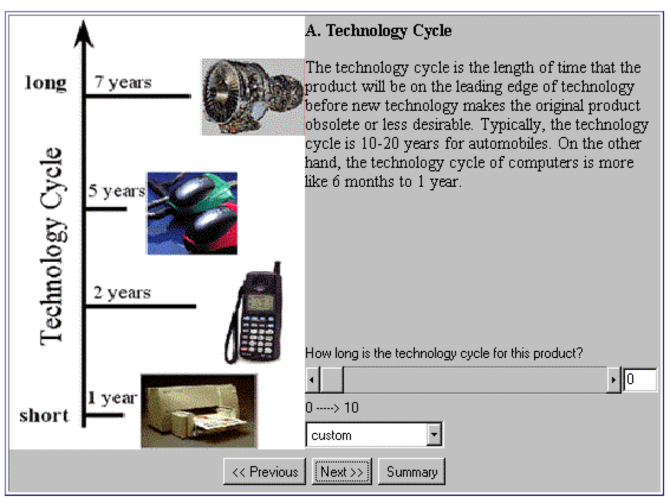


Figure 4-4. Example ELDA input screen

ELDA first asks users to evaluate product characteristics illustrated by examples. Figure 4-4 is an example of an input screen from ELDA, and the other screens are given in Appendix IV. There are several ways the user can input data including typing the exact value, using a scroll bar, or by choosing a product that has similar attributes to the user's product. The user is able to follow the clear commands given in this tool to move from screen to screen and answer the questions.

After receiving input from the users, the End-of-Life Design Advisor tool compiles an input summary to facilitate user verification. ELDA processes the information using the results from the classification tree and makes a recommendation for end-of-life strategy to the user. From the determined end-of-life strategy, ELDA provides design recommendations and guidelines based on the particular end-of-life strategy. Individual web pages outline recommendations for improvements to designs and also give examples of other products for the designer with which to compare the product.

ELDA is provided as a tool on the internet to allow product designers and product planners to communicate and collaborate about the end-of-life issues during product development. In recent years, there has been a convergence of communication and computing technologies most notably observed in the development and use of the world wide web. The internet is increasingly being utilized to synchronize efforts globally. Remote members of project teams could also update the product information online. ELDA facilitates communication between globally separated design teams and works well for environmental concerns. Applying ELDA on the internet takes advantage of a familiar and easy to use interface, the independence of the platform (i.e. hardware and operating system), and the low costs associated with the development and maintainability of web-based solutions (Rodgers et al. 1999). Moreover, it is platform independent and data independent (Liang et al. 1999).

ELDA takes advantage of the internet to facilitate communication and the use of the computer to speed data transfer and calculation. Further application in terms of recommendations to address challenges in realizing the potential end-of-life strategy is limited. Neither computers nor the internet can replace design creativity and problem solving. By providing information and guidance, with easy access, gives keys to improve end-of-life strategy decisions.

4.2 Evolution of Technical Product Characteristics

The cluster technique, CART, was used to determine the product characteristics necessary to form the backbone of ELDA. Evolution and selection of technical product characteristics has gone hand in hand with the collection of case studies. The original product characteristics (Rose et al. 1998a, Rose et al. 1998b) were based on examining similarities between case studies performed at Stanford University. These twenty-four characteristics were categorized by external, material, disassembly, and inverse supply chain. Later research revealed that six key characteristics were sufficient to classify the end-of-life strategy (Rose et al. 1999a, Rose et al. 1999b). Although not used in classification, another six were included in the implementation of ELDA, to sharpen the tool and increase accuracy. The final research results, described in this chapter, shows six final characteristics are necessary to classify product end-of-life strategies with 86% accuracy (Rose et al. 2000d). Table 4-2 gives the year of the research, number of characteristics and the product characteristics.

Table 4-2. Evolution of Product Characteristics (considered for establishing ELDA)

Year	1997	1998	1999
Number of characteristics	24	12	6
Characteristics	External Wear-out life, design cycle, technology cycle, technology research focus, company design focus, reason for obsolescence, functional complexity Material penalties associated with recycling, cleanliness of product number of materials, recycling value drivers, end-of-life path categorization Disassembly Disassembly time, disassembly steps, number of modules, number of parts, number of components, disassembly motivation, overall access to components Inverse Supply Chain responsibility for recycling cost, responsibility for collection and transportation cost, recycling drop-off centers, trade-in possibilities, beneficiaries of recycling	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 functional complexity.	Wear-out life Technology cycle Level of integration Number of parts Design cycle Reason for redesign

In general, the previous table shows that a wide variety of characteristics influence the end-of-life strategy of the product, many of which are external factors. However, the research seeks to understand how the technical characteristics influenced the end-of-life strategy.

4.2.1 Preliminary factors influencing to end-of-life strategies

The original characteristics, listed in Table 4-3, were chosen resulting from analysis on the case studies and discussions brainstorming characteristics influencing end-of-life strategies with leading researchers (Rose et al. 1998b). After analyzing the case studies and brainstorming, the following characteristics were identified as influencing the product end-of-life treatment.

Table 4-3. Original Factors influencing end-of-life strategies

FACTORS	CHARACTERISTICS	DEFINITION
External	design cycle	the length of time between successive generation of a product; e.g., 2-4 years for automobiles
	wear-out life	the length of time until the product no longer meets the original function(s); e.g., 7-10 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
	technology research focus	research initiatives in technology improving product features
	company design focus	a company's initiatives in environmental design; e.g., ISO 14000
	reason for obsolescence	reason a product is no longer is able to perform its intended function; e.g., because of failure of key components or it is outmoded
	functional complexity	perception of complex interactions between parts and functions the product performs
Material	penalties associated with recycling	hazardous or unwanted materials that can contaminate components
	cleanliness of the product	amount of dirt or grime that hinders reuse and recycling
	number of materials	number of different materials; e.g., seven materials for single use cameras; forty materials for inkjet printer
	recycling value drivers	the components or materials with high profits that drive either material recycling or component reuse
	end-of-life path categorization	percentages of product parts in each end-of-life path assuming disassembly

Table 4-3. Original Factors influencing end-of-life strategies, Continued

FACTORS	CHARACTERISTICS	DEFINITION
Disassembly	disassembly time	best estimate available
	number of connectors	number and type of connectors, as given in bill of materials
	number of modules	number of subassemblies that are physically detachable while preserving functionality
	number of parts	approximate number of parts, as given in bill of materials
	disassembly times / step	step or time to disassembly part given for the actual or possible end-of-life paths
Disassembly Continued	Disassembly motivation	Retrieval of spare parts or material recycling that motivates cost effective disassembly; e.g., automotive parts or gold on circuit boards
	overall access to components	Estimated by the perception of disassembly time and complexity of interactions between materials
Inverse Supply Chain	responsibility for recycling costs	Participants who support the infrastructure for the recycling activities
	responsibility for collection and transportation costs	participants who support infrastructure for collecting and transporting end-of-life products
	recycling drop-off centers	facilitates consumers' returning the end-of-life products
	trade-in possibilities	reimbursement policy for returning end-of-life products
	beneficiaries of recycling	participants who receive the service parts or recycled components, providing them with profit

4.2.2 Original Technical Product Characteristics

The focus of the ELDA evolved to technical aspects of the product that designers could influence. Therefore, before the next step in the research, only the technical product characteristics were selected and their definitions are given in Table 4-4. Through the internet, the first implementation of ELDA collected case studies from the Design for Manufacturability course. From this data, CART analysis was performed to develop the first classification of the product characteristics. The resulting classification from these case studies agreed with best industry practice in only 46% of the products. The aim of the research was to have highest accuracy in the classification of the end-of-life strategies and 46% was considered low.

Table 4-4. Original Technical Product Characteristics

CHARACTER-ISTICS	DEFINITIONS
Wear-out life	The wear-out life is the length of time from product purchase until the product no longer meets original functions. For example, an automobile's average wear-out life is 10-15 years. For a computer, the wear-out life is approximately 7-10 years.
Design Cycle	The design cycle is the length of time between successive generations of the product. The design cycle is the frequency that a design team redesigns the product or designs a new product thus making the original product obsolete. For an automobile, the design cycle is 2-4 years. For inkjet printers, the design cycle is 1 year.
Technology Cycle	The technology cycle is the length of time that the product will be on the leading edge of technology before new technology makes the original product obsolete or less desirable. Typically, the technology cycle is 10-20 years for automobiles. On the other hand, the technology cycle of computers is more like 6 months to 1 year.
Repurchase Cycle	The repurchase cycle is the length of time that elapses before the user feels the need to upgrade their product to one with increased functionality. The repurchase cycle is highly dependent on the type of user, but consider an estimate for the "average" user. An example of repurchase cycle is automobiles, where an "average" user repurchases an automobile every 5 years.
Reason for Obsolescence	The reason for obsolescence is why a product is no longer able to perform its intended function. Products reach their end-of-life for a variety of reasons. A product typically reaches its end-of-life because it is worn-out or because it is outmoded. A product is worn-out when crucial components supporting the key functions of the product fail. A product is outmoded when the user feels the functions are not the best on the market due to technology innovation.
Functional Complexity	Functional complexity addresses the relationship between modules and the functions the modules perform. Given the modularity of the product, a functionally complex product has highly dependent modules that support a variety of functions. On the other hand, a product with low functional complexity has modules that independently support separate functions.
Size	The size is the approximate dimensions of the product. Please classify the products as either hand-held, arm-held or needs a forklift. A digital copier and washing machine require a forklift or hand truck to move them, thus they are considered large in size. An inkjet printer and television (standard) are medium-sized because they can be carried in the arms. A cellular phone or single use camera are hand-held and therefore small.
Number of parts	The number of parts is the approximate number of parts in the product.
Cleanliness Measure	As a product is used, different amounts of dirt or filth build up. The more dirt or filth, the more work that has to be done to prepare the product for reuse and recycling. The product may provide the function of cleaning dirty materials or may produce a dirty substance during use. For example, a washing machine is designed to remove dirt from clothes while the single use camera does not get dirty from normal use.

Table 4-4. Original Technical Product Characteristics, Continued

CHARACTER -ISTICS	DEFINITIONS
Number of Materials	For the product, try to count the number of different materials to your best knowledge. A single use camera excluding the film has seven different materials, while an inkjet printer has forty different materials.
Number of Modules	The number of modules is the number of subassemblies that are physically detachable and still preserve function. The single use camera has 3 modules while the inkjet printer has 5 modules.
Hazards	The penalties associated with recycling include hazardous or unwanted materials that contaminate components. Included in this penalty is the need to remove certain materials before further recycling, because of hazards to humans, the environment or contamination of parts. For example, the single use camera batteries are considered hazardous.

Wear-out life, design cycle, technology cycle and repurchase cycle are continuous variables ranging from 0-10 years. Reason for obsolescence, functional complexity, cleanliness measure and hazards are categorical variables with ranges associated with the responses given by the user. Size (0-10), number of parts (0-1000), number of modules (0-100) and number of materials (0-100) are all continuous variables with the ranges given in parenthesis.

Using the collected input data, the variables used in CART were altered to see which product characteristics had the greatest effect on the classification tree. In the initial iteration, the twelve product characteristics, twenty products and their end-of-life strategies were used. In sixteen possible classification trees identified, six product characteristics were relevant for establishing a classification tree – number of functions, level of integration, number of parts, cleanliness measure, technology cycle and number of materials. The other product characteristics – size, number of modules, reason for obsolescence and functional complexity – were not used in the classification trees. Wear-out life, design cycle, repurchase cycle and hazards were used infrequently in the classification tree.

The resulting classification tree, shown in Figure 4-5, has three main branches separated by the product's technology cycle. The three branches are roughly equivalent with number of parts and level of integration used as the second and third level classifiers, respectively.

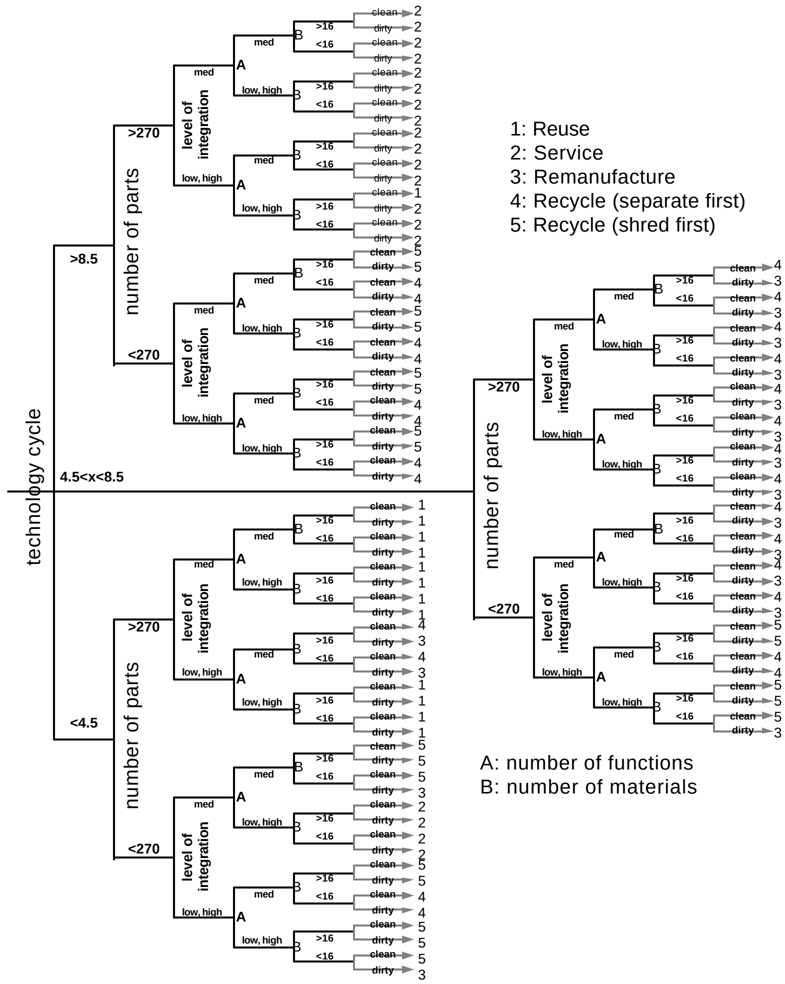


Figure 4-5. Resulting classification

Application revealed that some characteristics required excessively detailed information, information not available to designers, and ambiguous description. Number of parts required designers to have a specific idea of the number of parts the finished product would have. The product characteristic – reason for obsolescence – required information not available to designers regarding the reasons consumers were discarding the products. Functionality complexity, from the varied responses from users, was too ambiguous and users of ELDA were confused by the combination of level of integration and number of modules. Requiring more generic information, requesting information accessible by designers and clarifying characteristics would lead to an improved ELDA.

This classification tree is complicated, with 144 final nodes that made implementation difficult. Added to the fact of its inaccuracy, research pushed ahead to collect more case studies and develop a simpler, more accurate and elegant classification of product end-of-life strategies. Examination of the product characteristics and prior research suggested that higher agreement between the industry practice and classified end-of-life strategy was possible through additional case studies, refined product characteristics and second analysis through CART.

4.3 Final Analysis

The final analysis sought to achieve higher accuracy in the classification of products according to the end-of-life strategies. The first analysis showed promise but the desired accuracy (46%) was low. Additional case studies and refinement of product characteristics were hypothesized to provide the desired accuracy.

The collection of case studies between 1998 and 1999 resulted in a total of 37 distinct product data sets. Another CART analysis was performed and a new classification tree was developed. The result is an accuracy of 86% based on a classification tree based on six technical product characteristics.

4.3.1 Case Studies

During the past four years, a total of thirty-seven products have been collected. Table 4-5 lists the products and their technical product characteristics. All of the case studies were used to develop ELDA and the classification of end-of-life strategies.

Table 4-5. Complete List of Case Studies and Product Characteristics

PRODUCT	WEAR-OUT LIFE / TECHNOLOGY CYCLE	WEAR-OUT LIFE	TECHNOLOGY CYCLE	LEVEL OF INTEGRATION	NUMBER OF PARTS	REASON FOR REDESIGN	DESIGN CYCLE
Air Bag	1.5	12	8	2	31	1	4
Aircraft Engine	2.9	20	7	3	1000	2	7
Automatic Transfer Switch	2.0	20	10	2	116	2	7
Automobile	1.9	13	7	2	1000	3	4
BubbleJet Printer	1.6	8	5	1	25	2	1
Cell Structure	2.8	11	4	2	1000	1	2
Computer	4.0	6	1.5	2	200	2	1.5
Computer Mouse	1.5	6	4	1	5	5	3
Computer-Video Projector	2.5	5	2	2	25	2	1

Table 4-5. Complete List of Case Studies and Product Characteristics, Continued

PRODUCT	WEAR-OUT LIFE / TECHNOLOGY CYCLE	WEAR-OUT LIFE	TECHNOLOGY CYCLE	LEVEL OF INTEGRATION	NUMBER OF PARTS	REASON FOR REDESIGN	DESIGN CYCLE
Connections	2.0	20	10	1	2	2	7
Digital Copier	2.5	5	2	2	533	3	2
Electric Power Steering Motor	0.5	5	10	2	20	5	3
Elevator	2.0	20	10	2	1000	3	4
Fiberoptic Transceiver	3.3	10	3	1	11	2	1
Filter	1.2	12	10	2	30	4	1
Generators	1.4	14	10	2	718	2	7
Hand Held Vacuum	0.7	4	6	1	15	2	2
Inkjet Printer	2.7	4	1.5	1	100	3	1.5
Klystrons	2.0	20	10	2	1000	2	7
Laserjet Printer	1.6	8	5	2	26	2	3
Lead Acid Batteries	2.0	20	10	1	8	3	6
Line Printer Floor cabinet	2.0	20	10	1	20	2	5
Miniature Robot	1.0	5	5	3	201	2	3
Network Routers	10.0	10	1	1	10	2	2
Network Server	9.0	9	1	3	135	2	1
NLC Support Structure	2.1	19	9	2	20	1	6
Photocopier	1.0	5	5	3	100	5	2
Portable Radio	5.0	10	2	2	20	3	2
Printer Hammerbank	1.0	5	5	1	25	4	2
Shipping Container	0.5	5	10	1	100	5	7
Single Use Camera	0.5	2	4	1	25	3	3
Telephone	2.5	5	2	3	22	2	1
Television	5.0	15	3	2	100	2	3
Typewriter	1.7	15	9	2	55	2	1
Vacuum Cleaner	1.1	8	7	2	75	3	3
Washing Machine	2.0	10	5	1	101	3	2
Washing Machine Electric Motor	2.4	12	5	1	27	3	4

4.3.2 Final Technical Product Characteristics

The product characteristics are particularly meaningful because they can be used to classify products to the appropriate end-of-life strategies. By collecting case studies and analyzing their product characteristics and end-of-life strategies, these final characteristics were chosen because of their strong influence over the product end-of-life strategy.

These characteristics were chosen on the basis of observations of the recycling industry, designer knowledge at early stages of product development process and governmental initiatives. Collecting data through the ELDA has given an extensive database of products and their characteristics. The indicator was that the ability to classify the end-of-life strategies in agreement with current practice. The final product characteristics classify the end-of-life strategies with 86% accuracy, whereas the previous classification had an agreement of 46%.

Table 4-6. Final Technical Product Characteristics with input ranges

PRODUCT CHARACTERISTICS	INPUT RANGES
Wear-out life	0-20 years
Technology cycle	0-10 years
Level of integration	High, medium, low
Number of parts	0-1000
Design cycle	0-7 years
Reason for redesign	1. Original design (new for company with no existing design history) Evolutionary design (significant redesign of an existing or current product) 2. -function improvement 3. -aesthetic change Feature change (small feature or function change to existing product) 5. -function improvement 4. -aesthetic change

Table 4-6 lists the product characteristics and the data ranges. In depth definitions are given in sections 4.3.2.1-4.3.2.7. In contrast to other end-of-life design tools, this research sought to identify product characteristics that were generic, easy to define and simple to understand.

One major factor in improving the accuracy in classification is the use of relative numbers. The addition of the ratio between wear-out life and technology cycle, described in more detail in section 4.3.2.3, contributes substantially to the improvement in agreement between classified and observed end-of-life strategy – increasing from 46% to 86%. By using a relative scale, or the ratio between technology cycle and wear-out life, it shows the critical issue is the relationship of these two product characteristics. Rather than an absolute scale, where some products have very similar numbers on either technology cycle or wear-out life, using the ratio shows how these are linked in the product developers and consumers mind-sets. Consumers do not want outdated or worn-out products, therefore regard to the technology cycle and the wear-out life is necessary. Relating to end-of-life, if the product is outdated by technology, then possible end-of-life strategy is recycle but refurbishing the product would still be undesirable for the consumer. Similarly, products with worn-out parts can be refurbished or remanufactured to return the product to consumer use. A product with very slow technology change is expected to have a long wear-out life, by consumers. However, it is notable to recognize that products with short technology cycles often have long wear-out lives as well.

The next sections will describe each technical product characteristic in detail. The text from the ELDA tool is given in boxes followed by more in-depth description.

4.3.2.1 Wear-out life

The wear-out life of a product is the point at which the product no longer attains its level of function that consumers want. The wear-out life is influenced by product design and choice of materials, manufacturing quality, consumer use, and service. In other words, the product has a long wear-out life if decisions during design of the product have been to provide the longest life, use durable materials in the design of the product, use high quality manufacturing techniques, assume reasonable consumer use, and use frequent and appropriate service.

> *Definition used in ELDA:*
> *The wear-out life is the length of time from product purchase until the product no longer meets original functions. For example, an automobile's average wear-out life is 10-15 years. For a computer, the wear-out life is approximately 7-10 years.*

In other words, the technical wear-out life can be measured by these three definitions:

- time until the critical part, providing function, wears out or fails
- time until the complete product fails, losing all functions
- mean time to failure

Products can also become worn-out gradually over time, losing their original mint condition and therefore being discarded by consumers not because of loss of functionality. This product characteristic does not address emotional wear-out, as very little can be controlled by product designers in that regard.

4.3.2.2 Technology cycle

The technology cycle of a product depends on market pressures, scientific advances and company focus. Various groups propel technology changes, including:

- consumers (preferences on 'high tech', best performance, higher functionality),
- governments (to stimulate growth),
- scientists, Engineers and Inventors (looking to reach higher performance while lowering costs in products or processes),
- competition (in sectors over market share or profits, sell new products)

Companies rely on changes in technology to increase functionality (hopefully, to sell more products), hence investment in science and research development. The advance of science or engineering provides opportunities to include new techniques in manufacturing or new functionality in products, at a reduced cost. Consumers, either private or industrial, express need for faster or better performing products and companies react by developing products to meet these needs. Governments also fund research to develop new technology to stimulate growth.

> *Definition used in ELDA:*
> *Technology Cycle: The technology cycle is the length of time that the product will be on the leading edge of technology before new technology makes the original product obsolete or less desirable. Typically, the technology cycle is 10-20 years for automobiles. On the other hand, the technology cycle of computers is approximately 6 months to 1 year.*

Another important influence is technological change, which leads people to replace aging products with new models that may appear of higher quality or offer more extensive functions (Copper 1994). For example, computers have become more powerful with each generation of microprocessor, washing machines have faster spin speeds, telephones contain new features such as last number redial, and televisions have remote control and stereo sound. Occasionally environmental improvements are offered, such as increased energy efficiency.

For some products, the basic enabling technology has not changed in approximately twenty years, which allows for longer use of product by the original consumer and higher value at end-of-life. Such products include small kitchen appliances (juicers, can openers, toasters, blenders, choppers), large kitchen appliances (ranges, refrigerators, microwaves), vacuum cleaners, cars, and TVs (CRT-based). Such products have long replacement cycles from the consumer and have become very durable to attract consumers to extended product use. By the introduction of integrated circuitry in products, more product functionality can be achieved for a similar price. The result is more products become outdated because of their electronics, resulting in technology cycles shorter than previously.

The advancement of technology development results in the following products:

- Products whose technology changes with customers demanding it: faster, quicker, better;
- Products whose technology changed because government demanded it: cars (energy efficiency, catalytic converters); electric utilities (scrubbers, lower emissions); product processes for semiconductor manufacturers (use of fewer toxic chemicals, TRI data)
- Products whose technology was completely new and revamped consumers mindsets (need unanticipated by consumers): Palm Pilot; Computer (for home use); fax machine / email / internet.

4.3.2.3 Wear-out life over Technology cycle

Technology cycle is relevant for product end-of-life treatment. Not only does product age (wear-out life) affect the end-of-life, but also the changes in technology during that time period. Products with few changes in technology have high reuse potential and retain their value at end-of-life. However, products with rapid technology cycles are not prone to reuse after the first consumer. For instance, from Electronic Product Recycling in the United States (SRI 1999), the product age and the technology cycle were documented for computers. The following table shows a comparison of the wear-out life and the technology cycle for the present study of products.

Table 4-7. Product Wear-out Life and Technology Cycle

PRODUCT	WEAR-OUT LIFE	TECHNOLOGY CYCLE	WEAR-OUT LIFE / TECHNOLOGY CYCLE
Air Bag	12	8	1.5
Aircraft Engine	20	7	2.9
Automatic Transfer Switch	20	10	2.0
Automobile	13	7	1.9
BubbleJet Printer	8	5	1.6
NLC Cell Structure	11	4	2.8
Computer	6	1.5	4.0
Computer Mouse	6	4	1.5
Computer-Video Projector	5	2	2.5

Table 4-7. Product Wear-out Life and Technology Cycle, Continued

PRODUCT	WEAR-OUT LIFE	TECHNOLOGY CYCLE	WEAR-OUT LIFE / TECHNOLOGY CYCLE
Connections	20	10	2.0
Digital Copier	5	2	2.5
Electric Power Steering Motor	5	10	0.5
Elevator	20	10	2.0
Fiberoptic Transceiver	10	3	3.3
Filter	12	10	1.2
Generators	14	10	1.4
Hand Held Vacuum	4	6	0.7
Hand Held Vacuum	4	6	0.7
High Speed Line Printer Floor Cabinet	20	10	2.0
Inkjet Printer	4	1.5	2.7
Klystrons	20	10	2.0
Laserjet Printer	8	5	1.6
Lead Acid Batteries	20	10	2.0
Miniature Robot	5	5	1.0
Network Routers	10	1	10.0
Network Server	9	1	9.0
NLC Support Structure	19	9	2.1
Photocopier	5	5	1.0
Portable Radio	10	2	5.0
Printer Hammerbank	5	5	1.0
Shipping Container	5	10	0.5
Single Use Camera	2	4	0.5
Telephone	5	2	2.5
Television	15	3	5.0
Typewriter	15	9	1.7
Vacuum Cleaner	8	7	1.1
Washing Machine	10	5	2.0
Washing Machine Electric Motor	12	5	2.4

The products' wear-out life and technology cycle can be classified in Figure 4-6.

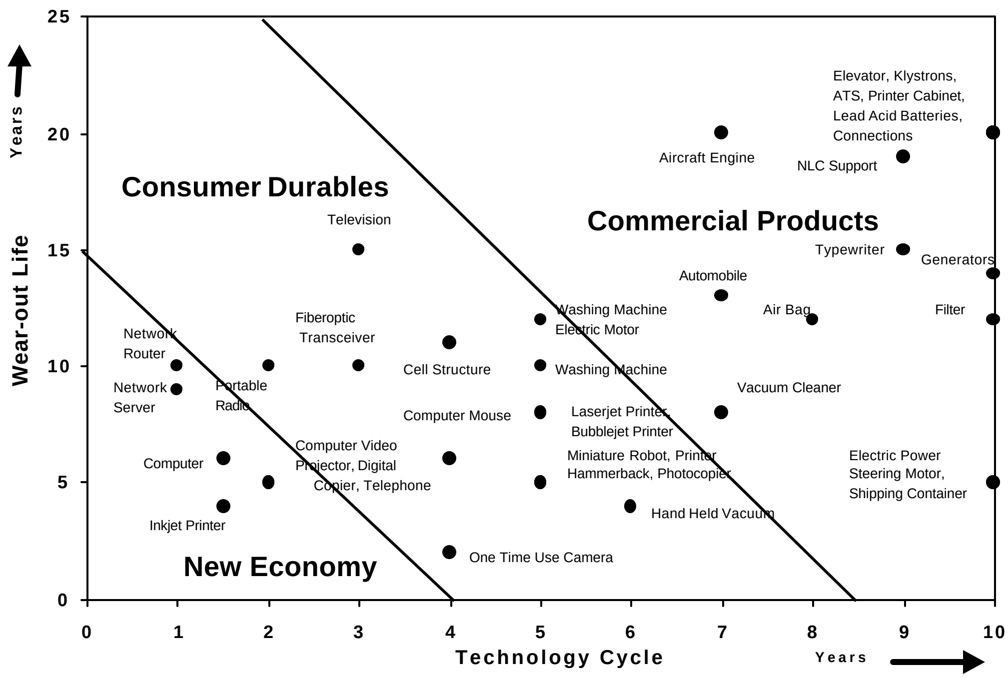


Figure 4-6. Product wear-out life and technology cycle with product sectors identified

Figure 4-6 is useful because the two axes, technology cycle and wear-out life, separate the products into three sections. The high technology products, or new economy products, are located in the lower-left hand corner, until the first diagonal. The region in the middle, between the two diagonal lines, is comprised mostly of consumer products. Commercial products dominate the region in the upper right hand corner.

The following table summarizes the differences in wear-out life and technology cycle according to product sectors.

Table 4-8. Product sector characteristics

PRODUCT SECTOR	WEAR-OUT LIFE		TECHNOLOGY CYCLE		WEAR-OUT LIFE / TECHNOLOGY CYCLE	
	Low	High	Low	High	Low	High
New Economy / Information Technology		10 years		5.5 years		1.8
Consumer durable goods	5 years	15 years	5.5 years	7 years	0.7	2.7
Commercial products	5 years	20 years	7 years	10 years	0.5	2.9

If the product wear-out is longer than the technology cycle, there are various redesigns of the product released before the first product released reaches its wear-out life. For some products, the number of technology cycles to each wear-out life is approximately 1, whereas for new economy products, there can be ten updates in the technology during the time that the first product wears out. There are products with technology cycle longer than product wear-out life such as single use camera, shipping container and electric power steering motor.

4.3.2.4 Level of integration

The level integration, as defined in ELDA, intends to assess the interrelation between modules and functions. If there are many unique functions for each module, then the level of integration is high. On the contrary, if each module performs one or two different functions, the level of integration is low. This addresses the concept that if a module or subassembly of the product is broken, would the product lose all functions or only few functions?

> *Definition used in ELDA:*
> *A product with a high level of integration has a single 'chunk' that implement many functions. Additionally, a product with high level of integration has complexly-defined interactions between chunks. Alternatively, a product with low level of integration has single 'chunks' that implement few functions. The interactions between chunks for a product with low level of integration are well defined or obvious.*
> *High?*
> *Medium?*
> *Low?*

The level of integration seeks to combine two product characteristics – product functionality and the number of modules. The number of functions, or functionality, performed by a product can vary greatly depending on the definition of 'function' and the range of products examined. The 'assembly' modules or the 'disassembly' modules are frequently used to define the number of modules. Two frequent misinterpretations of level of integration are one as the number of 'disassembly' modules, the other as the number of 'assembly' modules. Assembly modules do not apply because rarely the grouping of components during assembly is rather arbitrary and more based sourcing of the subassembly than on actual engineering. Disassembly modules are inappropriate because many recycling companies are based on material recovery rather than module recovery. Disassembly modules are only relevant in actual disassembly, either manual or automated. For some end-of-life strategies, reuse and recycle through shredding, disassembly is not needed. In remanufacturing, service and recycling (with separation), some disassembly is needed.

4.3.2.5 Number of parts

This technical characteristic, number of parts, is the number of assemblies in the product relevant for end-of-life treatment. Number of parts is not intended to account for each individual part in the product, but rather the ones relevant for recycling. For this product characteristic, printed circuit boards are considered one part because in most cases they will be disassembled as a complete ‘entity’ and further processed intact, realizing that in isolated memory or processor chips are removed for resell (Fox-Electronics 1998, Knoth et al. 2000). Small wires and screws are not included in this count.

Definition used in ELDA:
The number of parts is the approximate number of parts in the product.

So for example, televisions have 3000 distinct parts that make up the product, but realistically there are some 40-50 relevant subassemblies performing distinct functions. Relevant refers to assembly and disassembly modules as well as size and weight. A possible redefinition of number of parts is to include the weight of parts, for example number of parts divided by weight. More research into detailing this characteristic is necessary because an application test on data gathered from Philips Consumer Electronics was inconclusive.

4.3.2.6 Reason for Redesign

The reasons companies design or redesign products depends on customer demand, competitor behavior and scientific progress. Scientific progress allows companies to add new functions to products. Customer demand and competitor behavior push the company to release products with aesthetic alterations to follow trends. Aesthetic changes are related to presentation or external design. Changes in function require improvement in mechanics or electronics controlling performance of the product. With regard to changes in products, they can be small or large. Evolutionary design is a significant redesign of an existing or current product, and is the most common type of design. Feature change is a small feature or function change to an existing product (Allen et al. 1998).

Definition used in ELDA: *Original design (new for company with no existing design history)?* *Evolutionary design (significant redesign of an existing product)?* *- function improvement* *- aesthetic change* *Feature change (small change to existing product)?* *- function improvement* *- aesthetic change*

The following table (4-9) shows examples of possible design changes for an automobile.

Table 4-9. Examples of possible design changes

REASON FOR REDESIGN	FUNCTION OR AESTHETIC	EXAMPLE PRODUCT
Original Design		Hybrid Energy Car
Evolutionary design	Function improvement	Improved energy efficiency of engine
	Aesthetic improvement	New body panels
Feature change	Function improvement	Better steering mechanism
	Aesthetic improvement	Upgrade of dash board

This product characteristic, reason for redesign, determines if the product will experience an end-of-life of remanufacturing, recycle with disassembly or recycle without disassembly. Original design, functional changes (big or small) distinguish a product to have an end-of-life of remanufacture or recycle without disassembly. Products redesigned for aesthetic improvements (big or small) have an end-of-life strategy of recycle with disassembly. This characteristic evolved from the original characteristic, reason for obsolescence. The possibilities for the original characteristic, reason for obsolescence, were outdated or worn-out. Many companies do not have this type of information because the end-of-life was not traditionally an area of focus. However, the service organization within a company collects information concerning warranty complaints for worn-out products but not usually issues associated with the products' 'outdatedness'. By asking the reverse question ('why is the product being designed or redesigned'), designers are able to use knowledge they actually have. New products brought to market have affect on consumer purchasing and discarding behaviors (Rose et al. 2000d).

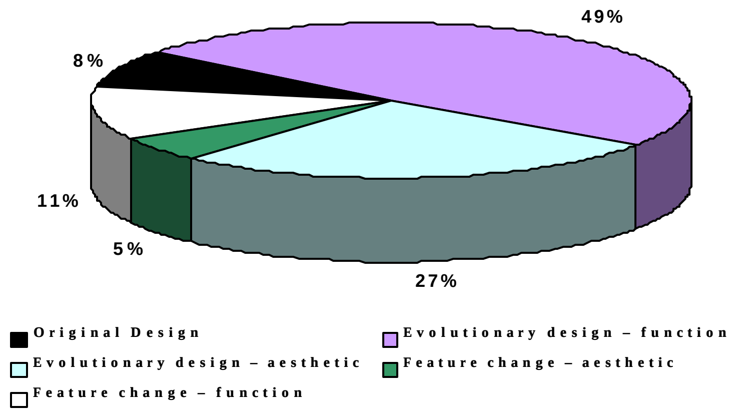


Figure 4-7. Reason for Redesign Percentages

Figure 4-7 displays the results from the case studies according to their reason for redesign. 49% of the products are evolutionary design with most improvements made to the function of the product. There are 27% of the products studied that list the reason for redesign to minor changes in aesthetics. For products dominated by technological changes, major function improvements are possible and very frequent. For products with stable technology, aesthetic changes are more frequent. This characteristic is interrelated with the next question, the frequency of new design or redesign of the existing products.

4.3.2.7 Design Cycle

The design cycle is the frequency with which companies design new products or redesign their existing products. This product characteristic tries to address frequency in which design changes, as outlined in 4.3.2.6, are implemented. Design cycle relates to competition's release of new products, marketing plans and actual research and development successes. For example, Philips Consumer Electronics releases their redesigned (for aesthetic reasons) product line through their yearly trade show on consumer electronics. Approximately every three years, major functional changes are included in their products.

Definition used in ELDA: *Original design (new for company with no existing design history)?* *Evolutionary design (significant redesign of an existing product)?* *- function improvement; How recently?* *- aesthetic change; How recently?* *Feature change (small change to existing product)?* *- function improvement; How recently?* *- aesthetic change; How recently?*

Some companies may have set dates for releasing redesigned products into the market. Other companies may have design release dates set by competition or market demands. For the case studies examined, the average design cycle was 3.3 years.

4.3.2.8 Discussion of product characteristics

These 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 with diverse functions. The characteristics also describe the product's physical composition and the technology development.

Material content, especially environmentally relevant material content, appear to be important product characteristics for end-of-life strategies; however, no correlation has been found with the current product case studies. Managing environmentally relevant materials at the end-of-life of the product requires more research and is currently the main focus of an indepth examination (Huisman 2002). Environmentally Weighted Recycling Quotes (EWRQ) weigh each material fraction according to its real environmental impact and includes the enviornmental impact of recycling process (Huisman et al. 2000b). The advantages of this approach over conventional weight based quotes are greater ability to maximize the control of enviornmental impact at minimum cost, characterizes true environmental performance of products in their end-of-life, and improve communication on environmental value and performance to consumers (Huisman et al. 2000a). An alternate approach using the Toxic Potential Indicator developed by Fraunhofer IZM is possible but requires extensive product data on the material content of the product (Nissen et al. 2000). The major advantage is the resulting score is a ranking of products and could easily be implemented into the current ELDA format. However, the detailed data required would contradict the aim of ELDA, of being a tool that could be implemented easily early in product design.

4.3.3 Resulting Classification Methodology

As discussed in 4.1.2, the analysis of the end-of-life strategies is based on a statistical technique (CART) that maps the technical product characteristics to the end-of-life strategies. Classification is a type of cluster analysis, used to group items with similar characteristics into classes. Other statistical techniques are not appropriate because they rely on continuous variables rather than the necessary categorical data. Classification analysis allows for categorical independent and dependent variables. Linear regression can not be easily applied because some of the independent variables are categorical. More importantly, because the end-of-life strategies are categorical variables, linear regression can not be used because the dependent variable must be continuous.

Table 4-10. Variables used in CART

TYPE OF VARIABLE	PRODUCT CHARACTERISTIC	INPUT RANGES	CONTINUOUS OR CATEGORICAL?
Independent	Wear-out life	0-20 years	Continuous
Independent	Technology cycle	0-10 years	Continuous
Independent	Level of integration	High, medium, low	Categorical
Independent	Number of parts	0-1000	Continuous
Independent	Design cycle	0-7 years	Continuous
Independent	Reason for redesign	1. Original design 2. Evolutionary design– function improvement 3. Evolutionary design– aesthetic change 4. Feature change– aesthetic change 5. Feature change– function improvement	Categorical
Dependent	End-of-Life Strategy	1 – Reuse 2 – Service 3 - Remanufacture 4 – Recycling (separate) 5 – Recycling (shred) 6 – Disposal	Categorical

Few assumptions were made to proceed with the CART methodology. While the characteristics describe the actual product characteristics, the end-of-life strategy used in the methodology is the industry best practice end-of-life strategy. 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. The classification trees were compared and the ones with the highest percentage of correctly correlated dependent variables, end-of-life strategies, were combined into a best classification tree. Performing several iterations of CART analysis on the data yielded different classification trees.

This iteration determined that the product characteristics that influence the end-of-life strategies most are wear-out life, technology cycle, level of integration, number of parts, reason for redesign and design cycle. The most important product characteristics were wear-out life and technology cycle. Both seemed equally important to the classification, found in many locations throughout the classification tree. The result was to use wear-out life and technology cycle as a ratio as the first classifier in the classification tree.

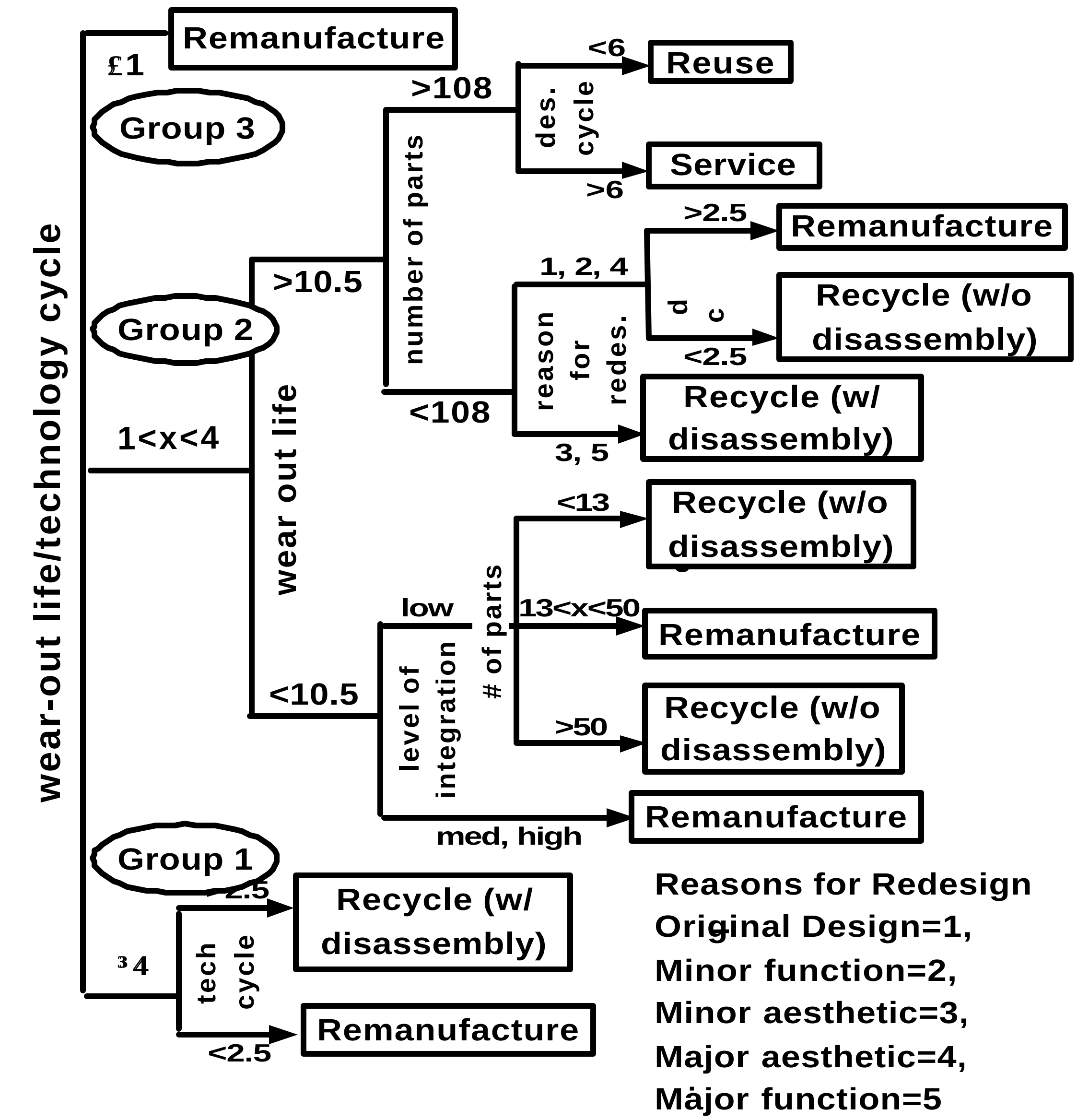


Figure 4-8. Final Classification Tree

In contrast to the previous classification tree, the final classification tree yields an accuracy of 86%. This increase is attributed to the use of normalized product characteristic – wear-out life divided by technology cycle. Using this ratio minimizes the variation in the responses. As well, the improvements result from increased number of case studies and redefined product characteristics. The evaluation and validation of this classification scheme is given in Chapter 5.

4.4 Conclusion

This research proves that possible end-of-life treatments are indeed influenced by the technical product characteristics and that best end-of-life strategy actually depends on technical characteristics. Many researchers have pushed for generic solutions across product sectors for end-of-life treatment. However, this work shows the contrary, that individual product characteristics require tailored product end-of-life strategies and treatment programs.

ELDA deals with product characteristics that determine the product end-of-life strategy. The case studies drive the correlation between technical product characteristics and end-of-life strategies. Providing designers with information about the factors they are able to control gives them the freedom to make choices on how to reduce the environmental impact of the product end-of-life. ELDA enables designers to create products with the best end-of-life performance in mind, according to the product end-of-life strategy. Other tools only provide a number with no relation to gauge process or choosing the right avenue for improvements. This is in stark contrast between ELDA and the other tools.

Evaluating the results and collection methodology yields possible improvements to the method. The validation of ELDA is through comparison between the industry practice and ELDA classification. The ability to accurately classify end-of-life strategies makes ELDA powerful.

5 EVALUATION AND VALIDATION

Chapter 5 demonstrates the validation and evaluation of the ELDA tool. The products' classified end-of-life strategy and industry practice are compared and analyzed. Agreement between ELDA and industry practice validates the method. It shows that ELDA succeeds in classification of product end-of-life strategies in agreement with current industry practices. The mismatch between ELDA and current best practice identifies areas for improvement in design and business practices. The application of ELDA to the case studies, provided by Philips Consumer Electronics, yields interesting results that are relevant to the evaluation of the model and understanding the implications of the work.

5.1 Evaluation of Results

5.1.1 Interpretation of Results

Closer examination into the results yields interesting findings such as the wear-out life to technology cycle diagram. The classification uses the ratio between product wear-out and technology cycle. In Rose et al (Rose et al. 1998b), the mapping of wear-out life to technology cycle is used to make recommendations for end-of-life treatment.

Figure 5-1 shows graphically the first two levels of the classification tree in Figure 4-8 from Chapter 4. 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, consists 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. These boundaries are drawn according to the classification of end-of-life strategies by the CART analysis.

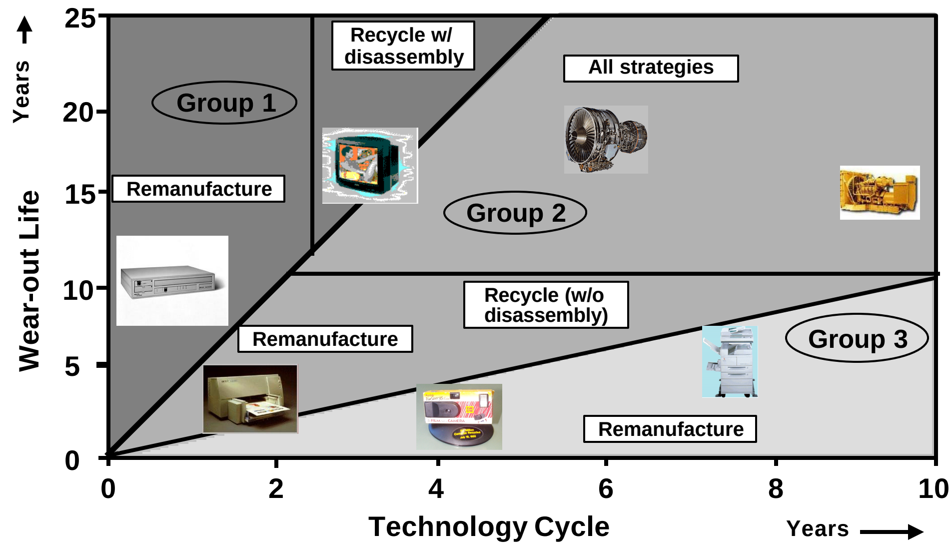


Figure 5-1. Wear-out life and technology cycle with end-of-life strategies

The products in Group 1 include a network router, a network server, a computer and a television. According to the classification methodology, products within this category should be remanufactured or recycled, through disassembly. The products with technology cycle less than 2.5 years should be remanufactured whereas products with technology cycle greater than 2.5 years should be recycled with disassembly. 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, an aircraft engine and other products. Products with wear-out life less than 10.5 years should be remanufactured or recycled without disassembly according to the classification. On the other hand, products with wear-out life greater than 10.5 years have a diverse set of product characteristics and experience the complete range of end-of-life treatment options – from reuse to recycle (without disassembly). Examples in Group 3 include a single use camera, a photocopier, a hand held vacuum cleaner, an electric power steering motor and a shipping container. According to the classification, 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. These recommendations and others are discussed in more detail in Chapter 7.

The results, according to end-of-life strategy, of the classification of ELDA are shown in Figure 5-2. Two products are classified for reuse. Four products have end-of-life strategies of service to prolong the life of the product. Twenty of the thirty-seven products are classified for remanufacture at the end-of-life according to their product characteristics. Eleven products should be recycled, four with some disassembly, and the other seven without disassembly according to the ELDA classification. ELDA does not classify products for disposal, because ELDA seeks to match the best industry practice, excluding disposal.

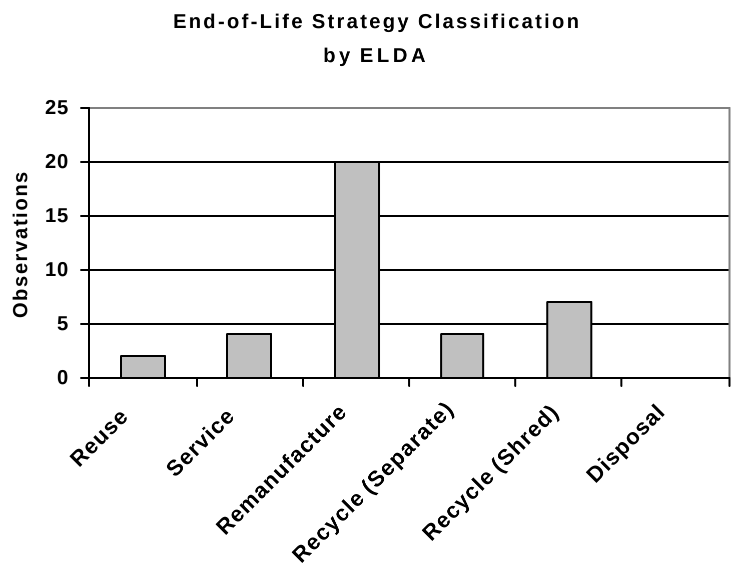


Figure 5-2. Classification Results by end-of-life strategy

5.1.2 Robust Data Acquisition

ELDA uses definitions of product characteristics that are new to the designer. Although a description is given, designers interpret the definitions according to their understanding and experience. Therefore, a small study was carried out to examine the effect of designer interpretation on the actual effect on the classified end-of-life strategies. The result is that in practice the methodology is robust to designer interpretation.

The data in Table 5-1 was collected from nine designers. The designers were asked to describe the product characteristics of a cell phone, television and vacuum cleaner. They were given a brief description of the technical characteristics as well as representative pictures of the three products. Their answers varied rather widely as shown in the following table for the cell phone. The data for the television and vacuum cleaner is provided in Appendix V.

Table 5-1. Variation in Responses for Cell Phones

PRODUCT CHARACTERISTICS	CELL PHONE			
	Lowest answer	Highest answer	Average answer	Standard Deviation of answers
Technology cycle	1	15	4.3	5.4
Wear-out life	2.5	5	4.1	1.1
Technology cycle / Wear out life	0.3	4	2.0	1.1
Level of integration	medium	high	High	N / A
Number of parts	5	200	51.7	74.2
Reason for redesign	Major changes in function	Major changes in aesthetics	Major changes in function	N / A
Design cycle	0.25	3	1.2	1.1

The resulting classification according to ELDA was robust even with the wide variety in the technical product characteristics. The effect on the end-of-life classification is given in table 5-2.

Table 5-2. Robustness Validation

VALIDATION RESULTS		PRODUCTS		
		Cell phone	Television	Vacuum cleaner
ELDA classified end-of-life strategy	Reuse			
	Service			
	Remanufacture	100%	63%	89%
	Recycle with disassembly		25%	
	Recycle without disassembly		12%	11%
Observed in Industry (best)		Remanufacture	Recycle with disassembly	Recycle without disassembly
Observed in Industry (average)		Disposal	Recycle with disassembly	Disposal

The results of this comparison reveal that the product characteristics may vary but the classified end-of-life strategy is similar in all three cases. For the cell phone, the classified end-of-life strategy was remanufacture with all respondents' identified product characteristics. For the vacuum cleaner, once again the product's characteristics determined an end-of-life strategy of remanufacture for 89% while only 11% of the observations suggested an end-of-life strategy of recycled without disassembly. For the television, 63% of classification pointed to remanufacture, 25% to recycle through disassembly and 12% to recycle through shredding. The cell phone and television have similar validations with the current best practices in industry. The vacuum cleaner's characteristics imply a recommended end-of-life strategy of remanufacture although the actual best practice is recycle without disassembly.

The ability to classify products in the appropriate end-of-life strategy with this wide variety in product characteristics shows the robustness of the tool. Technology cycle and wear-out life both seem to have wide interpretation, perhaps pointing to misinterpretation of the characteristics. However, using the ratio eliminates some of the variability and is more robust parameter for classification.

Number of parts has a wide standard deviation, suggesting difficulties in interpretation of the product characteristic definition. Better description of this characteristic and more guidance should improve the data collected and reduce the error in classification. A possible redefinition of number of parts is to include the weight of the product (i.e., number of parts divided by weight (parts / kg)) (Rose et al. 2000d).

5.1.3 Design control of product characteristics

Product designs and managers are able to work as a team to decide the appropriate values for the product characteristics. Data can be acquired by experience and also through in-depth research from previous products. Some disciplines of the product development team may be more familiar with the characteristics. The following table shows the product characteristics and the members most familiar with their values.

Table 5-3. Product characteristics and discipline that controls

PRODUCT CHARACTERISTICS	PRODUCTION	DESIGN	MANAGEMENT
Wear-out life		X	
Technology cycle		X	
Level of integration	X		
Number of parts	X		
Reason for redesign			X
Design cycle			X

Production and manufacturing design control or influence the number of parts and level of integration. For manufacturing simplicity, sourcing cost reduction, serviceability concerns the number of parts or level of integration may be affected by production managers' decisions. The designers influence the introduction of new technology in the products and are responsible for incorporating design elements that prolong the life of the product (by performing analysis such as robust design, FMEA, FEA). Product management influences the reasons for redesign (for example, addressing concerns from marketing or service departments) and design cycle (responding to marketing demands). Collecting these product characteristics is a collaborative process. Taking steps forward to control these product characteristics requires support from all three disciplines.

Based on the classification tree, the end-of-life strategies and associated product characteristics are shown in the following table. Each end-of-life strategy is listed with the corresponding characteristics that control the end-of-life strategy, according to the case studies collected in this research. This information can be used to influence product designers and managers decisions concerning product characteristics in order to achieve higher levels on the end-of-life hierarchy.

Table 5-4. End-of-Life Strategies and Critical Product Characteristics

END-OF-LIFE STRATEGY	WEAR-OUT LIFE / TECHNOLOGY CYCLE	OTHER PRODUCT CHARACTERISTICS
Reuse	1 < x < 4	wear-out life > 10.5 number of parts > 108 design cycle < 6
Service	1 < x < 4	wear-out life > 10.5 number of parts > 108 design cycle > 6
Remanufacture	≤ 1	
	1 < x < 4	wear-out life > 10.5 number of parts < 108 reason for redesign 1, 2, 4 design cycle > 2.5
	1 < x < 4	wear-out life < 10.5 level of integration, low 13 < number of parts < 50
	≥ 4	Technology cycle < 2.5
Recycle with disassembly	1 < x < 4	wear-out life > 10.5 number of parts < 108 reason for redesign 3, 5
	≥ 4	Technology cycle > 2.5

Table 5-4. End-of-Life Strategies and Critical Product Characteristics, Continued

END-OF-LIFE STRATEGY	WEAR-OUT LIFE / TECHNOLOGY CYCLE	OTHER PRODUCT CHARACTERISTICS
Recycle without disassembly	1 < x < 4	wear-out life > 10.5 number of parts < 108 reason for redesign 1, 2, 4 design cycle < 2.5
	1 < x < 4	wear-out life < 10.5 level of integration, low number of parts < 13
	1 < x < 4	wear-out life < 10.5 level of integration, low number of parts > 50

Product wear-out life and technology cycle affect each of the end-of-life strategies. The characteristics that are important for the reuse of a product are long wear-out life, high number of parts and design cycle less than six years. The product characteristics that affect servicing of a product are long wear-out life, high number of parts and long design cycle. Products that should be remanufactured range the divisions set by the ratio of wear-out life to technology cycle. Remanufactured products can have long wear-out life, moderate number of parts, various reasons for redesign and design cycle greater than 2.5 years. Other products that have remanufacturing as the end-of-life strategy have shorter wear-out life, low level of integration and number of parts ranging from 13 to 50 parts. Products that have recycle with disassembly have long wear-out life, moderate number of parts, and various reasons for redesign. Recycled products (without disassembly) sometimes have long wear-out life, moderate number of parts, various reasons for redesign and short design cycle. Other times, the recycled products have shorter wear-out life, low level of integration and have number of parts greater than 50 parts or less than 13 parts.

5.2 Validation Method

The ability to classify strategies enables companies to design future products that attain higher level on the end-of-life hierarchy. Once again, the definitions of end-of-life strategies are given to guide the following discussion about the validation method.

Table 5-5. Definitions of End-of-Life Strategies

Name	Definition
Reuse	Reuse is the second hand trading of product for use as originally designed
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.
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.
Recycling with disassembly	Recycling reclaims material streams useful for application in products. Separation into material fractions increases the value of the materials recycled by removing material contaminants, hazardous materials, or high value components. The components are separated mostly by manual disassembly methods.
Recycling without disassembly	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.
Disposal	This end-of-life strategy is to landfill or incinerate the product with or without energy recovery

The procedure for collecting the current end-of-life strategies practiced in industry included observing and questioning recycling organizations, producers and consumers. As well, the legislation requiring a particular end-of-life treatment and internet sales were monitored to have a better view of the end-of-life treatment situation. Literature describing end-of-life treatment was also very helpful in collecting the end-of-life strategy data. During the collection of this data, the question ‘for the majority of the products received, how are they processed at the end-of-life?' (What is the end-of-life strategy?) was posed.

With the responses, if the answers were consistently the same (for example, reuse), then the product end-of-life strategy was reuse. If there are conflicting answers, the one higher on the hierarchy is labeled best and the one lower labeled average. If multiple answers were given, then the observation most frequently cited is used as the average. Even if there was only one case where reuse was the end-of-life strategy implemented on a regular basis, it was identified as the best end-of-life strategy. The following tables present the observations of industry practice and the classification by ELDA.

Table 5-6. Strategy classified by ELDA and the observed industry practice

PRODUCTS	ELDA	BEST INDUSTRY	AVERAGE INDUSTRY
Air Bag	Remanufacture	Remanufacture	Disposal
Aircraft Engine	Service	Service	Service
Automatic Transfer Switch	Service	Service	Recycle without disassembly
Automobile	Reuse	Reuse	Reuse
BubbleJet Printer	Remanufacture	Remanufacture	Remanufacture
Computer	Remanufacture	Reuse	Recycle without disassembly
Computer Mouse	Recycle without disassembly	Recycle without disassembly	Disposal
Computer-Video Projector	Remanufacture	Reuse	Recycle without disassembly
Connections	Recycle without disassembly	Recycle without disassembly	Recycle without disassembly
Digital Copier	Remanufacture	Remanufacture	Remanufacture
Electric Power Steering Motor	Remanufacture	Remanufacture	Remanufacture
Elevator	Remanufacture	Service	Service
Fiberoptic Transceiver	Recycle without disassembly	Recycle without disassembly	Recycle without disassembly
Filter	Recycle without disassembly	Recycle without disassembly	Disposal
Generators	Service	Service	Service
Hand Held Vacuum	Remanufacture	Remanufacture	Recycle without disassembly
High Speed Line Printer Floor Cabinet	Remanufacture	Remanufacture	Recycle without disassembly
Inkjet Printer	Remanufacture	Remanufacture	Recycle without disassembly
Klystrons	Service	Service	Service
Laserjet Printer	Remanufacture	Remanufacture	Remanufacture
Lead Acid Batteries	Recycle with disassembly	Recycle with disassembly	Recycle with disassembly
Miniature Robot	Remanufacture	Remanufacture	Recycle without disassembly
Network Routers	Remanufacture	Remanufacture	Recycle without disassembly
Network Server	Remanufacture	Remanufacture	Recycle without disassembly
NLC Cell Structure	Reuse	Reuse	Reuse
NLC Support Structure	Remanufacture	Reuse	Reuse
Photocopier	Remanufacture	Remanufacture	Remanufacture
Portable Radio	Recycle with disassembly	Recycle with disassembly	Disposal

Table 5-6. Strategy classified by ELDA and the observed industry practice, Continued

PRODUCTS	ELDA	BEST INDUSTRY	AVERAGE INDUSTRY
Printer Hammerbank	Remanufacture	Remanufacture	Recycle without disassembly
Shipping Container	Remanufacture	Recycle without disassembly	Disposal
Single Use Camera	Remanufacture	Remanufacture	Remanufacture
Telephone	Remanufacture	Remanufacture	Disposal
Television	Recycle with disassembly	Recycle with disassembly	Recycle with disassembly
Typewriter	Recycle without disassembly	Recycle without disassembly	Disposal
Vacuum Cleaner	Recycle without disassembly	Recycle without disassembly	Disposal
Washing Machine	Recycle without disassembly	Recycle without disassembly	Recycle without disassembly
Washing Machine Electric Motor	Recycle with disassembly	Recycle with disassembly	Recycle with disassembly

The examination and analysis of this table shows the differences between the end-of-life strategies recommended by ELDA, current industry average practice and current industry best practice. The current industry average is the end-of-life treatment of the product most often found in industry. For many electronic products in the United States the current average end-of-life strategy is recycle, with or without some disassembly, and disposal. This is different in other countries of the world, mostly due to legislation concerning product end-of-life treatment.

5.2.1 Comparison between ELDA and Industry Practice

Further examination and analysis of the differences between the end-of-life strategies recommended by ELDA, current industry average practice and current industry best practice reveal useful information. The first application of CART resulted in a classification method, described in section 4.2.2, which yielded 46% agreement with industry best practice. The final classification method, shown in figure 4-8, yields an 86% agreement with the best practices observed in industry.

Table 5-7. Percent agreement between Original and Final and industry best practice

METHODOLOGY	PERCENT AGREEMENT BETWEEN CLASSIFICATION AND INDUSTRY BEST PRACTICE
Original	46%
Final	86%

The final classification shows greater agreement than original classification as a result of larger sample size used in CART and more appropriately defined product characteristics. Better defined product characteristics provide greater accuracy and thus a better classification. Larger sample size provided more proof or verification that the classification method is appropriate.

A Venn diagram (figure 5-3) shows the ELDA classification along with the industry average and best practices. Between the ELDA classification and the industry best practice there is 86% agreement in the end-of-life strategies. However, there is only 46% agreement between ELDA classification and average industry practice.

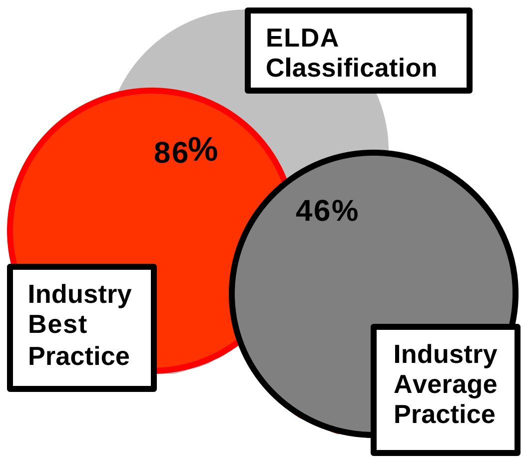


Figure 5-3. Percentage agreement between ELDA and industry practice

The following picture shows the different end-of-life strategies with the ELDA classification, current best practice and current average practice. ELDA classifies twenty products to be remanufactured. Currently, sixteen products have remanufacturing as industry best practice. Six products experience remanufacturing, on average. There are eight products, out of the thirty-seven products examined that have disposal, either through incineration or landfill, as the end-of-life strategy as observed in average industry practice. ELDA does not recommend disposal as an end-of-life strategy for products.

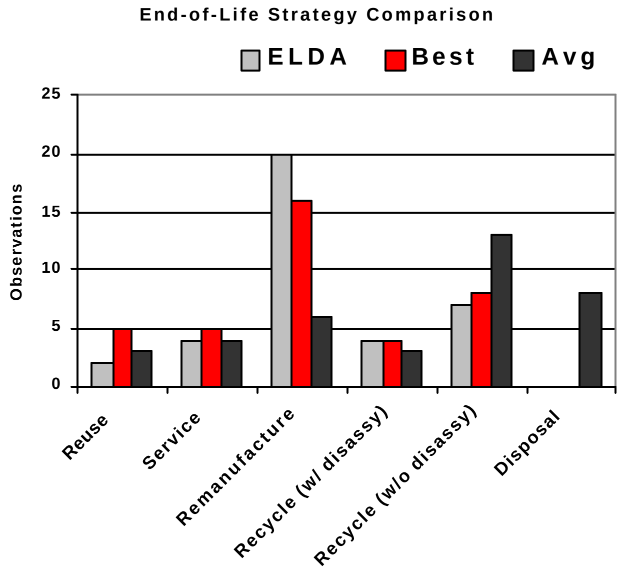


Figure 5-4. Observations of End-of-Life Strategies

By numbering the end-of-life strategies (1-reuse, 2-service,…, 6-disposal), it is possible to distinguish how accurately or inaccurately the classification is in comparison to the industry practice. Table 5-8 shows the ranges from –4 to 2, where the numerical quantity denotes the separation between the two quantities. Negative quantities show that the first quantity has lower end-of-life strategy than the second quantity. Positive quantities imply that the first quantity has higher end-of-life strategy than the second quantity. For example, there are two products that have industry best practice three end-of-life strategies higher on the hierarchy than the industry average practice.

Table 5-8. Degree of Agreement and Disagreement -- Number (Percentage)

Difference comparison	-4	-3	-2	-1	0	1	2
ELDA – Best industry practice			1 (3%)		32 (86%)	1 (3%)	3 (8%)
Best – Average industry practice	2 (5%)	3 (8%)	8 (22%)	5 (14%)	19 (51%)		
ELDA – Average industry practice		4 (11%)	10 (27%)	4 (11%)	17 (46%)	1 (3%)	1 (3%)

The following table graphs the percentages of products that have different end-of-life strategies from industry practice. The values are listed in parenthesis in Table 5-8. The percentage of products with end-of-life strategies classified by ELDA equivalent to the industry best and average practice is 86% and 46%, respectively.

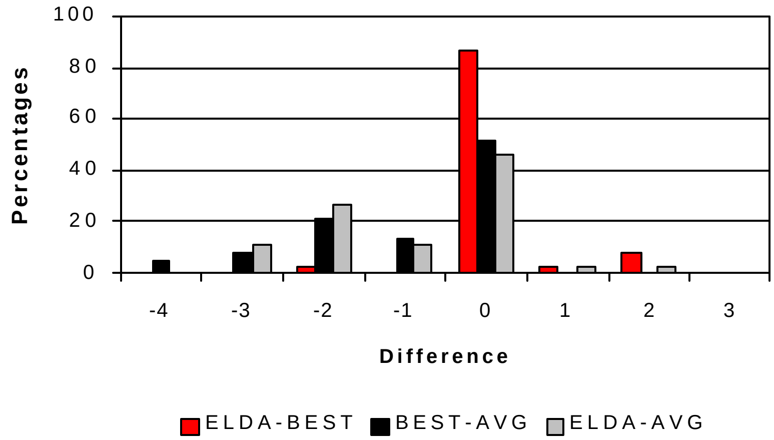


Figure 5-5. Comparison between ELDA and industry practice

Of the products, 86% of the time the classification used in ELDA matches industry best practice. 3% of products ELDA classifies two levels lower on hierarchy than current best practice (NLC support structure). Therefore, there were cases of companies that were reusing these products although through ELDA's classification the suggested end-of-life strategy was remanufacture. This disagreement results from a very small ratio of wear-out life/technology cycle. 3% of products ELDA classifies one level higher on hierarchy than current best practice (elevator). 8% of products, ELDA classifies two levels higher than current best practice (shipping container, computer and computer video projector).

Table 5-9. Comparison of ELDA and best industry practice

ELDA AND BEST INDUSTRY PRACTICE	ELDA	BEST INDUSTRY PRACTICE	REASONS WHY THERE IS A MISMATCH
Computer-Video Projector, computer, NLC Support Structure	Remanufacture	Reuse	High cost product, good reuse
Elevator	Remanufacture	Service	Difficult to remove product for end-of-life, better to service product where it is
Shipping Container	Remanufacture	Recycle without disassembly	Bulky, high transportation costs to original manufacturer

There are companies that are implementing end-of-life systems taking advantage of the opportunities offered from product characteristics. Of the 37 products studied, representing information technology, consumer durables and commercial sectors, 32 show that technical product characteristics indeed control the end-of-life strategy. This is the first work to demonstrate this correlation between product characteristics and end-of-life strategies. The work also demonstrates that product sectors do not always have exactly same end-of-life strategies, but rather the end-of-life strategy depends on the characteristics of the individual products. The five products, with mismatched end-of-life strategies to their best industry practice, have varying reasons ranging from high value product to high transportation costs. Generally, ELDA is not successful in classifying products that are expensive or pose logistical or transport challenge. The computer-video projector and computer retain their value over time while the elevator and shipping container have high transportation costs.

Looking only at the success stories does not provide insight into influencing factors that will guide product improvement. Therefore, the examination is only focused on where the classification analysis was incorrect, rather than on the correct classification of end-of-life strategies. The following graph shows the products with mismatches between the ELDA classification and industry practice. The vertical axis is the different end-of-life strategies - from reuse to disposal. The horizontal axis is the products that have mismatches.

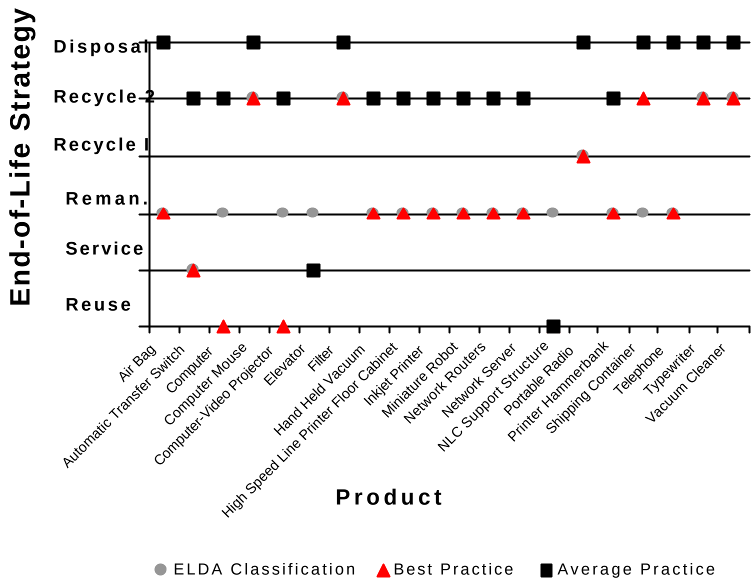


Figure 5-6. ELDA, best and average industry practice

In comparing best and average practice, the expectation would be that there are no differences. However, companies react to market pressures, government regulations and competitive threats uniquely depending on financial barriers, investment opportunities and image enhancement possibilities. Of the seventeen products that have differing average and best industry practice (46%), there is an approximately fifty-fifty split between products aimed at private consumers or industrial or institutional consumers.

Table 5-10. Comparison of Best and Average

BEST AND AVERAGE INDUSTRY PRACTICE	BEST	AVERAGE	REASONS WHY
Computer, computer video projector	Reuse	Recycle (without disassembly)	Reapplication depends on length of original owner use
Automatic Transfer Switch	Service	Recycle (without disassembly)	Difficult to check reliability after in service for long time
Handheld Vacuum, Miniature Robot, High Speed Line Printer Floor Cabinet, Printer Hammerbank, Network Routers, Network Server, Inkjet Printer	Remanufacture	Recycle (without disassembly)	Impossible to collect all products at end-of-life, little direct communication with consumers

Table 5-10. Comparison of Best and Average, Continued

BEST AND AVERAGE INDUSTRY PRACTICE	BEST	AVERAGE	REASONS WHY
Airbag, Telephone	Remanufacture	Disposal	Small, little value; difficult to reapply in market
Portable Radio	Recycle (with disassembly)	Disposal	Impossible to collect product from consumer
Computer Mouse, Filter, Typewriter, Vacuum Cleaner	Recycle (without disassembly)	Disposal	Impossible to collect product from consumer, products collected in attics, spare rooms
Shipping Container	Recycle (without disassembly)	Disposal	Damaged in usage, Too bulky to transport

On average, there are companies that do not take advantages of opportunities offered by the technical product characteristics. In many cases, they may not have been confronted with the need to do something to products at end-of-life. In other cases, efforts have been made to improve product end-of-life treatment but not as successfully. This means that there are differences external to the technical product characteristics influencing the company behavior. Generally, the differences between industry best and average practice occur when products are impaired by collection difficulties, resulting from the perception that products are not valuable at their end-of-life.

5.3 Additional Case Studies

Courtesy of Philips Consumer Electronics, a database of benchmarked consumer electronic products was made available for this analysis. These case studies were based on a sample of 50 different consumer electronic products from a number of different product categories. The following chart shows a sample of these products and their characteristics based on interviews with designers at Philips.

Table 5-11. Philips case studies and product characteristics

PRODUCT	WEAR-OUT LIFE	TECHNOLOGY CYCLE	WEAR-OUT LIFE / TECHNOLOGY CYCLE	LEVEL OF INTEGRATION	NUMBER OF PARTS	REASON FOR REDESIGN[1]	DESIGN CYCLE
Portable CD Players (AZ7382)	5	10	0.5	Med	18	2	0.5
Audio System (FW870)	9	3.5	2.6	High	69	3	2
CD-Recordable (FW-R8)	7	2.5	2.8	High	65	2	3
CD-Recordable (CDR 785)	7	2.5	2.8	Low	54	2	3
DECT Cordless Phone (Onis)	10	5	2	Low	25	3	2
Cellular Phone (Diga)	3	0.5	6	Med	32	2	1
VCR (860)	7.5	2.0	3.75	Low	36	3	1
DVD (950)	5	1.3	4	Low	38	2	1
Upmarket Television (32PW9515)	11	4	2.75	Med	51	5	1
Mainstream TV (21PT4465)	11	4	2.75	Low	32	5	1
LCD Monitor (Brilliance 151AX)	5	2.0	2.5	High	69	2	2
CRT Monitor (Brilliance 107)	6	3.0	2	High	88	2	1
Fax (PPF241)	6	2.0	3	High	70	2	2

[1]Reason for redesign: 1=Novel Design, 2=Minor evolution (function), 3=Minor evolution (aesthetic), 4=Major evolution (aesthetic), 5=Major evolution (function)

The products were plotted according to their wear-out life and technology cycle, as shown in Figure 5-7. The majority of the products examined were clustered in the lower left-hand corner of the wear-out life and technology cycle diagram. The recommended end-of-life strategy for 77% of the products was remanufacturing. Only 15% of the products had suggested end-of-life strategies of recycling for material value with moderate disassembly. The remaining 8% of the products should be recycled for material value without any disassembly, according to the ELDA analysis.

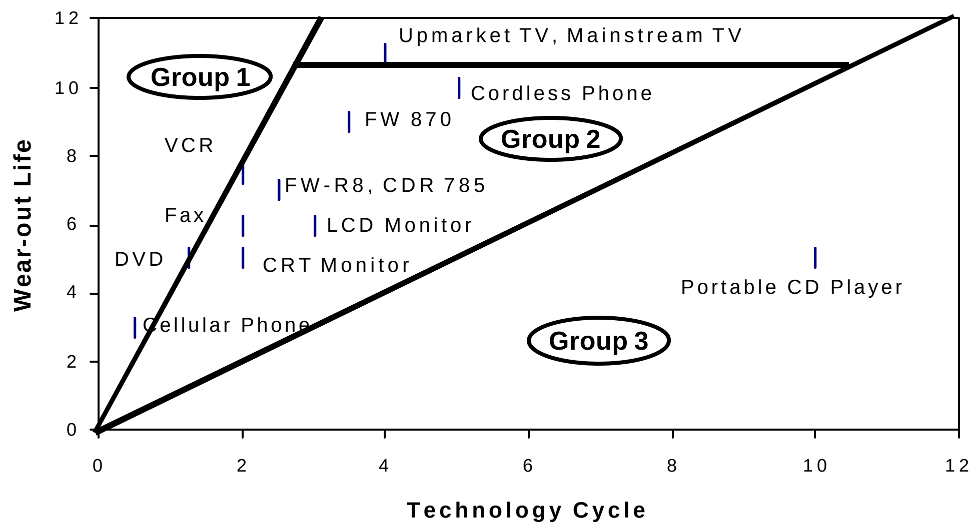


Figure 5-7. Grouping of case products according to wear-out life and technology cycle

Digital video disc (DVD) player and cellular phone fall into Group 1, where the technology cycle is rapid. The television falls into Group 2 with wear-out life greater than 10 years. The other products cluster in the Group 2, with quite similar product characteristics, including cordless phone, audio products and monitors. The portable CD player has relatively long technology cycle for its wear-out life, and therefore is located within Group 3.

Table 5-12 shows the ELDA classification, best industry practice and average industry practice for the Philips Consumer Electronics products. The Dutch take back regulation requires that producers recycle certain electronic products, thus making the best end-of-life treatment higher, most frequently recycling.

Table 5-12. ELDA and Best End-of-Life Treatment Results

PRODUCT	END-OF-LIFE STRATEGY RECOMMENDED BY ELDA	BEST END-OF-LIFE TREATMENT (NL)	AVERAGE END-OF-LIFE TREATMENT (NL)
Portable CD Players (AZ7382)	Remanufacture	Recycle (with disassembly)	Recycle (without disassembly)
Audio System (FW870)	Remanufacture	Recycle (without disassembly)	Recycle (without disassembly)
CD-Recordable (FW-R8)	Remanufacture	Recycle (without disassembly)	Recycle (without disassembly)

Table 5-12. ELDA and Best End-of-Life Treatment Results, Continued

PRODUCT	END-OF-LIFE STRATEGY RECOMMENDED BY ELDA	BEST END-OF-LIFE TREATMENT (NL)	AVERAGE END-OF-LIFE TREATMENT (NL)
CD-Recordable (CDR 785)	Recycle (without disassembly)	Recycle (without disassembly)	Recycle (without disassembly)
DECT Cordless Phone (Onis)	Remanufacture	Recycle (with disassembly)	Disposal
Cellular Phone (Diga)	Remanufacture	Recycle (with disassembly)	Disposal
VCR (860)	Recycle (without disassembly)	Recycle (without disassembly)	Disposal
DVD (950)	Remanufacture	Reuse	Disposal
Upmarket Television (32PW9515)	Recycle (with disassembly)	Reuse	Recycle (with disassembly)
Mainstream TV (21PT4465)	Recycle (with disassembly)	Recycle (with disassembly)	Recycle (with disassembly)
LCD Monitor (Brilliance 151AX)	Remanufacture	Reuse	Recycle (with disassembly)
CRT Monitor (Brilliance 107)	Remanufacture	Recycle (with disassembly)	Recycle (with disassembly)
Fax (PPF241)	Remanufacture	Service	Recycle (with disassembly)

Examining the difference between the ELDA classification and the best industry practice yields interesting results. ELDA classifies three of the thirteen products in agreement with the end-of-life treatment practiced in industry. The remaining products have differing end-of-life strategies, from ELDA and best practice.

Table 5-13. Comparison of current end-of-life treatment and strategy recommended

PRODUCTS	MATCH	MISMATCH
Portable CD Players (AZ7382)		X
Audio System (FW870)		X
CD-Recordable (FW-R8)		X
CD-Recordable (CDR 785)	X	
DECT Cordless Phone (Onis)		X
Cellular Phone (Diga)		X
VCR (860)	X	
DVD (950)		X
Upmarket Television (32PW9515)		X
Mainstream TV (21PT4465)	X	
LCD Monitor (Brilliance 151AX)		X
CRT Monitor (Brilliance 107)		X
Fax (PPF241)		X

This mismatch between the recommended end-of-life strategy and actual end-of-life treatment pursued by industry is relevant to defining steps for improvement. As shown in Table 5-13, for a sample of consumer electronic products, the end-of-life strategy recommended by ELDA does not agree with the current end-of-life treatment practiced in industry. For the mainstream television, audio system (with CD-recordable) and VCR, the end-of-life strategy and treatment indeed agree. The other audio systems, cell and cordless phones and monitors are actually recycled but their recommended end-of-life strategy according to their product characteristics is remanufacture. It is also important to notice for three of these example products (televisions, monitors and audio), legislation mandates the end-of-life treatment -- recycling.

In some cases, the recommended end-of-life strategy is not currently possible because of lack of infrastructure and incentive systems. Additionally, market demands and consumer preferences change very quickly in this product sector, so that information must be included as well.

5.4 Lessons learned from Evaluation and Validation

Evaluation of the results from the classification of the end-of-life strategies shows evidence that products do not have generic end-of-life strategies, but are influenced heavily by the product characteristics. The methodology applied for collecting data from designers concerning product characteristics is robust, with the same classification resulting from a wide variety of answers. As far as validation, the comparison between the end-of-life strategies practiced in industry and the classification according to the product characteristics is powerful and agrees remarkably. The inaccuracies of the classification are due to the non-technical aspects of the end-of-life systems.

The validation and evaluation of ELDA through additional case studies suggests avenues for further investigation. Chapter 6 will explain two important add-ons to ELDA, providing the link to inverse supply chain issues, market developments and consumer issues. The alignment or misalignment of the case studies reveals opportunities and identifies areas of improvement in relying completely on technical solutions.

As discussed extensively in Chapter 4, product characteristics determine the product end-of-life strategies. ELDA accurately classifies the end-of-life strategies for products by the technical product characteristics with an accuracy of 86%. As well, companies themselves decide end-of-life treatment based on external circumstances and pressures (consumers, government, and recyclers). In some cases, business decisions rather than the technical characteristics of the product control the actual end-of-life treatment. The simple diagram below demonstrates the link between these two concepts.

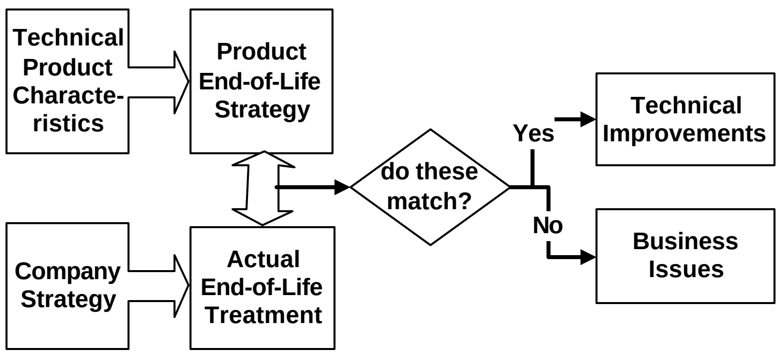


Figure 5-8. Relationship between ELDA and actual practice

The mismatch between recommended end-of-life strategy and the actual end-of-life treatment is due to having inefficiencies in the end-of-life systems, developing end-of-life systems for inappropriate end-of-life strategies, and lacking incentives for participation and innovation towards higher levels of reuse. These bottlenecks, or inefficiencies, can be eliminated through work on the value chain, both internal and external.

The improvement of end-of-life strategies currently observed in industry through improved strategy building depends on technical solutions as a base or starting point. After using ELDA, the technical description gives the recommended end-of-life strategy further evaluation is required for full solution. Consumer issues, such as reactions to increased functionality in products, can influence purchasing, discarding and usage behaviors. As well, the internal and external issues associated with the value chain of the company can control the successfulness of end-of-life strategies.

Apparently, 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. Knowing how the classification deviates from the real situation gives insight into how to improve the current practice. In depth examination of these factors, given in Chapter 6, helps achieve eco-efficient end-of-life strategies.

5.5 Conclusion

Understanding the factors that affect end-of-life of a product gives designers keys to reduce environmental impact, by moving to higher end-of-life strategies on the hierarchy. Consumers, policy makers and competitors are pushing reducing environmental impact, but the final responsibility is on product designers and managers to design new products addressing these issues. ELDA is a method that systematically classifies products into end-of-life strategies according to technical product characteristics.

Evaluating the product characteristics and their robustness improves the application of ELDA. Validation of the classification method yields agreement with the end-of-life strategies practiced currently in industry. The agreement was 86% for the research results and industry best practice.

The misalignment between average and best industry practice can be corrected through other techniques. The mismatch is due to factors external to the product technical characteristics. These external factors are influenced by the organization of the value chain and developments in the market.

6 ELDA AND OTHER PERSPECTIVES

Chapter 6 discusses business issues affecting the end-of-life systems including the Environmental Value Chain and market developments. Preliminary work is presented into examining value relationships that are particular to the company (internal value chain) and business in general (external value chain) influencing the product end-of-life. The market developments, or changes of functionality over time, are discussed as well. These tools will be described briefly and their usage in conjunction with ELDA. Understanding these items will be instrumental in realigning the mismatch between ELDA and industry practice.

6.1 Need to assess business issues

The need of integrated technical and business solution has become apparent through the research, as described in Chapter 5. Although ELDA shows what product characteristics control the end-of-life design strategy appropriate for products, to date, companies have relied on other items to determine end-of-life treatment. As shown in Chapter 5, the simple diagram below demonstrates the link between these two activities.

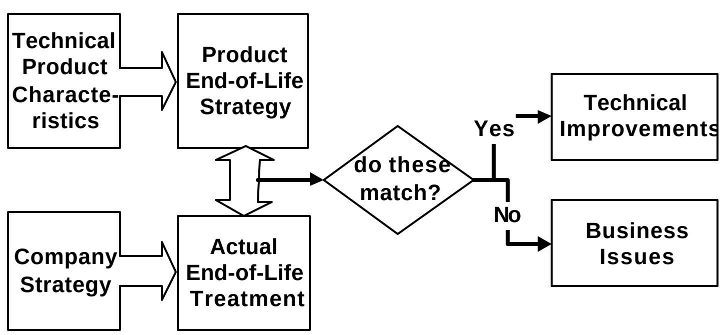


Figure 6-1. Relationship between ELDA and actual practice

The mismatch between recommended end-of-life strategy and the actual end-of-life treatment is due to:

- having inefficiencies in the end-of-life systems,
- developing end-of-life systems for inappropriate end-of-life strategies, and
- lacking incentives for participation and innovation towards higher levels of reuse.

These bottlenecks, or inefficiencies, can be eliminated through work on the value chain, both internal and external.

6.2 Environmental Value Chain Analysis

Linking business and end-of-life management is possible through examining the value systems inside and outside the company. Besides the producing companies, parties in this endeavor include government, producers, recycling companies, and consumers. After product characteristics, the complex interactions between these four stakeholders determine what happens to a product at the end-of-life. As will be shown below in several case studies, the drivers are diverse and the incentives are relevant (Rose et al. 2000a). Evaluating the effectiveness of these case studies will give important learnings which can be used to improve government policies, initiatives established by producers and programs created by recycling companies.

The Environmental Value Chain Analysis (EVCA) pulls from Inverse Supply Chain Management and Customer Value Chain Analysis. Inverse supply chain management aims to control the return of products and to provide needed service to products that the customer no longer finds suitable. This ranges from replacing old products with new products in lease situations (Xerox), collecting products and providing a service (Kodak), repairing or providing maintenance to product (GE), and upgrading or providing trade-in value for the old product (HP). These activities can differ greatly depending on if the consumer is an individual or an institution (i.e., company, governmental organization, or university).

Environmental Value Chain Analysis has also been developed from Customer Value Chain Analysis (CVCA). Wilson (Wilson 1993) cites that identification of the deficiencies in understanding the value proportions for the stakeholders is the most prevalent and critical failure mode of product development. Briefly, the basic steps to Customer Value Chain Analysis (Ishii 2000) are to:

- identify the pertinent parties involved
- identify the relationship by defining the flow of money, products and information
- analyze graph to address concerning value proposition.

EVCA looks different depending on the reasons for initiating the end-of-life system and end-of-life strategy. An end-of-life system focused on the end-of-life strategy – product reuse – looks different from one aiming to achieve high percentages of material recycling

– product recycling through disassembly and without disassembly, leads to different relationships as well. The results of Environmental Value Chain Analysis allow decision makers to identify the critical success factors of such programs upfront.

In searching for a more direct route of communication of value, EVCA is able to reduce complexity and cost of building programs for eco-efficient treatment of products at the end-of-life.

EVCA can be used to understand the relationships between the players: producers, consumers, government and recyclers. Like CVCA, the first step is to determine the pertinent players in the end-of-life discussion. A generic view of the relationships between government, producers, consumers and recyclers is shown in the following table.

Table 6-1. Relationships among Players

Actors	Government	Consumers	Producers	Recyclers
Government	Political decision making	Votes! Taxes $	Lobbying Taxes $	Lobbying Taxes $
Consumers	Representation, services	Feelings, Fads	Products Services	Used Products Services
Producers	Regulation, representation, services	Complaints Product $ Preowned $	Competition	Material $ Recycled material
Recyclers	Regulation, representation, services	Products	Products Recycling cost $	Competition

In table 6-1, the items along the diagonal show what happens within the stakeholder groups. The items in the upper quadrant demonstrate the actions or services that the rows contribute while the lower quadrant reveals what the stakeholders, along the column, receive from the stakeholders, in the rows. For example, consumers receive representation and services from government, but they contribute votes and taxes to government.

Figure 6-2 demonstrates an external EVCA applied generally to the relationships among producers, consumers, recyclers and government, an illustration of the information provided in table 6-1.

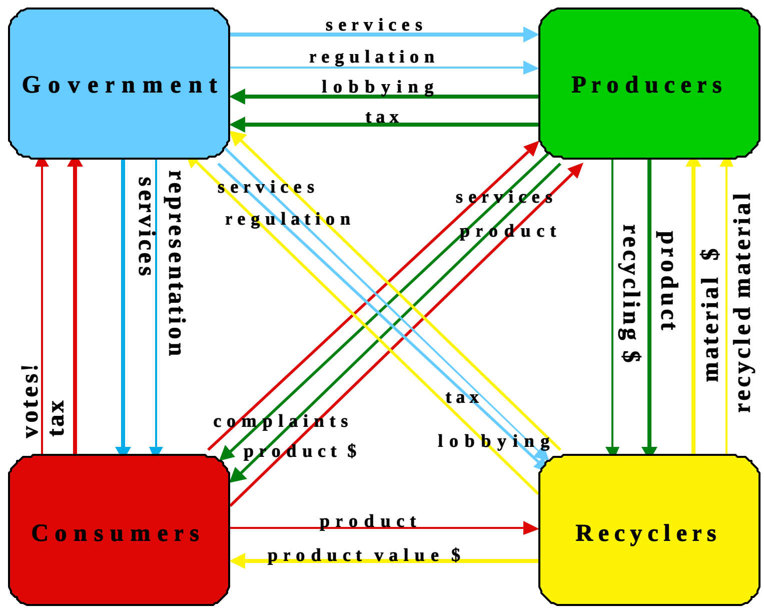


Figure 6-2. Representation of relationships among players

Within each of these groups, especially government and producers, there are issues for the internal value chain as well. The internal value chain includes the interrelationships between departments in the company or within the governmental agency. In some cases, there is no incentive inherent to the organization to promote innovation and change. The next sections briefly outline the participants individually (Rose et al. 2000c).

Government: Many levels within the government establish laws about environmental issues. In the European Union, the Directorate General for Environment is responsible for take back and recycling regulation. However, other Directorates General must be consulted before presenting a proposal to the EU Council and the European Parliament. In the individual member states, similar relationships exist. As one can imagine, having numerous organizations responsible for environmental legislation can be very complicated and at least will be time consuming.

Consumers: In the end-of-life stage, consumers possess a product that no longer satisfies their needs, which they desire to dispose. This process can cause discomfort to the consumer if they are unable to get rid of the product in an easy way or have to pay for its disposal. Van Nes (van Nes et al. 1999) identifies nine reasons for consumers discarding products in her work; however, it can be simplified into three main categories: breakdown, functionality changes, or design aesthetics.

Producers: The group of producers includes suppliers, manufacturers and assemblers of products. Increasing legal and consumer pressure pushes producers to develop take back systems. Sometimes, however, it is profitable to take products back and many are already in place for this reason alone. Before the external issues are addressed associated with implementing take back systems, producers must work on their internal value chain, the relationships internal to the organization, for instance, to provide appropriate incentives for further innovation. Only through such internal support and systems will designers have incentives to improve designs specifically with end-of-life in mind.

Recyclers: Recyclers consists of the collectors, processors, and distributors of discarded products, either disposing of waste or retrieving value from products and materials. Collection may be through retail or municipal infrastructure, through charitable donations, or through individual curbside pick-up. End-of-life processing includes repair, servicing, remanufacturing, recycling through shredding with or without disassembly and disposal through incineration or landfill. Recyclers seek to minimize the costs and maximize the profits mostly by focusing on specific material or product streams. This should be aligned with characteristics of products to be treated.

Others: Other players of relevance in end-of-life systems are distributors, retailers and pre-processors of secondary materials and waste. The first two members provide direct links between the customers and producers. These groups often have little motivation to participate in product end-of-life treatment because they make money by keeping new products on their shelves or in storage, not for storing old products that have been returned from the customer. To remove this barrier, the Dutch take back system provides and incentive, paying retailers 2 NLG ($0.75) for handling old televisions.

6.3 Case Studies of End-of-Life Systems

Voluntary take back programs in many ways mirror those created through legislation or public-private negotiated agreements. Individual companies or specific industries set up mechanisms to recover products, either directly by the manufacturer or through a designated collection network. Costs are borne either by an individual firm or through fee systems established collectively by the sponsoring industry (Scarlett 1999). Using the EVCA method, case studies demonstrate the implementation and benefits from performing EVCA. The case studies represent a wide range of products and companies, including Kodak single use camera, Philips Medical Systems, Philips television (not voluntary), Nike athletic shoes, GE aircraft engines, Xerox photocopiers, IBM servers and HP inkjet printers (Rose et al. 2000a, Rose et al. 2000c).

Due to differences in product characteristics, the end-of-life costs can be substantially different. For products with end-of-life costs, including end-of-life collection and processing, that yield a monetary surplus, end-of-life systems are best developed through voluntary means, according to the market forces. In cases where the product processing and collection costs yield a deficit, the end-of-life system is best managed and developed through regulatory means. These issues are summarized in the following table.

Table 6-2. Need for Mandatory and Voluntary end-of-life systems

EOL PROCESSING AND COLLECTION COSTS YIELDS:	TYPE OF CUSTOMER	
	OEM	Private
Surplus	End-of-life System best developed through voluntary means	
Deficit	End-of-Life System best developed through mandatory or regulatory influences	

In order to reduce the costs that are being passed on in the case that products' end-of-life treatment yields a deficit, EVCA can help producers reduce costs and provide value in their end-of-life treatment activities. Where product end-of-life treatment actually provides financial benefit or incentives, producers can use EVCA to make further improvements.

In voluntary take back systems, there are large differences between private and institutional consumers. Private consumers typically make purchases in small volumes and small monetary amounts. For private consumers, collection is difficult to organize effectively since private customers are anonymous, may be emotionally attached to products, and discard products for different reasons. The differences between institutional (OEM) and private consumers are exacerbated at the end-of-life phase, requiring additional effort placed in the development of private consumer end-of-life systems.

6.3.1 Voluntary Take Back Systems

Product end-of-life systems have been established by individual businesses independent of other firms operating in the same industry. These programs include: Nike's Reuse-A-Shoe program; IBM, Dell and Hewlett Packard's computer-recovery programs; Hewlett-Packard's printer toner cartridge return program; several brand-name clothing return programs; a number of returnable transport packaging programs; and Saturn's bumper fascia return program (Scarlett 1999). To date, voluntary take back programs appear to have emerged in circumstances where there are one or several of the following characteristics:

- a high value associated with the discarded product;
- relatively low frequency, high-value transactions between a manufacturer and a consumer;
- a relatively close or ongoing relationship between the customer and manufacturer;
- specialty or high-end products for which environmental or other social goals may enhance customer loyalty; and
- risk of improper disposal and associated liabilities (Scarlett 1999).

The next few sections describe voluntary end-of-life systems at Kodak, HP, GE, Philips and Siemens Nixdorf.

Kodak has developed an extensive remanufacturing organization for their single use cameras. Consumers return the cameras in order to have the film developed. After removing the film for processing, photofinishers are encouraged to return the cameras to Kodak for recycling and reuse, reimbursing the photofinishers for each camera returned and pays the shipping costs. The company reported that more than 80 million one-time-use cameras had been recycled and/or reused, representing a 77 percent recycling rate, exceeding recycling rates for both aluminum cans and soft drink bottles (Kodak 2000). A total of 26 of the 27 (96.3%) parts that make up Kodak's single-use camera are either recycled or reused in a new camera (some components are reused up to 8 times). That works out to between 76 and 90% of the camera by weight.

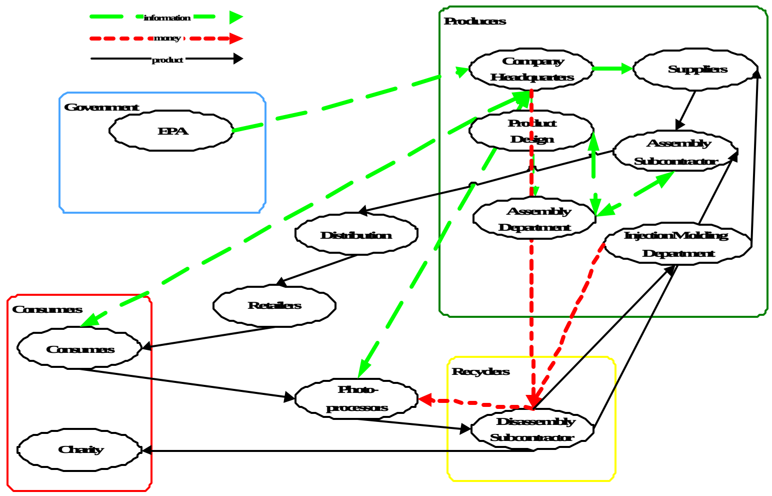


Figure 6-3. Kodak Single Use Cameras

Hewlett Packard sells a wide variety of information technology equipment including, for example, computers, servers, and printers. The Hewlett Packard and Micrometallics partnership between an original equipment manufacturer and a recycling company recovers service parts and recycles useful materials from end-of-life products (St. Denis et al. 1998). HP realizes great savings to the company by collecting products to harvest for service parts. As of yet, they have had limited success in reuse, or reselling their products on the market. To provide incentives for consumers to return their broken or outdated products, HP has started a program, Trade-in Trade-Up that gives trade-in value to apply towards the purchase of a new product (HP 2000).

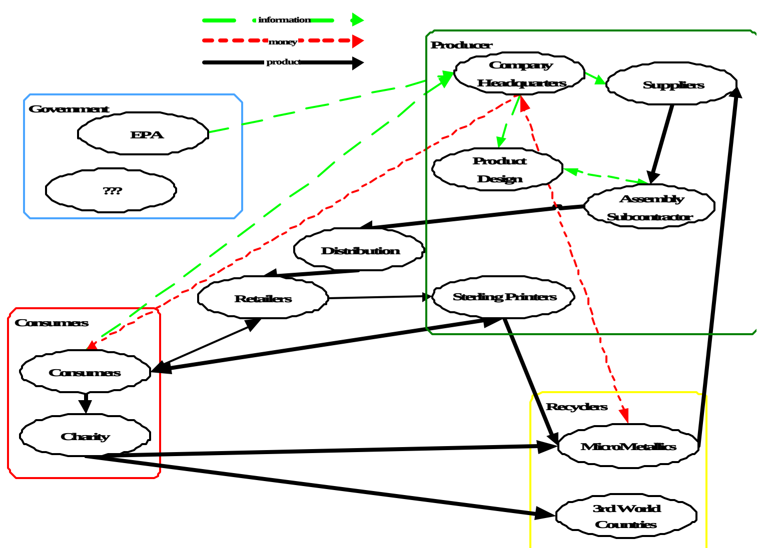


Figure 6-4. HP Printers

General Electric provides aircraft engines for military and commercial applications. They also include an extensive service contract through the life of the product, in which service is performed by the company as well (Wiggs 1999). The long life and the high price of the product mean high reuse and refurbishment; whereas, the high value of recycled materials at the final disposition yields profits, proving to be quite lucrative to the business. The incentives are inherent to the product characteristics. The largest challenge for GE is staying informed on changing regulations regarding fuel efficiency and usage conditions.

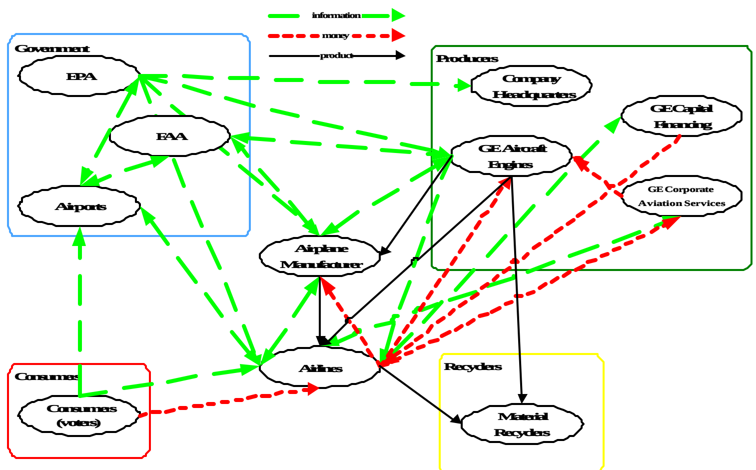


Figure 6-5. GE Aircraft Engines

Philips Medical Systems refurbishes and resells their medical equipment, from ultrasound equipment to MRI equipment (Gruben 2000). The competition with brokers over sales and returns is a large challenge to increasing their market position. Some consumers perceive the reliability is lower, although both new and refurbished are certified by the same procedure.

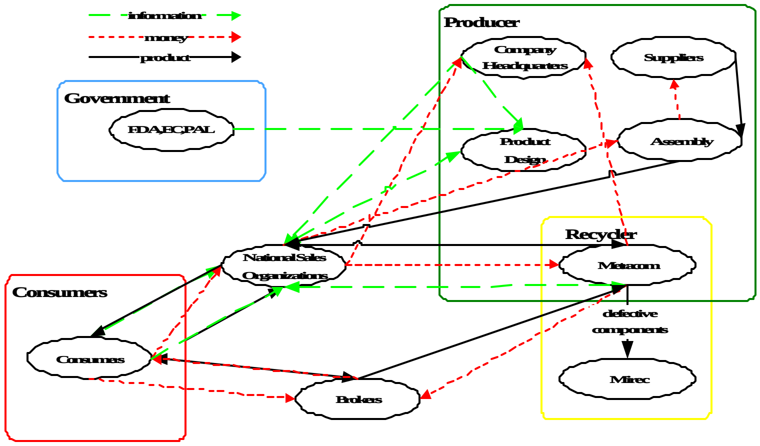


Figure 6-6. Philips Medical Systems

The following example shows a voluntary program established by Siemens Nixdorf, in anticipation of the proposed legislation in Germany. The end-of-life products, mostly electronic equipment, flow directly from the consumer to the recycler. The in-house recycling company works with other component refurbishers to remanufacture parts to be returned to Siemens Nixdorf for reapplication. This system of harvesting service parts and reusing them in the repair of existing equipment has been quite successful, from a financial and environmental impact perspective. Depending on if recycling of the product category produce a yield or a deficit, the in-house recycling company either credits or debits to the appropriate business unit. In this system, the incentives are linked directly to the business unit producing the goods, therefore giving strong encouragement to improve designs.

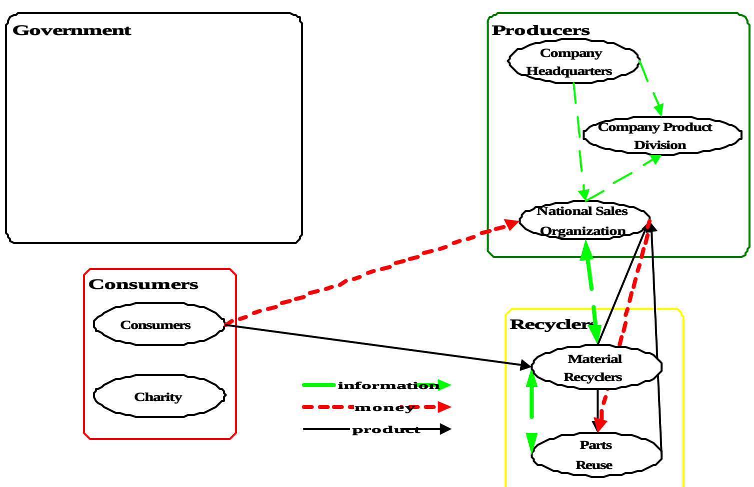


Figure 6-7. Siemens Nixdorf IT equipment

Of the examples included in section 6.3.1, this system represents the most effective communication, providing direct links between the producing departments and the recyclers.

Observing the differences and similarities of these voluntary end-of-life systems, several trends become apparent. Generally, the products have perceived value at end-of-life. Either the products are completely reused, refurbished or serviced to prolong the life or are harvested for spare parts, all activities producing value for the company. Kodak and HP remanufacture their products for continued use to keep costs low, which augments their market share. Although not covered as an example in this work, Xerox has redefined their market by examining the “bundling and unbundling of property right” in their take back of used copiers and office equipment (Reinhardt 2000).

These collection systems have linked their end-of-life systems with existing operations. Kodak links with photo-processors to supply the products for remanufacturing. HP links with the consumer’s need for service and with sales of new products through their trade-in trade-up program to collect products. Philips’ national sales organization uses the new purchase transaction to recover the used products.

The use of Environmental Value Chain Analysis shows the paths of communication and product transfer. The most successful end-of-life systems take advantage of the opportunities to provide value to the customers at the end-of-life. Additionally, these end-of-life systems do not require fees from consumers since most cases the system is profitable or saves money and time for the company.

6.3.2 Legislation Mandated Systems

Due to such legislative pressures in Europe, a number of manufacturers are participating in take back systems and some companies have responded through designing their products for recycling and other are setting up the infrastructure to collect and manage end-of-life products.

As a consequence of the new Dutch legislation on producer responsibility and product take back, the branch organizations initiated a collection system for discarded white and brown goods. Figure 6-8 depicts the situation for Philips Consumer Electronics and the collection of televisions from consumers. The collection system is based on several waste collection streams, coming from municipalities and retail outlets. The products are collected through the retailers and municipalities, then processed by existing recyclers. A new organization, NVMP, coordinates the recycling efforts. Consumers pay a deposit to defray costs of the systems when they purchase a new product.

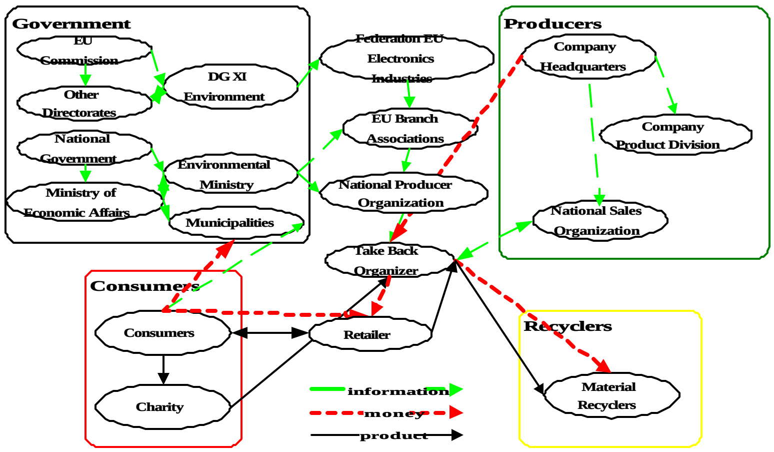


Figure 6-8. Dutch Television take back

In Germany, the proposed product take back system is not as complicated because less governmental intervention exists. Excluding the collection costs, the system is more or less cost neutral for participants. The financial and information flows are more direct as compared to the Dutch take back system.

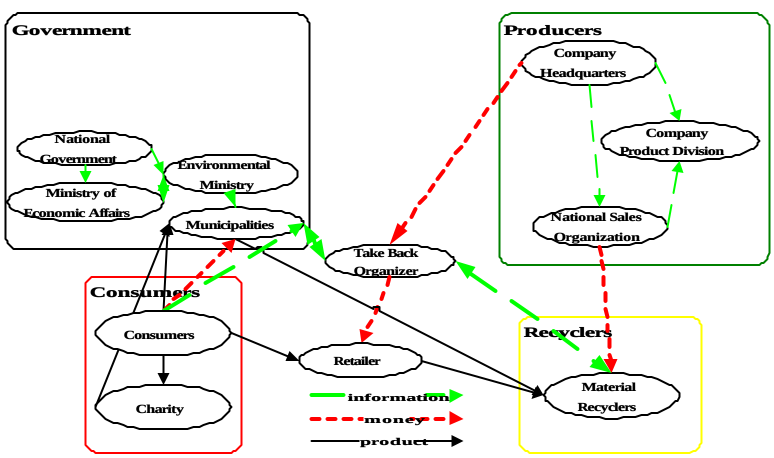


Figure 6-9. IT equipment take back in Germany (Proposed)

Although not directly related to the take back of electronic products, there are relevant observations to be made about the packaging take back and collection system in Germany. Germany's Packaging Ordinance of 1991 was the first to shift the costs of collecting, sorting, and recycling used packaging from municipal government to private industry (Fishbein 2000). The motivation for this directive was a looming shortage of landfill capacity, which pushed to decrease the amount of materials sent to landfills by reducing the waste generated and increasing recycling. Private industry responded by establishing a nonprofit company, Duales System Deutschland (DSD), which licenses the Green Dot logo for a fee to the participants.

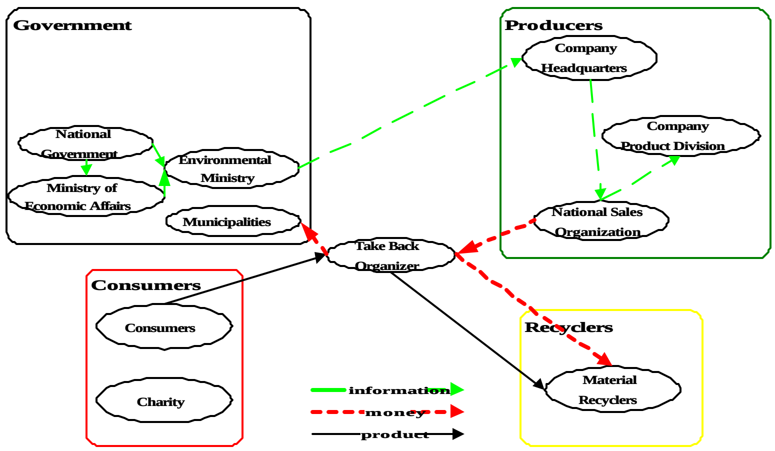


Figure 6-10. Packaging Take Back in Germany

To date, the legislation mandated systems have outside organizations coordinating efforts between consumers, recyclers and producers. The government typically manages these external organizations. In establishing the systems, there are examples of extensive government involvement (Dutch product take back and German packaging take back). In most cases, the consumers' contribution covers most of the cost.

Originally, one of the prominent drivers behind take back was to require producers to be financially responsible for waste management, giving them an incentive to make less wasteful and more economically recyclable products (Fishbein 2000, Tatom 2000). However, through the examination of the actual results of these systems, the proposed incentives are not provided by the systems.

In these systems, the financial system charges all producers equally, even if some products are cheaper to treat the end-of-life. Therefore, there is no incentive for companies to redesign products to reduce environmental impact. Financial incentive systems must be carefully detailed further, making sure that the metrics for comparing products is accurate and dependable, and the departments developing the products are charged or credited.

Such incentives will work well when the systems are structured in such a way that the departments held financially responsible can actually manage their efforts. For instance, recycling targets set by authorities should be possible to achieve in an eco-efficient way (e.g. by design). As well, collection costs should remain in the public domain because there are already eco-efficient systems in place.

6.4 Market Based Developments

Through examination of the additional case studies, the effect of market developments was observed. The practice of developing an end-of-life strategy is not a static activity; it is dynamic because the market is constantly changing. Consumer behavior, in reaction to market developments, influences the reason for discarding used products and purchasing new products. These issues are not addressed in ELDA, but are included as an add-on tool to further investigate the appropriate end-of-life strategy (Rose et al. 2000d).

ELDA, as a static tool, only accounts for what is possible at product end-of-life based on technical product characteristics at a certain point in time. ELDA does not account for changes in product functionality or market developments. These market developments can have a strong influence over product end-of-life through different consumer behaviors and their interaction with products.

This section will focus on technology changes in products and how functionality relates to consumer behavior at product end-of-life. Market developments influence the discarding and replacement of products. Improving functionality by technology changes is one of the ways customers are encouraged to replace their existing products for newer models. Knowing the functionality changes over time for a specific product is an important aspect of this research. The functionality-time diagram makes it possible for the business to analyze their specific products with regards to end-of-life and possible effect of product redesign in the market place.

First, the functionality-time diagram provides a check with the ELDA classification, demonstrating the time component of the ELDA classification. The functionality-time diagram also shows what the possible end-of-life strategies are based on product functions and consumer demands. Finally, the functionality-time diagram can explain the reasons why there are not a lot of reapplication or reuse for certain electronic products because development is so fast. The time dimensions are frequently omitted from discussion, but are crucial as technology cycles get shorter.

Sometimes, the aesthetic appearance of the product is outdated and consumers are influenced to buy new products offered on the market. The superficial changes made to appearance, for no purpose other than to make past models appear out of date, encourages people to replace them even if they still function properly (Copper 1994). Non-technical aspects also play a role as presented in the research carried out by Blonk (Blonk 1993). It is often suggested that aspects such as aesthetics and features are important in the replacement decision (van Hinte 1997, Creusen 1998).

Regarding consumer behavior, studies by national consumer organizations in the Netherlands have shown that approximately half of the first users discard their electronic products because of irreparable breakdown (Boks et al. 2000). The other half consists of increased functionality demands (higher aspirations) and emotional grounds (‘do not like the product anymore and can afford to buy a new one’). Different reasons account for a product reaching the end-of-life, including technical, economic, ecological, aesthetic, ‘feature’, and psychological obsolescence (van Nes et al. 1999). The following table from van Nes' work gives an example and brief description of the possible reasons for obsolescence.

The effect of market developments and consumer preferences on product end-of-life can be demonstrated with functionality-time diagrams. Increases in functionality are pushed by consumer desires or pulled by advances in technology. Generally, as technology becomes more developed, it is incorporated into lower-end models and industry standards, thus increasing consumer expectations. The comparison of functionality of a variety of products (competitors or even levels within a company) at two different moments in time is necessary to establish product reuse strategies which are recommended from a technical perspective by ELDA.

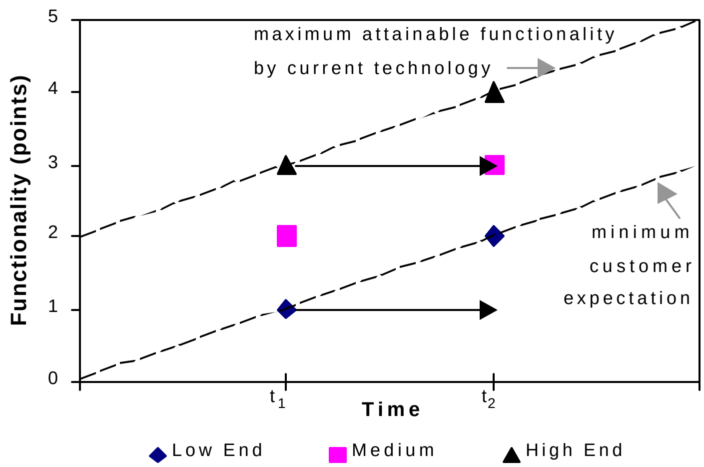


Figure 6-11. Generic functionality changes over time

Figure 6-11 shows the low, medium and high end products at a given year t_1. The lower line, on the graph represents the minimum level of consumer expectation. The positive slope means that customers expect more functionality as time passes. The upper line indicates the maximum attainable functionality through current technology. The product lines can run either horizontally, as shown in the graph, or gradual negative slope indicates that the product experiences slow-wear losing functionality or catastrophic failure is indicated by a vertical drop.

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:

- the high-end product now has the equivalent functionality of a new medium level product,
- the medium level product is now just sufficient to meet customer expectation, and
- the low-end product drops out of the required functionality range and is not suitable for product reuse anymore.

The time horizon of these changes may be in months, years or decades. In the case of computer chips, advances in functionality are expected every six months; whereas for a washing machine, the advances in functionality are approximately every 20 years.

Using the definitions given the work by van Nes, examination of the high end product can also become obsolete from aesthetic or psychological reasons. Consumers, who are fashion purchasers, purchase the latest design to satisfy psychological needs or aesthetic preferences rather than technological requirements. In the case of the high-end product, the reuse of the product is possible because the functionality at t_2 still falls into the range of the currently offered functionality.

The low-end product at t_2 shows an example of feature or economic obsolescence, according to the definitions given in van Nes. The low-end product will not fall into the desired functionality at the time t_2 because it has dropped out of the range of interest even to value buyers. The possible end-of-life routes for the low-end product are remanufacture (with upgrades to functionality), recycle (with disassembly or without disassembly), or disposal.

Consumers of electronic products can be divided into three main categories: technology-philes, fashion and value buyers. The technology-philes are consumers that demand the latest and greatest technology without regard to price. Fashion purchasers are motivated to have the latest design and most stylish models, with relatively little regard to price. The price conscientious purchasers are 'value-buyers' and seek quality in addition to low cost.

6.4.2 Effect on product end-of-life

The functionality-time diagram demonstrates the end-of-life strategies – reuse, service, remanufacture and recycle. Take for example, an information technology equipment company's original fax machine that has evolved into a all-in-one home use printer, scanner, fax machine, copier with color. As given in table 6-4, the original was released to market in 1989 for approximately $1500 and the most recent product with all of the functions was released in 1999 for $350.

Table 6-4. Functionality of IT product

INTRODUCTION	FUNCTIONS	PRICE
1989	Fax	$1500
1994	Fax, Print	$850
1995	Fax, Print, Scan	$450
1997	Fax, Print, Scan, Copy	$400
1999	Fax, Print, Scan, Copy in Color	$350

For the example given in Figure 6-12, below, the product following path (a) has no change in the functionality between the product release (1997) and the current time (2000), the end-of-life strategy is reuse. The product is not obsolete and still satisfies customer expectations.

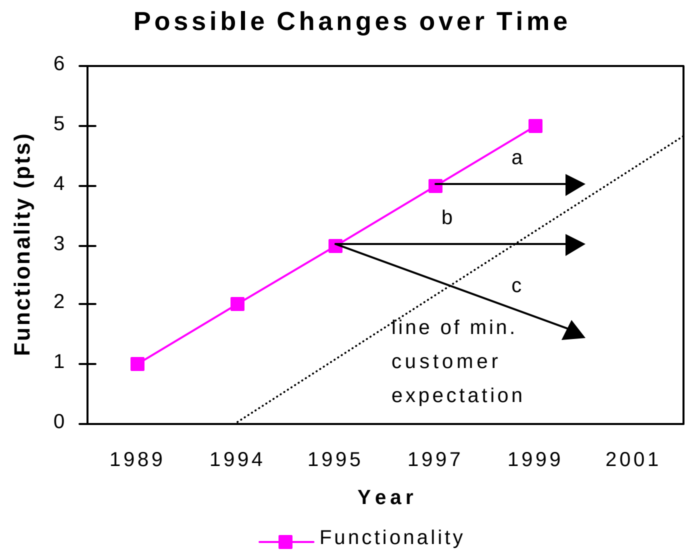


Figure 6-12. Influence of functionality over time

For the product following path (b) that was released in 1995 and is now five years old, experiences feature obsolescence. This means that the consumers demand better products with higher functionality. Remanufacturing the product is possible, but improvements must be made to the functionality to return profits to the company. New features through software or hardware could be solutions to this problem and a more modular design would help the remanufacturing process.

The same product following path (c) experiences technical obsolescence when the product itself is worn out and no longer has the functionality it originally had. Servicing the product to the original functionality can only help a little because the original functionality is not within the lower limit of the consumer expectations. Therefore, the product should be remanufactured, upgrading the functionality; or the product should simply be recycled for material value.

For example, the home use printer has a maximum reapplication life-time of four years, resulting in new products falling within the desired consumer range for only four years and then the demands are not met. This work shows that end-of-life opportunity is very much related to time management and managing time's effect on product functionality.

More work is required to completely understand the effect of market developments on product end-of-life. This preliminary work provides the framework for future investigation but additional case studies must be examined to develop an extensive methodology.

6.5 Conclusion

ELDA's success in classification depends on the implementation of end-of-life systems. Currently consumer pressure, competition and legislation have pushed the few operating end-of-life systems. This chapter shows successful implementation of ELDA recommendations depend not only on design strategies, but also on how the value chain is organized and the functionality-time relationship is exploited. In cases where ELDA reveals a gap between current end-of-life strategy and practice, either the internal or external value chain should be addressed. There are some eco-efficient end-of-life systems as well as inefficient ones; both of which are operating through trial and error.

To reduce product end-of-life environmental impact and cost of end-of-life treatment, close examination to the functionality and the value chain between producers, recyclers, consumers and government is necessary. This can generate valuable results to the ELDA recommendations and are the indication of success.

As companies and countries move to implement end-of-life systems, including collection and treatment plans, a view of the complete picture is needed. The crucial stakeholders of these discussions are producers, policy makers and recyclers. These three groups can learn from this research, from the technical aspects that should be controlled as well as the information concerning the end-of-life value chain.

7 IMPLICATIONS ON DECISION MAKERS

Chapter 7 describes the implications of this work on decision makers, including product designers, recyclers and policy makers. Chapter 7 explains the impact of these tools in application and the usefulness to decision makers. The focus is placed on product designers and managers with brief description of the impact of decisions made by recyclers and policy makers. Companies and other organizations, both governmental and non-governmental, seeking to establish product end-of-life treatment systems can also learn from this research on product end-of-life strategies.

7.1 Decisions relating to end-of-life systems

The first three chapters described the importance of the field of product end-of-life and the current research and industry efforts in this field. Many decisions must be made, taking each party's interests into consideration. Chapters 4 through 6 have described the current end-of-life research, showing that end-of-life strategies are influenced by technical factors. ELDA's classification of end-of-life strategies according to technical product characteristics provides crucial results to help guide decisions made by product designers, recycling organizers and policy makers. It is important for these decision makers to understand that the opportunities for end-of-life treatment are limited by the technical product characteristics. In building end-of-life systems, a company must develop the business strategy keeping in mind the life cycle perspective. Strategy relies heavily on knowledge of current activities and foresight into what is possible in the future. Managing or deciding how to manage information, money and product flow in the end-of-life systems efficiently is a key to success. These decisions are not only technical, but relate to greater issues such as consumer behavior, relationship with government and recycling infrastructure.

Decisions concerning environmental policy have taken into account various factors as a part of a total decision matrix. Research indicates that designers must accurately define the end-of-life strategy before considering recyclability or designs will be optimized incorrectly. Appropriate design for end-of-life requires knowledge, rather than assumptions, about how recyclers will treat various subassemblies, components, and materials to recover the residual value.

Much of the extended product responsibility legislation suggests that producers have full control over decisions made at the product end-of-life. However, consumers, recycling organizers and policy makers contribute to the decisions as well. Consumers prefer activities without hassle, that are easy or that bring themselves benefit. Consumers seek to protect their money and investment in a product and depending on their category of buyer – whether they want lower cost of ownership, top-notch functionality or excellent design. Consumers, unless provided incentives, hold onto products during the end-of-life stage. Businesses, especially the electronic products industry, move toward growth areas that provide increased profits, market share or improved image. The underlying goal in business is to make profit, so items that require expenditure or risk are thoroughly analyzed for profit potential. There is a misconception that all end-of-life treatment opportunities will be cost centers within the business. Recyclers make decisions about acceptable incoming product streams, available outlets for materials, capacity, recycling technology when dealing with end-of-life products. Recycling organizations are established to make a profit, therefore they must be very knowledgeable about the possible product streams. Policy makers, in government organizations or agencies, have established or are in the process of establishing legislation outlining certain behavior from producers and recyclers in treating products at the end-of-life.

Until now, government mandates and voluntary industry programs have made decisions concerning end-of-life treatment systems. These systems require the support of consumers, and in many cases changing their behaviors. These end-of-life systems also require recycling infrastructure and capacity. Understanding how decisions are currently being made helps devise recommendations for improving product design and then maximizing the opportunities in end-of-life systems.

7.1.1 Influencing these decisions

Designers increasingly have the responsibility for many aspects of products – and now environmental performance. Few tools address the need of the design for strategy and methods to help prioritize the conflicting goals associated with environmental aspects of a product. Generally, the current tools lack strategic thinking when it comes to environmental performance. While the tools provide information helpful to the particular end-of-life strategy, they do not guide strategic goals. The research field is divergent, some activities lack focus and are difficult to assess the implementation. The LiDS wheel gives designers a tool to help organize and prioritize general environmental goals (van Hemel 1998). STRETCH helps with the strategic benchmarking and implementation of higher level environmental strategies in the business (Cramer et al. 1997). The decision makers need methods to identify preferred strategies that prioritize options for the end-of-life phase of products.

First, the decisions can not be examined in isolation; the system must work as a whole unit and previous experience has revealed negative ramifications of decisions made in isolation. The current state of the industry is an important starting point. End-of-life treatment or systems are becoming more prevalent. Data and know-how that already exist within companies provides an excellent baseline. Understanding what is happening in reality and implications about the end-of-life of products is necessary. Developing end-of-life systems from scratch only tells industry what they already know and does not help address specific challenges industry faces in developing end-of-life systems.

Unlike other tools, ELDA guides product designers, recycling technology developers and policy makers to coordinate to specify end-of-life strategies and improve decisions influenced by end-of-life strategies. ELDA provides available technical information that is relevant for decision making on take back and recycling systems. Knowing the end-of-life strategy leads to better redesign of products.

Examining the difference between the industry practice and ELDA recommendation determines the focus for future efforts for product designers and managers, recyclers and policy makers. Table 7-1 shows the recommended actions if the ELDA classification corresponds to the best practice and in the cases that it does not correspond to best practice. If the two strategies match, then the focus should be placed on technical aspects of the particular end-of-life strategy, understanding items such as reason for discarding, functionality changes over time and recycling technology development. For the cases that the ELDA classification and industry best practice do not match, then the focus should be on the business issues including value chain concerns. Product management should understand the reason for discarding, functionality changes over time and the recycling technology infrastructure. If there is a mismatch, the producers should focus on internal value chain and other consumer and political issues. The recyclers must work to reduce costs while increasing yields in the end-of-life processing. In the case of a mismatch, the recyclers must find new outlets for materials, talk to producers, and talk to organizers of take back systems. The policy makers' focus is to improve overall efficiency of the system or helping to redefine the systems so that higher targets are possible.

Table 7-1. Efforts needed from Product Management, Recyclers, and Policy Makers

MATCH OR MISMATCH?	PRODUCT MANAGEMENT	RECYCLERS	POLICY MAKERS
Match = ELDA classification corresponds to best practice	• reason for discarding • functionality over time • recycling technology, infrastructure	• lower costs, improve yields	• improve efficiency of system
Mismatch = ELDA classification does not correspond to best practice	• internal value chain • consumer, political issues	• find new outlets • talk to producers • talk to organizers of take back systems	• redefine system so that it can handle higher targets

Section 7.2 describes the issues and recommendations for action for product management within producing organizations. Sections 7.3 and 7.4 summarize the recommendations for recyclers and policy makers, respectively.

7.2 Product Design

ELDA provides the technical end-of-life strategy, based on data inputted about products. With an accuracy of 86%, EDLA classifies end-of-life strategy, helping designers use guidelines appropriate for the strategy. ELDA's suggested end-of-life strategy is identified to inspire and guide designers to achieve higher levels on the end-of-life strategy hierarchy. By doing this, ELDA allows designers to prioritize their efforts and focus on the strategy and possible improvements that have been successful for other products with similar characteristics. ELDA is unique in this field and provides something that is not currently available.

The classified end-of-life strategy provides a starting point or a goal to be achieved as the end-of-life systems is developed. As well, the end-of-life strategy classification shows the starting point for redesign of the product. The research results show that indeed products experience a wide variety of end-of-life strategies. Redesigning a product for an incorrect end-of-life strategy may cause inefficiencies at the end-of-life as well as inefficient use of designer time and other resources.

The table used in section 7.1 described the decision relating ELDA with business practice. As product designers and managers move forward to improve end-of-life design, the following order of priorities must be followed.

Table 7-2. Prioritization of Tool Usage

PRIORITY	TOOL	ASPECT VALIDATED
1	ELDA	Determine technical feasibility according to product characteristics
2	Environmental Value Chain Analysis	Verify that value chain organized appropriately
3	Functionality-time	Identify the affect of functionality changes over time on the recommended end-of-life strategy

For products where the current treatment and strategy coincide, the future activity should emphasize design improvements. For products that have end-of-life strategies of reuse, service and remanufacture, the focus should be to understand the reason consumers discard products and the functionality changes over time. By focusing on these two issues, higher percentages of products to which the best strategy can be applied will be attained. For products with end-of-life strategy of recycling, product designers and mangers must look into the recycling technology and the materials used in the products in order to harvest maximum conservation of resources and value.

7.2.1 Focus on technical issues

For products that the recommended end-of-life strategy does correspond to the industry best practice, design improvements must be focused on the particular end-of-life strategy. Designers must understand the reasons consumers discard products at the end-of-life. As mentioned in Chapter 6, van Nes' reasons for obsolescence can be simplified into three main categories: breakdown, functionality changes, or design aesthetics (van Nes et al. 1999). Consumers may discard their products because they no longer function or are worn out. Increasing product functionality encourages consumers to buy products that have more features and lower costs. Changes in design aesthetics affect consumers' satisfaction or dissatisfaction of a product and there are some design improvements that can be made such as timeless design or modular design. As the following table shows that modular design is particularly relevant for the high end strategies, such as reuse and service strategies.

Table 7-3. Design Focus areas for End-of-life Strategies

END-OF-LIFE STRATEGY	RECOMMENDED STRATEGY IN CASE OF:		
	Breakdown, wear and tear	Functionality deficiency	Design aesthetics not satisfying
Reuse	Robust design	Design for variety	Timeless design
Service	Design for service	Modular design	
Remanufacture	Design for disassembly, Robust design	Design for disassembly	
Recycling with disassembly	Design for disassembly		
Recycling without disassembly	Material selection		
Disposal			

Tools common to improving other facets of the product are useful to improving the product end-of-life. Design for assembly, disassembly, design for service and material selection can greatly affect the end-of-life of the product. These tools, including guidelines and design aids, are useful if applied for the particular end-of-life strategy appropriate for the product characteristics. For instance, design effort is lost when designing for disassembly when the product has the potential for the end-of-life strategy of reuse. For the lower ranked end-of-life strategies such as recycling, there is little effect from the consumer's discard behavior. Therefore, more concern should be given to improving the material selection and disassembly process than understanding the consumer behavior.

Other generic tools such as Environmental Benchmarking and Ecodesign matrix can help guide product designers. Environmental benchmarking rates products on energy usage, environmentally relevant materials, end-of-life, material composition, and packaging (Jansen et al. 1998). Environmental Benchmarking has been successful for many companies for comparing products of similar functions or in similar market segments, allowing designers to brainstorm opportunities for improvement. The Ecodesign matrix, similar to Pugh Concept selection, can organize the options for improvement by outlining the benefits to the environment, business, customer and society before assessing the technical and financial feasibility (Jansen et al. 1998).

Other tools, which can be helpful for a specific end-of-life strategy, examples are included in table 7-4.

Table 7-4. Example Tools for Design Improvements

END-OF-LIFE STRATEGY	EXAMPLE TOOLS
Reuse	Functionality-time diagram (Rose et al. 2000d) Optimizing product life time (van Nes et al. 1999)
Service	Best levels of disassembly and recovery of subassemblies, components, or materials for reuse or recycle (Ishii et al. 1994) Life Cycle Serviceability (Gershenson et al. 1991) Transforming services business (Wiggs 1999)
Remanufacture	Linking qualitative measures of remanufacturability to CAD systems (Amezquita et al. 1995) Remanufacturing operations at Electrolux (Sundin et al. 2000)
Recycle with disassembly	Planning disassembly using Petri Nets (Zussman et al. 1998) Understanding disassembly layout planning (Gungor et al. 1999) Integrating disassembly analysis tools in their software (ASME 1998) Experiences from demanufacturing operations (Grenchus et al. 2000)
Recycle without disassembly	Estimating product recycling costs (Boks et al. 1998b) Shredding or disassembly of electronic products (Boks et al. 1999)
Disposal	Understanding environmental impact of hazardous materials (Huisman et al. 2000b)

A modular design and use of durable components should be considered when designing products with long term use and slower technology innovation cycle, such as a vacuum cleaner and washing machine. To enhance component reuse and material recycling, designers and engineers can embed strategic modularity into the product, thereby reducing the recycling organizations' costs. Guidelines for design improvements for material recovery and component recovery show designers options (Fiksel 1996). Embedded tricks to aid in disassembly of products are also an option for products that should be designed for efficient disassembly (Masui et al. 1999).

It may not actually be in the best interests of reducing environmental impact to achieve the end-of-life strategy recommended by ELDA and possible by the value chain. The most important contributor to this decision is the trade off between the environmental impact during manufacturing and usage stages of product life cycle (Rose et al. 2000b).

7.2.2 Focus on business issues

For products where end-of-life treatment and recommended end-of-life strategy differ, the business issues dominate. The organization must first tackle the value chain items, using Environmental Value Chain Analysis. Mapping the ideal product end-of-life system, necessary information and appropriate financial flows can identify the bottlenecks or inefficiencies of the current practice. Comparing the ideal with the current product end-of-life systems will help identify the bottlenecks or sources for inefficiencies. Benchmarking the end-of-life strategy with other existing systems is another helpful activity. Making sure that responsibility for a particular issue is assigned or attributed to the actor who can manage the item the best is a helpful tactic for eliminating inefficiencies.

Internal challenges should be addressed first. The internal value chain items include but are not limited to the following: financial incentives, design incentives and information flow. After addressing these internal challenges, the external issues including government, consumer and political issues should be examined. External value chain issues include needs for product returns incentives (from consumer), relationship with government, incentives for processors and retailers incentives. Increasing the percentage of consumer returns will increase the economy of scale for the processing of the products. Better relationship with the government gives insights to future expectations and targets to be realized. Incentives for processing can be achieved by using materials with high potential recycling percentages and components that can be reused. Retailer incentives can come as discounts in purchasing, trade-in reimbursements and direct payment for storage and collection of the products returned by consumers. Understanding the relationship through product, information and financial flow from the consumer to the producer or other take back organization can help improve the organization of the end-of-life system. Other incentives for retailers and distributors include items such as understanding the purchasing and discarding decisions and items like value of pre-owned products.

EVCA deals more with the business aspects of end-of-life strategy, realizing that end-of-life systems can not be improved solely based on technical changes to products. Therefore, EVCA is a tool to help designers and product planners develop (in conjunction with other participants) the best end-of-life system for their product. EVCA helps identify challenges or flaws in the end-of-life system that are costing the company money, causing poor communication, and reducing yields in end-of-life collection.

This work also shows that there are no generic solutions for the end-of-life treatment of products. Proposed legislation suggests recycling rates uniform across product sectors. This work demonstrates that a wide variety of end-of-life strategies are appropriate, even for products in the same sector. Therefore, there is not a generic solution appropriate for the product characteristics, as many have previously believed. Product designers and managers must understand that at product end-of-life, what is possible for one product may not be possible for another product.

7.3 Recyclers

ELDA gives information describing the possible end-of-life strategies appropriate for the product characteristics. In today's markets, recyclers must understand consumer discard behavior and new product technology. The traditional focus for recyclers has been recycling technology. However, working with producers and understanding consumer behavior allows recyclers to move ahead of the competition and reduce environmental impact of electronic products at the end-of-life stage. Being aware of the changes in functionality over time is crucial for recyclers. Trends towards embedded electronics in more products and increasing plastic percentages are making it necessary to reevaluate processes, as well.

Recyclers are organized according to their expertise: reuse and resell of products, remanufacturers and material recovery centers. Among the recyclers there is much substantial overlap and competition, with some alignment along product streams. For example, automobile recycling is very specialized with several large companies controlling the market. On the other hand, the end-of-life treatment of electronics is very diversified. According to end-of-life strategy, there are some motivating issues the influence the alignment, as shown in the following table.

Table 7-5. Alignment of Recyclers

END-OF-LIFE STRATEGY	ALIGNMENT IN INDUSTRY
Reuse	Consumer market potential
Service	Geographical, producers
Remanufacture	Producers, consumer market potential
Recycle with disassembly	Geographical, few, where labor rates are lowest
Recycle without disassembly	Geographical, few
Disposal	Geographical, many but decreasing

Reuse, as an end-of-life strategy, is controlled by the ability to resell the products in the market. Existing remanufacturing operations are most frequently linked with producers. Recycling through disassembly and without disassembly is aligned by geography as the economies of scale dictate the area of service (result of high transport cost and low material value recovered).

Knowing the end-of-life classification helps companies determine core competence and market potential for products they are receiving; which in turn helps determine

- possible incoming stream
- processing needs
- possible outgoing streams

ELDA helps determine the possible incoming streams by determining which products have which end-of-life strategies, according to the product characteristics. Therefore, recyclers are able to preview and determine their incoming streams. ELDA, by giving the classification, shows the end-of-life needed for the majority of the products and pushes for improved processing of products. ELDA helps determine the possible outgoing streams by using tools like the functionality-time diagram to show potential for remarketing or reuse of the product.

The following table explores the relationship between the size and amount of electronics in the products according to the end-of-life strategies. In general, smaller electronic products have end-of-life strategies of remanufacture with some products recommended for recycling. The larger electronic products have end-of-life strategies ranging from reuse to recycling. The products that are considered 'other' have end-of-life strategies of service and remanufacture according to the ELDA classification.

Table 7-6. ELDA recommendation according to product sectors

END-OF-LIFE STRATEGY	SMALL ELECTRONICS	BIG ELECTRONICS	OTHER
Reuse		Automobile	
Service		Automatic transfer switch	Aircraft engine Generators Klystrons
Remanufacture	Computer projector, Air bag, Bubblejet printer, Hand held vacuum, Inkjet printer, Single Use Camera, Portable telephone, Portable CD player, Monitors, Fax machine	Computer, Digital copier, Electric Power steering motor, Network routers, Network server, Photocopier, Audio systems, DVD player	NLC support structure Shipping container
Recycle with disassembly	Portable radio	Televisions	
Recycle without disassembly	Computer mouse	Typewriter Vacuum cleaner Washing machines Audio system (CD) VCR	

This work shows a need for better alignment in industry, as currently there are significant redundancies in the United States and in other parts of the world. In some areas the competition is adequate, but other areas there are some strong barriers to entry. Through ELDA, recyclers can understand what and where opportunities exist for further development. As recyclers work with technology designers to develop new recycling technology, there needs to be more focus on the products that will make up the incoming stream. The existing development of recycling technology is not uniform across all products; there is extensive research into the car recycling technology but very little work on electronics recycling. The learnings from other recycling development must be reapplied across all products, with adjustments when necessary due to the differences in product characteristics. Further work on collection systems, providing incentives to users to return their product, is also necessary.

7.4 Policy Makers

Legislation, as described in Chapter 1, is being enacted in countries in Europe, Japan and some states within the United States. The legislation varies from landfill bans on certain products or materials to mandated product take back systems. Some of the existing end-of-life systems were described in Chapter 6.

In the case of products that the recommended end-of-life strategy corresponds to the end-of-life treatment, policy makers should primarily seek to improve the efficiency of the end-of-life treatment. Policy makers should improve the overall efficiency by eliminating redundancies in the end-of-life systems and enable their smooth operation and execution. Policy makers must address a different set of issues when the products' end-of-life strategy does not correspond to industry's current end-of-life treatment. On the other hand, policy makers must work to redefine the conditions under which the end-of-life systems need to operate in order to be successful.

Understanding the effect of the technology cycle on the possible product end-of-life treatment options is important for policy makers. ELDA shows how products from different product sectors can display distinct end-of-life strategies. Not all products in product sectors have same end-of-life strategies. Much of the regulation focuses on recycling for material content. This work demonstrates that recycling is only one of six possible end-of-life strategies. Focusing solely on recycling of products overlooks other eco-efficient end-of-life strategies. ELDA has also shown that end-of-life systems must be developed specifically for products; there are no generic solutions that yield high eco-efficiency across a wide variety of products.

As policy makers move forward to develop new or improve existing end-of-life treatment programs, some concerns can be addressed with the aid of EVCA results. As described in Chapter 6, EVCA identifies product, money and information flows and was applied to end-of-life treatment systems.

In order to achieve these successes, policy makers must focus on the question 'what?', for example addressing metrics, goals or overarching desires. After determining the overarching goals, the producers and recyclers can set about to develop systems appropriate for their products and business; therefore, addressing the question 'how?'. It is in the best interest of policy makers to provide incentives for other stakeholders to develop and execute end-of-life systems. The incentives must come in three main areas, as discussed in Chapter 6, (a) design, (b) consumer returns and (c) processing improvements. The results are summarized in Table 7-7, whether the end-of-life system is a voluntary program or a mandatory.

Table 7-7. Types of Incentives for End-of-life Systems

INCENTIVES FOR	TYPE OF END-OF-LIFE SYSTEM:	
	Mandatory	Voluntary
Design	Linkage to design departments to be insured	Competition in market
Consumer returns	Collection through municipal systems	Service provided for customer
Processing	Funds to purchase new technology Achieve economy of scale	Increase value of products

Related to the product flow are the recycling and collection targets. Case studies suggest that the current collection targets are difficult to achieve without incentive systems, such as trade-in value or service provided. The recycling targets are unreasonable, as they are higher than the recycling levels of aluminum cans. As well, the basis for the material recycling efficiencies do not account for the embedded toxicity, a better metric is Environmentally Weighted Recycling Quotes being developed at Delft University of Technology (Huisman et al. 2000b). To date, the responsibility for the products has not been balanced among all stakeholders including consumers, producers, recyclers and government agencies. Other methods such as landfill restrictions have limited success because they encourage extended storage of products by consumers and shipping of products to markets overseas.

Policy makers must realize and take into consideration:

- not all product sectors have equal opportunities to make improvements
- improvement at other life cycle phases may make larger gains (energy reduction, for example)
- focus on what rather than on how

In the next few years, policy makers have the opportunity to control the development of product end-of-life systems; their influence is great and careful judgements are critical.

7.5 Conclusion

In conclusion, ELDA shows that products with different characteristics experience distinct end-of-life strategies. Currently, end-of-life treatment systems developed by industry voluntarily or as a reaction to legislation have been established but do not operate eco-efficiently.

Recommendations for improving product design, recycling and decisions concerning legislation are summarized in this chapter. Product designers and managers have control over technical characteristics that influence the end-of-life strategies. Recyclers examine the quality of the incoming and outgoing streams in order to maintain a profitable business. Policy makers must investigate more creative ways and unique solutions for the treatment of products at end-of-life stage.

The implications to decision makers concludes the research discussion. Previous work has focused excessively on technical aspects and does not describe the impact of technical improvements, especially in improving the end-of-life treatment of products. Solutions to this difficult subject must incorporate both technical and business perspectives.

8 CONCLUSIONS AND FUTURE WORK

Chapter 8 summarizes the main research points of this dissertation. It summarizes the crucial learnings and observations resulting from the research. This chapter also identifies opportunities for future research. Chapter 8 presents new avenues for research through creating minor ELDA changes, applying ELDA 'in reverse' and developing a methodology for Environmental Value Chain Analysis.

8.1 Contributions of Research

8.1.1 Main Objective

The main objective of this research was to develop methodologies to formulate end-of-life strategies across a wide range of products. This overall objective was divided into two core sections. First, the methodology determines what end-of-life strategy is possible according to the products' technical characteristics. Second, the determination of end-of-life strategies is compared with current industry practice, in order to evaluate and validate the method. By understanding better the end-of-life strategy appropriate for the product, the research results can help the company develop appropriate and profitable end-of-life strategies for their unique position, systematically.

To conclude, the current research:

- uses case studies to classify products' end-of-life strategies
- evaluates the current implementation of end-of-life systems in industry.

The ultimate goal was to use this information to communicate with (a) producers, (b) recyclers and (c) policy makers.

8.1.2 Summary of End-of-Life Design Advisor

ELDA's innovation focuses on using basic product characteristics to make end-of-life strategy decisions. ELDA succeeds in classifying products into end-of-life strategies in agreement with current practices. ELDA yields end-of-life strategy insights, from recyclers, to designers and product managers in early stages of design when changes to the design are still possible. Product designers and managers realize that different products have different characteristics, but ELDA is the first tool of its kind to show that those differences control the possible end-of-life treatment of the product. ELDA addresses the technical product characteristics controlled by product designers and managers, looking at the products as an issue conquered by technical solutions. Comparison between the classification method and the end-of-life treatment currently implemented by industry served as evaluation and validation of ELDA. The differences between the actual practice and the ELDA method shows that not all of the challenges for end-of-life can be achieved by technical solutions, non-technical business items are also needed. ELDA is very powerful, revealing in a very early stage of design, the end-of-life strategy of the product based on technical product characteristics. ELDA looks objectively and reduces the emotions associated with developing product end-of-life systems.

The case studies for this research came from Stanford University's graduate level Design for Manufacturability course (ME217). Examples were collected each year from 1996 to 2000, with approximately ten case studies a year. Case studies also came from countries including Japan, Korea, United States, Canada, Croatia, Finland, France, the Netherlands, Norway, Spain, Sweden and the United Kingdom. The case studies ranged from small electronic products (cell phones) to large electronic equipment (aircraft engines and generators). Additional case studies, from Philips Consumer Electronics, were used to validate the ELDA classification. Because the product characteristics are similar for the consumer electronic products, the resulting classification by ELDA was similar.

ELDA's backbone, the classification tree, utilized a statistical technique, Classification and Regression Trees, to map the technical product characteristics to the end-of-life strategies. Classification analysis is a type of cluster analysis, used to group items with similar characteristics into classes. Through the validation, the ELDA classification agrees 86% of the case studies with the current best case end-of-life strategy applied in industry.

An important addition to ELDA is the functionality-time diagram that shows consumer behavior and market developments' influence over product end-of-life strategies. The functionality-time diagram evaluates and promotes the possible reapplication of the product in the market. As the functions of the product are increased over time, through technology developments, the possible reuse of the existing or previous models is limited. For some products, the technology is changing rapidly and the functionality improvements are so frequent that material recycling is the only possible end-of-life strategy. On the other hand, there are other products that have much slower technology changes and therefore they are ideal for reuse in the market. Understanding the relationship between functionality and replacement practices of consumers is necessary to optimize end-of-life systems.

Another extension of this work is through Environmental Value Chain Analysis. Realizing that solutions to the product end-of-life challenge do not depend completely on technical solutions, Environmental Value Chain Analysis addresses non-technical business items. EVCA focuses simultaneously on all links in the chain that are responsible for the development, production, distribution, consumption and disposal of a product. It strives for the participation of all up-stream (suppliers, transporters) and down-stream (distributors, maintenance and repair services, remanufacturers, recyclers, disposers) actors in product and production improvements.

8.2 Significance of Contributions

Product designers and managers are responsible for many aspects of products, including environmental performance. Few tools address the need of the design for strategy and methods to help prioritize the conflicting goals associated with environmental aspects of a product. Generally, the current tools lack strategic thinking when it comes to environmental performance. While some tools provide information helpful to the particular end-of-life strategy, they do not guide strategic goals. The research field is divergent, some activities lack focus and other yet are difficult to assess the implementation.

The previous research did not identify any effective approach or method specifying how a company can systematically build strategy associated with product end-of-life. There are methods and tools available but these are either too wide in their scope, not providing sufficiently detailed assistance, or too narrow, only focusing on design recommendations that facilitate disassembly. Unlike these other tools, ELDA guides product designers, recycling technology developers and policy makers to specify end-of-life strategies and improve decisions about end-of-life strategies. ELDA provides available technical information in a form that is relevant for decision making on take back and recycling systems. Knowing the end-of-life strategy should in turn lead to redesigns that are better tailored to ecological and economical potential inherent to the product characteristics.

ELDA differentiates itself from traditional Life Cycle Assessment in several ways. ELDA is based on product characteristics and uses these product characteristics to determine the strategy appropriate. The redesign of the product according to the strategy results in monetary enhancements or environmental impact reduction at end-of-life. LCA is a validation tool that relies on a holistic approach and identifies external factors that influence the product. From these factors, attention fields are determined and then the feasibility is checked to see if the product characteristics actually allow for the improvements. Only after this stage does the LCA process impact product design. The following figure (8-1) contrasts these two tools, the top one representing the ELDA approach and the bottom one the LCA approach.

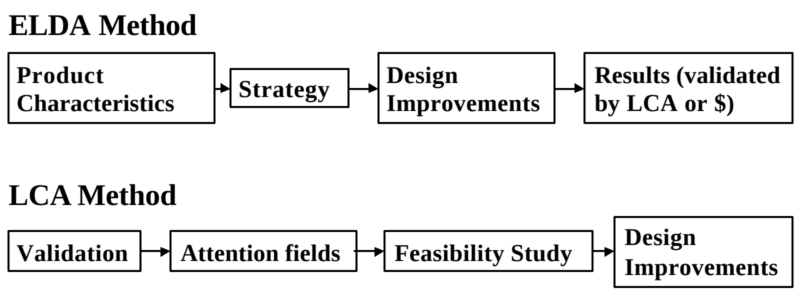


Figure 8-1. Comparison between ELDA and LCA method

8.2.1 Usefulness to Industry

This work is the first of its kind to develop strategies for product end-of-life management. Other work has focused on research into the specifics of end-of-life treatment but not into understanding the factors that control the end-of-life strategies possible for a product. By demonstrating which product characteristics influence the end-of-life strategy classification, ELDA provides an objective tool to help industry to develop end-of-life treatment systems. With the accurate classification of end-of-life strategies, ELDA helps reduce cost of implementing end-of-life systems and is a clear and quick tool to form a baseline and identify opportunities to improve product design.

ELDA identifies additional opportunities and with functionality-time and Environmental Value Chain analyses, it is possible to complete the methodology to develop the appropriate end-of-life strategy and prioritize future efforts is possible. Functionality-time diagram incorporates time effects into the research. EVCA takes into account business issues that may hamper the implementation of the recommended end-of-life strategy.

The research shows the need for tailor-made end-of-life solutions. Because products have different technical characteristics, the structure of the end-of-life system must be unique. New legislation mandating collection and recycling targets for wide variety of products fails to capitalize on the opportunities offered by the different product characteristics. Indeed, some products have more options for improved end-of-life treatment, whereas other products are limited by the product characteristics. This work has examined current industry processes with respect to end-of-life treatment systems, both proposed and existing. With these learnings and observations, improvements to the system must be made according to the product characteristics and using creativity in developing incentive systems.

8.2.2 Usefulness to government and non-governmental institutions

This methodology to determine product end-of-life strategies shows the importance of technical solutions along side of business solutions. The close inspection of actual business practice regarding end-of-life treatment of products has shown the opportunities according to the match or mismatch, as described in Chapters 6 and 7. The disparity between average practice and best practice identifies areas for perhaps legislation or other incentive systems.

As discussed in Chapter 7, ELDA shows that sector-based recycling quotes are not productive or appropriate because they assume all products are equal and have similar end-of-life. As governmental organizations and non-governmental institutions increase discussions concerning product end-of-life treatment, it must be realized that products are different, even within product sectors. In some cases, the expectations or directives given are too high and even unrealistic. Current approaches to mandate collection and recycling rates has not resulted in the desired results – to provide incentives for companies to redesign products for more effective end-of-life treatment. Further cooperation to establish voluntary systems and systems with adequate incentive systems will prove useful. Further discussion on the true motivation behind end-of-life systems, can help reduce costs and address the goal of reducing the environmental impact at the product end-of-life.

ELDA helps identify the current best strategy for a wide variety of products. From this information, government organizations benefit from looking at the end-of-life systems, examining the market forces and underlying incentive systems. Mimicking successful systems can provide opportunities for more success in products that have typically had negative end-of-life value. Also, governments must realize that not all end-of-life treatment challenges are a result of technical aspects of products, that incentives must be developed to encourage companies to build their internal value chain as well.

8.2.3 Usefulness to other design research

In regards to design theory research, this work is one of the first, within the Design for Environment field, to study a wide variety of case studies and draw conclusions from the case studies themselves. Other work has previously focused on one product sector (i.e., printers) or only on one product improvement area (i.e. disassembly). This work uses case studies to base decisions on observations on product characteristics and product end-of-life strategies.

The application of cluster analysis to engineering problems is novel. CART analysis, or equivalent techniques, is typically applied to marketing and decision making challenges. The use of CART to the end-of-life strategy classification proves its application is useful in the design theory research field. Further application of CART or other cluster techniques is possible in a variety of work. Potentially, CART could be helpful in the identification of likely failure modes or to simplify Quality Function Deployment. By using consumer purchasing behavior and the desired engineering characteristics, the design improvements could be prioritized.

The research results, ELDA and EVCA, build a stepping stone for more detailed research. ELDA is the first tool of its kind available to build product end-of-life strategy. Knowing the product end-of-life strategy, ongoing research into the specific end-of-life treatment is possible. ELDA is unique in organizing the project management to flow down specifications and recommendations to design engineers. As a stepping stone to other researchers work, this tool helps design engineers better apply tools available in industry.

Further work in increasing reuse of products through timeless design and prolonging product life is necessary as some consumers continue to demand higher performance even though the products have opportunities for reapplication in secondary use markets (for example in developing nations). Continued work on other end-of-life strategies is important as well. However, extensive focus on design for disassembly should be tempered with the fact that not all products should be disassembled or are going to be disassembled.

8.2.4 Universal application

The previous work in DFE yielded significant improvements in the areas of environmentally conscious manufacturing and packaging using action-oriented approaches. However, environmental improvements are becoming more complex, requiring more upfront planning and strategy before moving to the implementation phase. As a company's decisions and proposed legislation have wider societal implications, more thought and investigation is needed before acting.

As customers and societies demand more environmental performance from producers, developing metrics and formulating strategies are necessary for meeting customer and societal demands. Environmental marketing and communications must utilize metrics in order to understand how products compare to those of competitors. Although the Design for Environment field has become more advanced, it still needs to address a wider base of perspectives. Those perspectives include strategy, external stakeholders and consumer demands and preferences. ELDA helps to identify the right avenues in which to invest, whether that investment should occur in design, technology or organizational systems. Decision making tools, with similar intent to ELDA, should be given increased research so that developers are focused on:

- design effort (ELDA),
- technology changes (functionality-time), and
- organizing value chains (EVCA)

8.3 Directions of Future Research

There is potential to update the state of research and improve the current ELDA tool. There are several issues: creating minor ELDA changes, applying ELDA 'in reverse' and developing a methodology for Environmental Value Chain Analysis. The main intent of ELDA has been to provide a simple and fast tool to aid designers in decision making at the product end-of-life and should be preserved when considering alterations. There are opportunities to expand the usability and attractiveness of ELDA that were not included in this effort because of the focus on accuracy of classification and performance. Improvements to the usability and interface are welcome additions and would be relatively easy to implement.

8.3.1 Minor Changes to ELDA

A definite area of improvement for the ELDA concerns specific product characteristics, especially a product's hazardous material content. While researchers understand that hazardous, or environmentally relevant, material content affects the end-of-life strategy, methods to adequately account for these issues are still widely debated. An opportunity for improvement in ELDA is to include a ranking of ‘hazardousness’ in the analysis, which will be possible after the ongoing research (Rose et al. 2000b, Huisman 2002) develops appropriate methods to measure the environmental impact of a product at the end-of-life stage.

8.3.2 Reverse Application of ELDA

ELDA is currently being applied forward, using product characteristics to determine the appropriate end-of-life strategies. Another application of ELDA uses the classification tree in reverse, meaning that if the company desires a particular end-of-life strategy, which product characteristics are ideal or necessary. For example, a company could want cell phones to have an end-of-life strategy of reuse. The necessary product characteristics to achieve this goal are wear-out life / technology between 1 and 4, wear-out life greater than 10.5 years, number of parts greater than 108, and design cycle less than 6 years. The possible reapplication of ELDA, in reverse to the current application, could provide useful insights to companies as they plan for higher levels of eco-efficiency.

8.3.3 Methodology for EVCA

More research is necessary to develop a structured methodology for the Environmental Value Chain Analysis. Collection of additional case studies or examples of current take back systems is necessary to determine recommendations for success. While previously collected case studies describe the take back systems, validating the possible improvements while applying EVCA has, to date, not been achieved. Close interaction with producers or legislators developing the end-of-life systems is necessary to experiment and monitor the effect of changes (i.e., incentive programs). Additional improvements to EVCA are possible by applying techniques from Supply Chain Management research to closely analyze end-of-life systems to eliminate sourcing and flow problems.

8.4 Final Remarks

This work has constructed the first strategic methodology of its kind that addresses product end-of-life. The method guides product designers to improve product design, recyclers to improve their processes, and policy makers to develop more eco-efficient end-of-life systems and realistic goals.

As knowledge is gained about the environmental impact of products at the end-of-life, it is possible to provide this information to product designers and other decision makers. Further development of tools must take into consideration the intended audience and their access to information. The attractiveness of ELDA is because the information required is simple and readily accessible by the intended audience. Although the inputs are simple, the results of ELDA are powerful – providing the first level recommendation of end-of-life strategy for products according to product characteristics. Future researchers should develop tools that are based on observations of current industry practice as much was gained from industry interaction in this dissertation.

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APPENDICES

Appendix I. Terminology

Design for Environment means that 'the environment' helps to define the direction of design decisions. In other words, the environment is co-pilot in product development. In this process the environment is given the same status as the more traditional product values such as profit, functionality, aesthetics, ergonomics, image and overall quality. DFE considers the environmental aspects in each stage of the product development process, striving to achieve products that have the lowest possible environmental impact throughout their entire life cycle. Ultimately, design for environment should lead to more sustainable production and consumption (Brezet et al. 1997).

Being eco-efficient is delivering of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the Earth's estimated carrying capacity (WBCSD 2000). In more technical terms, the eco-efficiency of a product assesses what the product does or what is the delivered service over the generated environmental burden. The definition of a functional unit is the unit in which the desired output can be measured or quantification of the service provided by the product. Defining the functional unit proved to be helpful when obtaining a comparison of environmental products to its predecessors. Products that incorporate alternative fulfillment of its function can be objectively compared to its predecessors. The environmental burden is considered from cradle to grave. In the life cycle of this product or service the usage stage plays an important role. An important role because in the functional unit the usage pattern is determined. This usage pattern again determines more or less the environmental impact of the product or service.

Electronic products are products that are dependent on electric currents or electromagnetic fields for their correct function, equipment for generation, transmission or detection of electric currents or electromagnetic fields, and parts principally used for support, protection, cooling or heating of the electrically active parts are included. Various functions of electronic products are heating, cooling, lighting, generation of electricity, transmission of electricity, storage and treatment of information, transportation, motion, communication and ignition of flammable substances.

The end-of-life is the point in time when the product no longer satisfies the initial purchaser. End-of-life treatment is the actual series of steps the product undergoes when it no longer satisfies the needs of the original owner. End-of-Life strategies are the possible treatments of the product at end-of-life, including reuse, service, remanufacture, recycle and disposal.

Hazardous materials, or environmentally relevant materials, can be defined in a variety of methods (Stevels 1999):

- Scientifically proven to be hazardous in a certain form and a certain concentration for humans, animals and / or ecosphere
- Likely to be hazardous according to one source but not proven (precautionary principle applies)
- Legislated / regulated by authorities as 'hazardous' (legal opinion)
- Banned by companies because of 'hazardous' (company policy)
- Perceived to be hazardous by environmental organizations and / or parts of general public

Industrial ecology makes the analogy to natural ecosystems in order to incorporate environmental concerns in the design and manufacture of products and the processing of materials.

The life cycle approach targets the environmental impact of the complete product cycle from production through end-of-life. The life cycle approach is crucial for ecodesign as companies can prevent additional environmental impact over the entire life cycle. A company can select those suppliers that generate the least pollution in each individual phase. This paves the way for a concerted effort to reduce the total environmental load of the product in cooperation with suppliers, distributors, users, recycling companies and waste-processing firms.

Appendix II. Additional data for Environmental Impact

Table II-1 shows the environmental impact results for the Philips Consumer Electronics case studies. The individual contributions from manufacturing, transport, energy, packaging and disposal are given as well as the total environmental impact. The following tables present the data for television, cellular phone and audio product.

Table II-1. Environmental Impact Calculations for Television

CONTRIBUTION (MILLI-POINTS)	REUSE	SERVICE	REMANUFACTURE	RECYCLE WITH DISASSEMBLY	RECYCLE WITHOUT DISASSEMBLY	DISPOSAL
Manufacturing	396	435.6	554.4	792	792	792
Transportation	0	0.4	2.2	2.2	2.2	2.2
Energy (first life)	1611	1611	1611	1611	1611	1611
Energy (second life)	1611	1611	1611	1611	1611	1611
Packaging	0	0	12	12	12	12
Disposal	0	0	0	2.9	2.9	17
Bonus	0	0	-116.5	-291.3	-76.9	0
Total	3618	3658	3674	3740	3954	4045

Table II-2. Environmental Impact Calculations for Cellular Phone

CONTRIBUTION (MILLI-POINTS)	REUSE	SERVICE	REMANUFACTURE	RECYCLE WITH DISASSEMBLY	RECYCLE WITHOUT DISASSEMBLY	DISPOSAL
Manufacturing	51.4	56.5	72.0	102.8	102.8	102.8
Transportation	0.0	0.0	0.0	0.0	0.0	0.0
Energy (first life)	18.3	18.3	18.3	18.3	18.3	18.3
Energy (second life)	18.3	18.3	18.3	18.3	18.3	18.3
Packaging	0.0	0.0	0.3	0.3	0.3	0.3
Disposal	0.0	0.0	0.0	0.0	0.0	0.7
Bonus	0.0	0.0	-13.9	-34.6	-18.1	0.0
Total	88.0	93.1	95.0	105.1	121.7	140.4

Table II-3. Environmental Impact Calculations for Audio Product

CONTRIBUTION (MILLI-POINTS)	REUSE	SERVICE	REMANUFACTURE	RECYCLE WITH DISASSEMBLY	RECYCLE WITHOUT DISASSEMBLY	DISPOSAL
Manufacturing	535.0	588.5	749.0	1070.0	1070.0	1070.0
Transportation	0.0	0.4	2.1	2.1	2.1	2.1
Energy (first life)	1393.0	1393.0	1393.0	1393.0	1393.0	1393.0
Energy (second life)	1393.0	1393.0	1393.0	1393.0	1393.0	1393.0
Packaging	0.0	0.0	10.0	10.0	10.0	10.0
Disposal	0.0	0.0	0.0	1.6	1.6	23.9
Bonus	0.0	0.0	-190.7	-476.6	-395.7	0.0
Total	3321.0	3374.9	3356.5	3393.1	3474.1	3892.0

The following table combines the results of the environmental impact calculation for the Philips Consumer Electronics products studied.

Table II-4. Environmental Impact Results for Philips Products

PRODUCTS	REUSE	SERVICE	REMANUFACTURE	RECYCLE WITH DISASSEMBLY	RECYCLE WITHOUT DISASSEMBLY	DISPOSAL
Cell Phone	88 (63)	93 (66)	95 (68)	105 (75)	122 (87)	140 (100)
VCR	613 (76)	631 (78)	639 (79)	666 (82)	698 (86)	812 (100)
CRT Monitor	1877 (70)	1950 (73)	2035 (76)	2186 (82)	2463 (92)	2679 (100)
LCD Monitor	1942 (57)	2083 (62)	2473 (73)	3223 (95)	3260 (96)	3384 (100)
Portable CD Player	2590 (98)	2596 (98)	2609 (98)	2632 (99)	2636 (99)	2652 (100)
Audio Product	3321 (85)	3375 (87)	3357 (86)	3393 (87)	3474 (89)	3892 (100)
Mainstream TV	3618 (89)	3658 (90)	3674 (91)	3740 (92)	3954 (98)	4045 (100)

*Numbers given in parenthesis are percentage of disposal
**Disposal numbers averaged between incineration and landfill

Appendix III. Classification Analysis

The necessary components for using CART are the data file, control file, output file and the final command implemented on the leland server. The Data File gives the data values in this order response variable(s) for subject 1, x variables for subject 1, response for subject 2, ...the data values are separated by blanks. The complete data file for the case studies is given below.

eols	wote ch	techc yc	nuof parts	levof int	nuoff unc	nuof matl s	refor re	dgnc yc	wolif e	repu r	size	Haza rds
1	2.5	2	25	2	2	20	2	1	5	3	4	2.5
1	2.8	4	1000	2	1	10	1	2	11	10	5	3
3	2.5	2	533	2	3	3	3	2	5	4	6	0
1	1.2	10	1000	3	3	100	5	4	12	5	10	5
2	1.4	10	718	2	2	20	2	7	14	14	10	1
2	2	10	1000	2	1	35	3	4	20	20	9	1
2	2	10	1000	2	2	50	2	7	20	20	10	2
3	5	2	20	2	1	8	3	2	10	5	3	3
4	5	3	100	2	1	20	3	1	15	14	6	0.5
4	2.7	3	100	2	1	20	2	3	8	10	5	6.5
4	5	3	100	2	1	20	5	5	15	15	7	5.5
3	0	3	15	1	1	10	2	2	0	6	2	2.5
3	1.5	8	31	2	2	6	1	4	12	5	3	0
3	6	1	400	1	2	20	3	2	6	3	5	0.5
3	2.5	2	250	2	2	15	2	1.5	5	3	6	1
3	1.6	5	26	2	2	20	2	3	8	7	8	1
5	2	5	101	1	1	7	3	2	10	10	7	0
1	2.1	9	20	2	1	5	1	6	19	19	9	0
1	3	5	1000	2	3	100	2	5	15	7	10	6
2	2.9	7	1000	3	3	100	2	7	20	7	10	3.5
3	0.5	10	20	2	1	15	5	3	5	5	1	1
3	1	5	201	3	2	7	2	3	5	5	3	1
3	2	10	20	1	1	15	2	5	20	10	7	0.5
3	1.6	5	25	1	2	12	2	1	8	5	5	0
3	1	5	25	1	2	8	4	2	5	8	7	2
4	2	10	8	1	1	4	2	7	20	20	6	2
4	2	10	8	1	1	5	5	6	20	20	6	2.5
4	2	5	10	1	2	4	2	4	10	8	4	0
4	2	10	8	1	1	4	3	6	20	20	6	2
5	2	10	2	1	1	2	2	7	20	20	2	1.5
5	0.5	10	100	1	1	13	5	7	5	10	5	0.5
2	2	10	116	2	1	20	2	7	20	20	7	1.5
3	1.5	2	94	2	2	17	5	1	3	7	3	5
3	10	0 1.	10	1	1	25	2	2	10	15	3	6.5
3	0.5	4	25	1.	1.	7	3	3	2	1	1	3.5
3	2.5	2	22	3.	1.	30	2	1	5	2	1	0.5
3	9	1	135	3.	3.	52	2	1	9	2	7	2
3	1	5	100	3.	2.	20	5	2	5	3	7	3
3	0.5	4	25	1.	1.	7	3	3	2	1	1	0
3	10	0 1.	149	2	2	20	2	1	10	3	3	5.5
5	3.3	3	11	1.	1.	20	2	1	10	3	0	1.5
5	0.3	4	5	1.	1.	4	5	3	1	1	1	1
5	1.6	5	75	1.	1.	19	2	1	8	7	3	2
5	1.2	10	30	2	2	100	4	1	12	5	10	4
5	1.7	9	55	2.	1.	20	2	1	15	5	2	4.5

5	1.6	5	95	1.	1.	19	3	1	8	7	3	0.5
5	1.2	10	50	3	3	20	5	4	12	5	10	5

The control file is the file that runs the code. The following table outlines the specific format for each line of the control file.

Line Number	Content
1	name of the data file, not in quotes
2	nvar n # of variables and # of subjects, separated by one or more blanks
3 through p	The variable names, one per line, in the same order as in the data matrix. Each variable is followed by the number of categories. This is 0 for a continuous variable (or the response), >=2 for a factor.
p+1	Splitting option 1=anova; 2=event rates; 3=gini
p+2	Minimum bucket size suggested value =5
p+3	Minimum split size 10
p+4	primary splits to print >2
p+5	# surrogates to print >2
p+6	use of surrogates 3
p+7	Number of cross validations 10
p+8	Missing value depends on data
p+9	Complexity cutoff .005
p+10	Empty

An example control file is as follows:

```
/afs/ir.stanford.edu/users/c/a/catrose/cart/f1105wt.dat
13 46
eols 5
wotech 0
techcyc 0
nuofparts 0
levofint 3
nuoffunc 3
nuofmatls 0
reforre 5
dgncyc 0
wolife 0
repur 0
size 0
hazards 0
3
2
6
3
3
2
19
9999
.005
0
```

The CART program is located in the subdirectory: /afs/ir/class/stat315b/cart/rpmain on the leland server at Stanford University. To run the program, the command used in the leland subdirectory is: rpmain xxx > outfile, where xxx is the control file and then print the outfile. The output of the program is given below.

Table of complexity parameters

Tree	C.P.	#splits	rel error	cross-validated error
1	0.1538	0	1.0000	1.0000 +- 0.1293
2	0.0769	2	0.6923	1.0000 +- 0.1293
3	0.0577	5	0.4615	1.1154 +- 0.1259
4	0.0385	7	0.3462	1.0769 +- 0.1273
5	0.0050	8	0.3077	1.0000 +- 0.1293

```
Node number 1: 46 observations   Complexity param= 0.153846
  predicted class = 3, expected loss = 0.565217
    class counts:     5    5   20    7    9
    probabilities: 0.109 0.109 0.435 0.152 0.196
  left son=2 (27 obs), right son=3 (19 obs)
  Primary splits:
       wolife <  10.5 to the left, improve=5.068,  (0 missing)
    nuofparts < 625.5 to the left, improve=4.681,  (0 missing)
       dgncyc <   3.5 to the left, improve=4.470,  (0 missing)
  Surrogate splits:
      techcyc <     6 to the left, agree=0.870, adj=0.684, (0 split)
       dgncyc <   3.5 to the left, agree=0.870, adj=0.684, (0 split)
        repur <    12 to the left, agree=0.804, adj=0.526, (0 split)

Node number 2: 27 observations   Complexity param= 0.057692
  predicted class = 3, expected loss = 0.333333
    class counts:     1    0   18    2    6
    probabilities: 0.037 0.000 0.667 0.074 0.222
  left son=4 (13 obs), right son=5 (14 obs)
  Primary splits:
     levofint splits as RLL,          improve=2.086, (0 missing)
     nuoffunc splits as RLL,          improve=2.086, (0 missing)
        repur >   6.5 to the left, improve=1.905, (0 missing)
  Surrogate splits:
      techcyc <   2.5 to the left, agree=0.741, adj=0.462, (0 split)
       wotech >  2.25 to the left, agree=0.704, adj=0.385, (0 split)
     nuoffunc splits as RLL,          agree=0.704, adj=0.385, (0 split)

Node number 3: 19 observations   Complexity param= 0.153846
  predicted class = 2, expected loss = 0.736842
    class counts:     4    5    2    5    3
    probabilities: 0.211 0.263 0.105 0.263 0.158
  left son=6 (11 obs), right son=7 (8 obs)
  Primary splits:
    nuofparts <   108 to the left, improve=3.638,  (0 missing)
         size <     8 to the left, improve=2.274,  (0 missing)
        repur >    12 to the left, improve=2.001, (0 missing)
  Surrogate splits:
    nuofmatls <  27.5 to the left, agree=0.789, adj=0.500, (0 split)
```

```
        size <    8 to the left, agree=0.789, adj=0.500, (0 split)
    nuoffunc splits as LLR,        agree=0.737, adj=0.375, (0 split)

Node number 4: 13 observations
  predicted class = 3, expected loss = 0.153846
    class counts:     1     0    11     1     0
   probabilities: 0.077 0.000 0.846 0.077 0.000

Node number 5: 14 observations    Complexity param= 0.057692
  predicted class = 3, expected loss = 0.500000
    class counts:     0     0     7     1     6
   probabilities: 0.000 0.000 0.500 0.071 0.429
  left son=10 (5 obs), right son=11 (9 obs)
  Primary splits:
     nuofparts >    50 to the left, improve=1.813, (0 missing)
       hazards >  2.25 to the left, improve=1.675, (0 missing)
      nuoffunc splits as RL-,        improve=1.557, (0 missing)
  Surrogate splits:
     nuofmatls >  12.5 to the left, agree=0.786, adj=0.400, (0 split)
       techcyc >   4.5 to the left, agree=0.714, adj=0.200, (0 split)
       reforre splits as -RLRR,      agree=0.714, adj=0.200, (0 split)

Node number 6: 11 observations    Complexity param= 0.076923
  predicted class = 4, expected loss = 0.545455
    class counts:     1     0     2     5     3
   probabilities: 0.091 0.000 0.182 0.455 0.273
  left son=12 (4 obs), right son=13 (7 obs)
  Primary splits:
       reforre splits as RRLRL,      improve=2.597, (0 missing)
         repur <    12 to the left, improve=2.312,  (0 missing)
          size <   2.5 to the left, improve=1.899,  (0 missing)
  Surrogate splits:
        wotech >  3.55 to the left, agree=0.818, adj=0.500, (0 split)
       techcyc <   5.5 to the left, agree=0.818, adj=0.500, (0 split)
     nuofparts >  77.5 to the left, agree=0.818, adj=0.500, (0 split)

Node number 7: 8 observations     Complexity param= 0.076923
  predicted class = 2, expected loss = 0.375000
    class counts:     3     5     0     0     0
   probabilities: 0.375 0.625 0.000 0.000 0.000
  left son=14 (4 obs), right son=15 (4 obs)
  Primary splits:
        dgncyc >     6 to the left, improve=2.250, (0 missing)
        wolife >  17.5 to the left, improve=2.250, (0 missing)
         repur >    12 to the left, improve=2.250, (0 missing)
  Surrogate splits:
       reforre splits as RLR-R,      agree=0.875, adj=0.750, (0 split)
       techcyc >     6 to the left, agree=0.750, adj=0.500, (0 split)
     nuofparts <   859 to the left, agree=0.750, adj=0.500, (0 split)
Node number 10: 5 observations
  predicted class = 5, expected loss = 0.200000
    class counts:     0     0     1     0     4
```

```
    probabilities: 0.000 0.000 0.200 0.000 0.800
Node number 11: 9 observations    Complexity param= 0.038462
  predicted class = 3, expected loss = 0.333333
    class counts:     0     0     6     1     2
    probabilities: 0.000 0.000 0.667 0.111 0.222
  left son=22 (5 obs), right son=23 (4 obs)
  Primary splits:
    nuofparts >    13 to the left, improve=1.944, (0 missing)
    nuofmatls >   5.5 to the left, improve=1.730, (0 missing)
      hazards >  1.75 to the left, improve=1.244, (0 missing)
  Surrogate splits:
       wotech <   1.8 to the left, agree=0.889, adj=0.750, (0 split)
       wolife <     9 to the left, agree=0.889, adj=0.750, (0 split)
    nuofmatls >   5.5 to the left, agree=0.778, adj=0.500, (0 split)

Node number 12: 4 observations
  predicted class = 4, expected loss = 0.000000
    class counts:     0     0     0     4     0
    probabilities: 0.000 0.000 0.000 1.000 0.000
Node number 13: 7 observations    Complexity param= 0.076923
  predicted class = 5, expected loss = 0.571429
    class counts:     1     0     2     1     3
    probabilities: 0.143 0.000 0.286 0.143 0.429
  left son=26 (4 obs), right son=27 (3 obs)
  Primary splits:
      hazards >     1 to the left, improve=2.024, (0 missing)
       dgncyc <   2.5 to the left, improve=1.257,  (0 missing)
         size <   2.5 to the left, improve=1.257,  (0 missing)
  Surrogate splits:
      reforre splits as RL-L-,         agree=0.857, adj=0.667, (0 split)
      techcyc >   9.5 to the left, agree=0.714, adj=0.333, (0 split)
    nuofparts <    14 to the left, agree=0.714, adj=0.333, (0 split)

Node number 14: 4 observations
  predicted class = 2, expected loss = 0.000000
    class counts:     0     4     0     0     0
    probabilities: 0.000 1.000 0.000 0.000 0.000
Node number 15: 4 observations
  predicted class = 1, expected loss = 0.250000
    class counts:     3     1     0     0     0
    probabilities: 0.750 0.250 0.000 0.000 0.000
Node number 22: 5 observations
  predicted class = 3, expected loss = 0.000000
    class counts:     0     0     5     0     0
    probabilities: 0.000 0.000 1.000 0.000 0.000
Node number 23: 4 observations
  predicted class = 5, expected loss = 0.500000
    class counts:     0     0     1     1     2
    probabilities: 0.000 0.000 0.250 0.250 0.500
Node number 26: 4 observations
  predicted class = 5, expected loss = 0.250000
    class counts:     0     0     0     1     3
```

```
    probabilities: 0.000 0.000 0.000 0.250 0.750
Node number 27: 3 observations
  predicted class = 3, expected loss = 0.333333
    class counts:     1     0     2     0     0
    probabilities: 0.333 0.000 0.667 0.000 0.000
```

Appendix IV. ELDA Development

Figure IV-1 shows the classification tree used in the ELDA web tool.

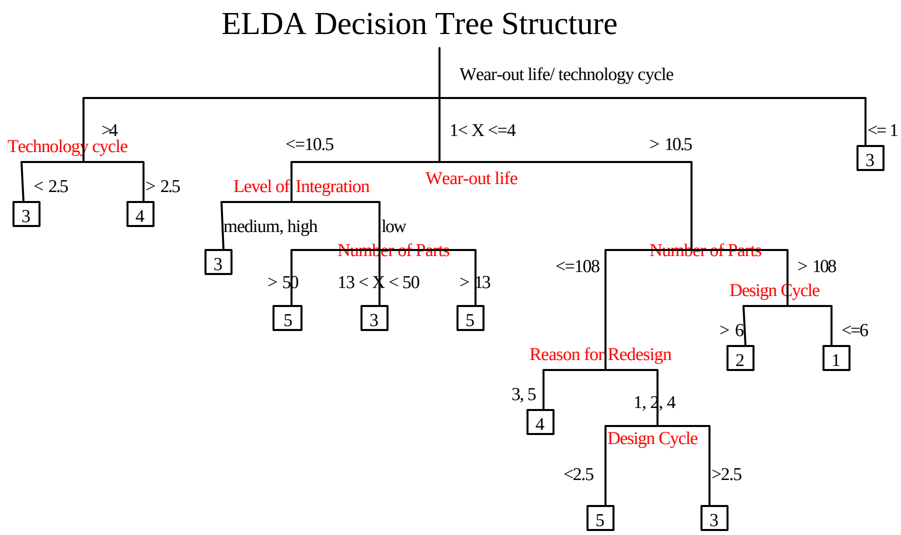

Figure IV-1. ELDA Decision Tree Structure for web based tool

The final nodes are the end-of-life strategies where 1-reuse, 2-service, 3-remanufacture, 4-recycle with disassembly, and 5-recycle without disassembly.

The login page requires user to input user identification and product information. The page includes directional buttons such as “Previous”, “Next”, and “Summary”. The user can use “Next” to get to the next screen, or use “Summary” to get summary screen. At the login page “Previous” is disabled. Users can get user login identification from the online form located at dfe.stanford.edu, under the link for ELDA. User identification (group id) will be e-mailed to the user, usually within 1 week.

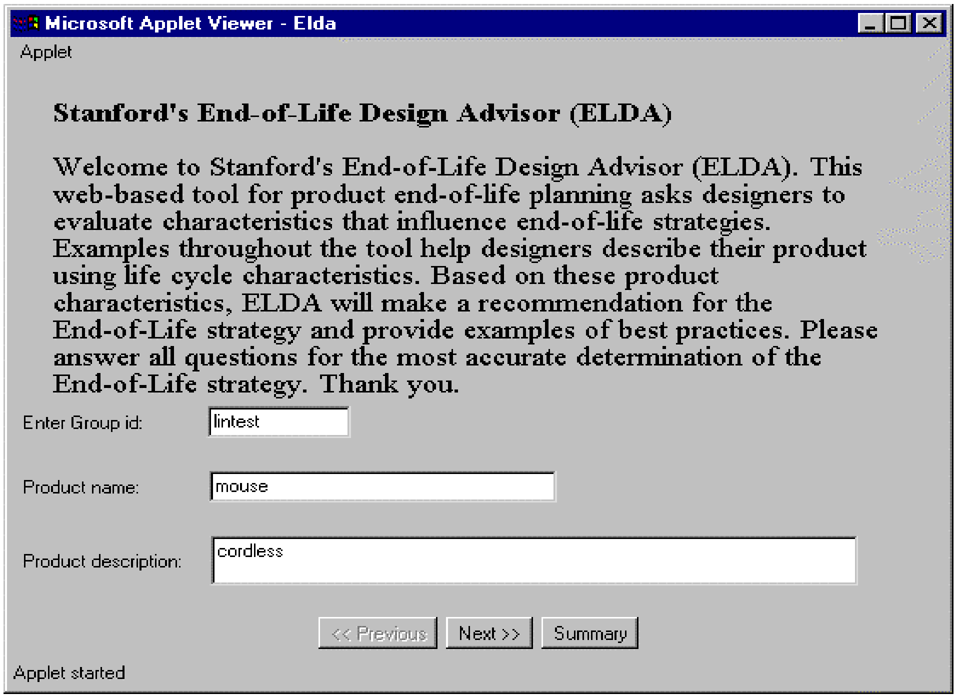

Figure IV-2. ELDA-Login Screen

If the user identification is invalid, the product name is omitted or product description is left out, the corresponding error message indicates the action needed by the user.

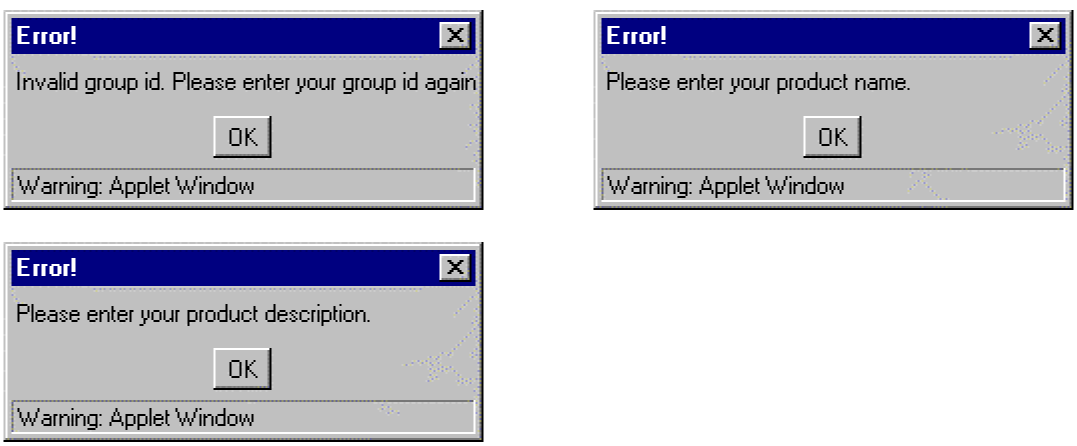

Figure IV-3. ELDA - error messages

The screens have the common characteristics. The user can manually type in the value. If there is a scroll bar, the text in the text field will change by sliding the scroll bar. The list window has several examples intended to guide the user. When the user clicks one of them, the text field will set to the number corresponding to the example product.

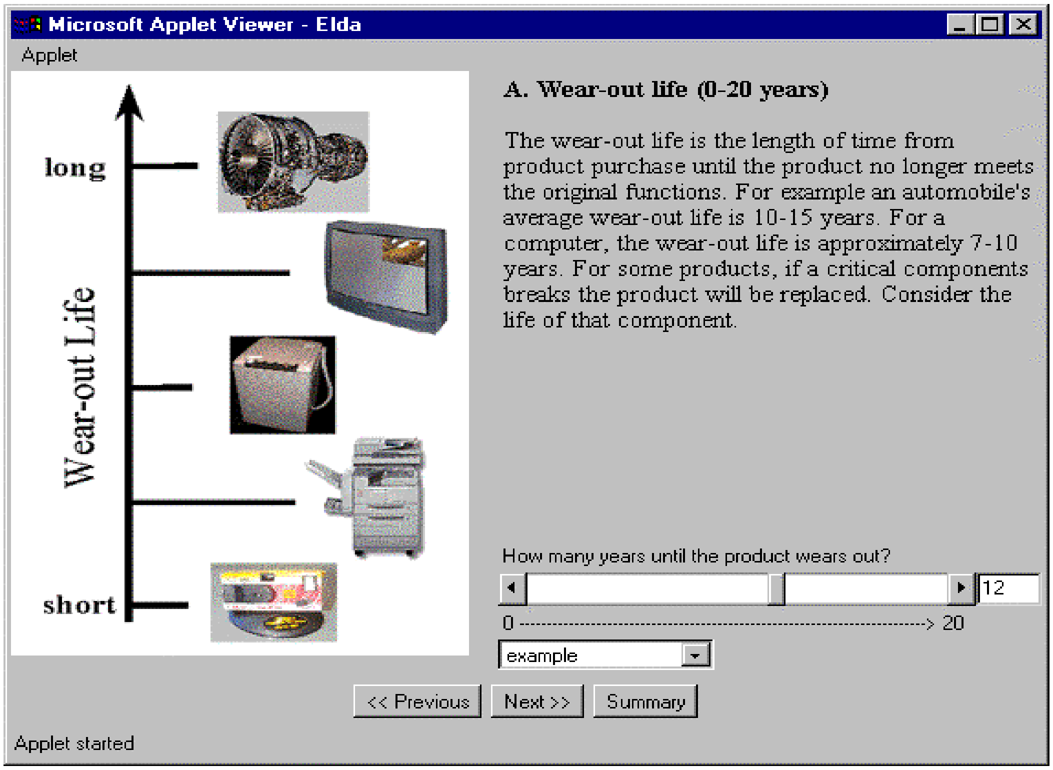

Figure IV-4. ELDA-wear-out life

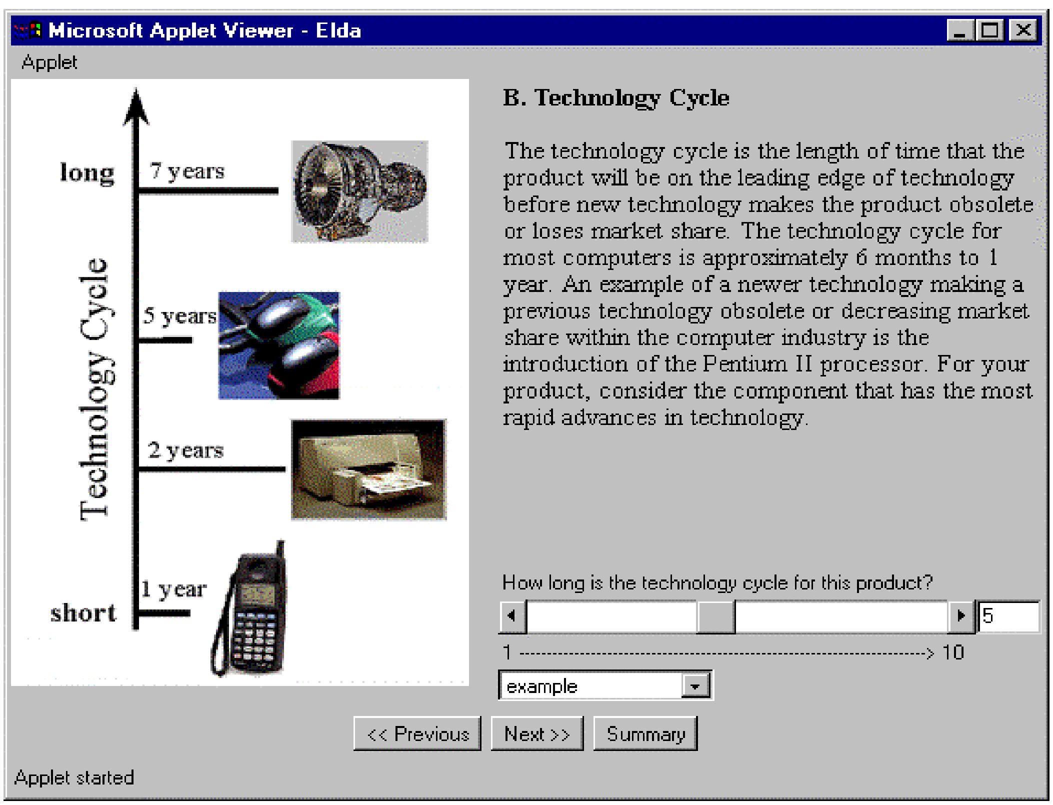

Figure IV-5. ELDA-technology cycle

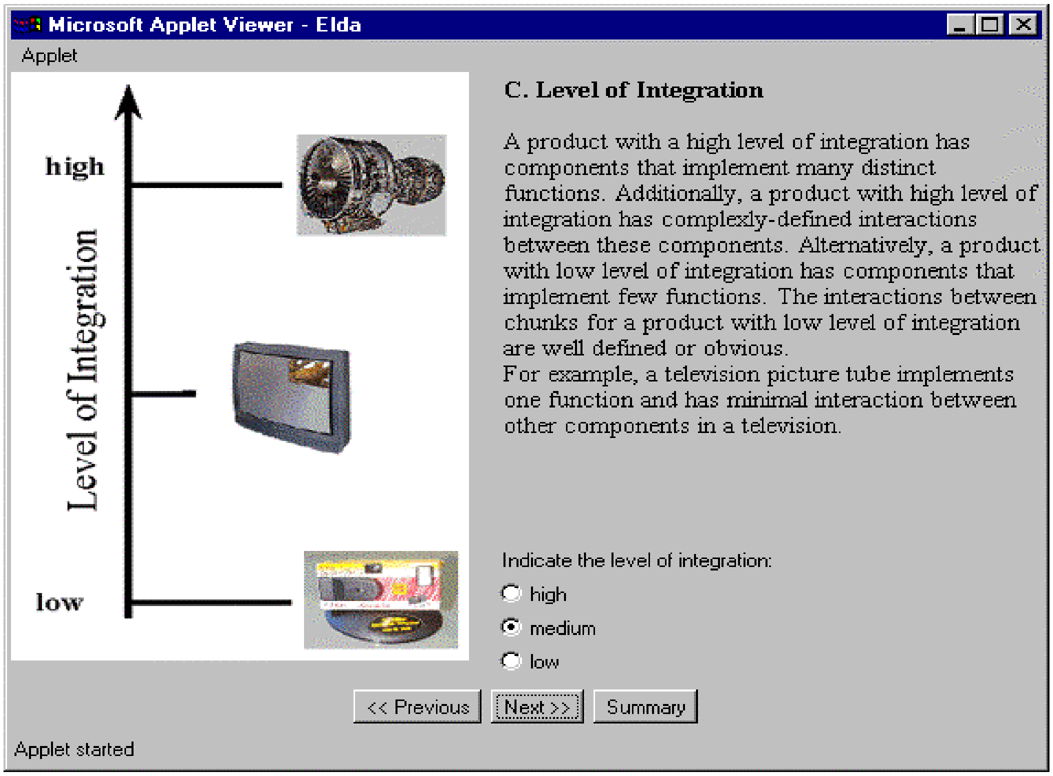

Figure IV-6. ELDA-level of integration

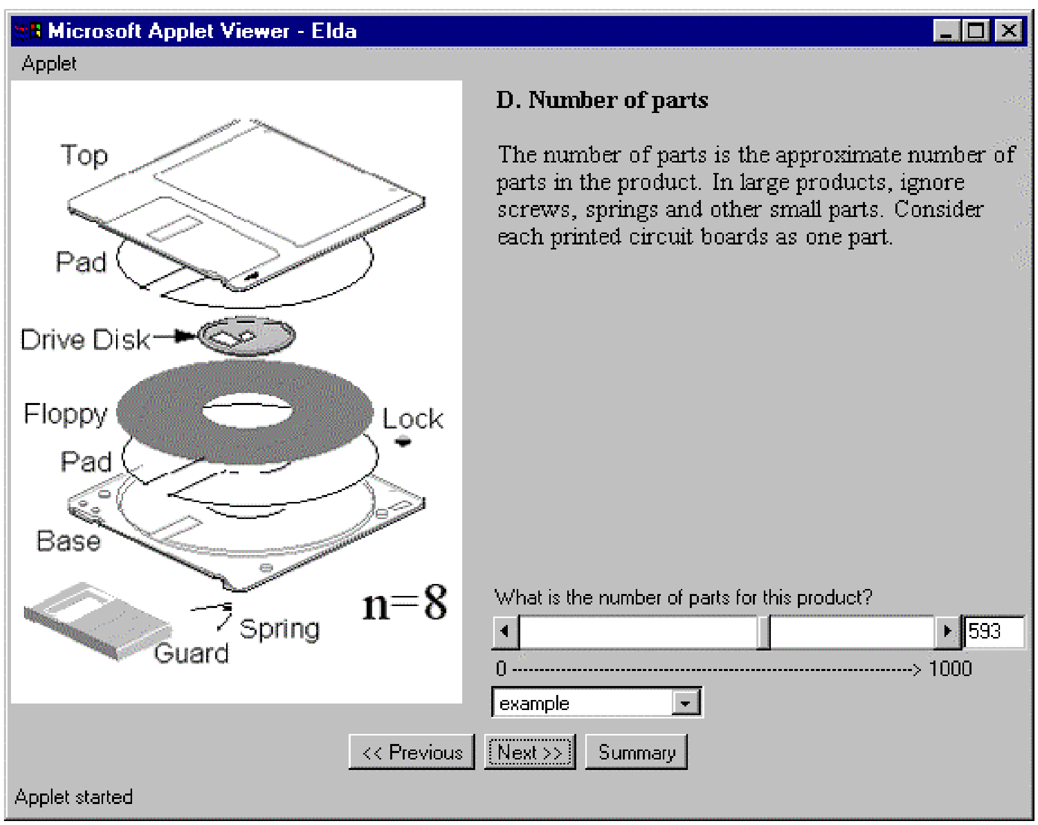

Figure IV-7. ELDA-number of parts

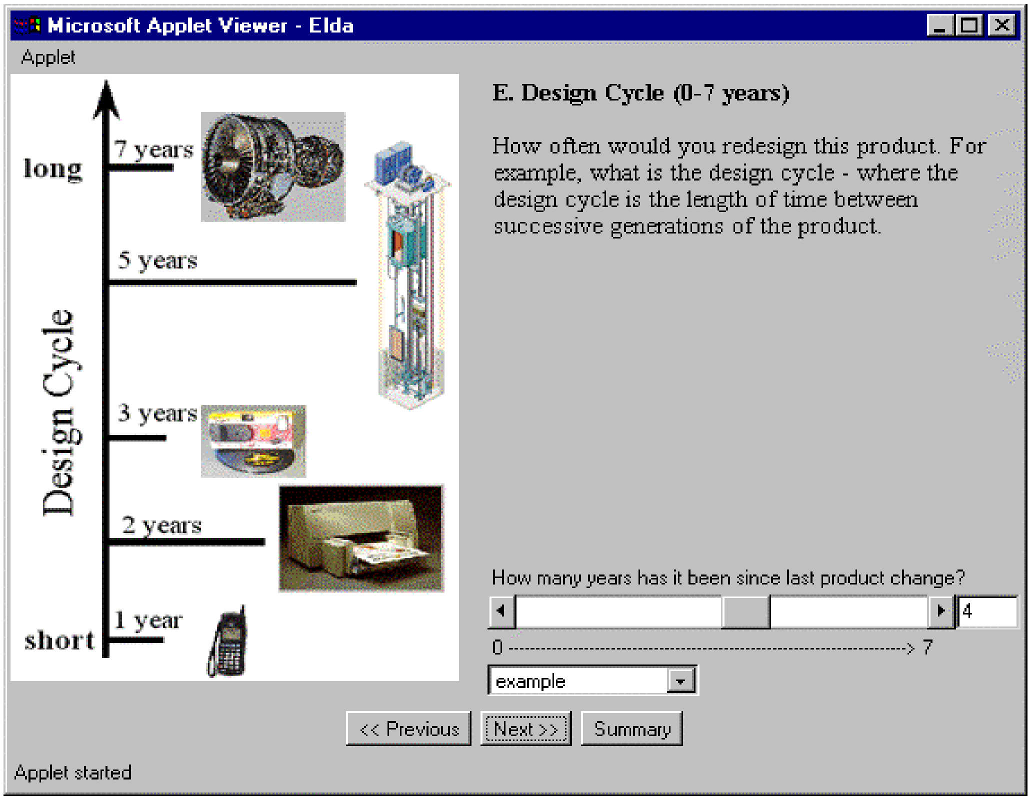

Figure IV-8. ELDA-design cycle

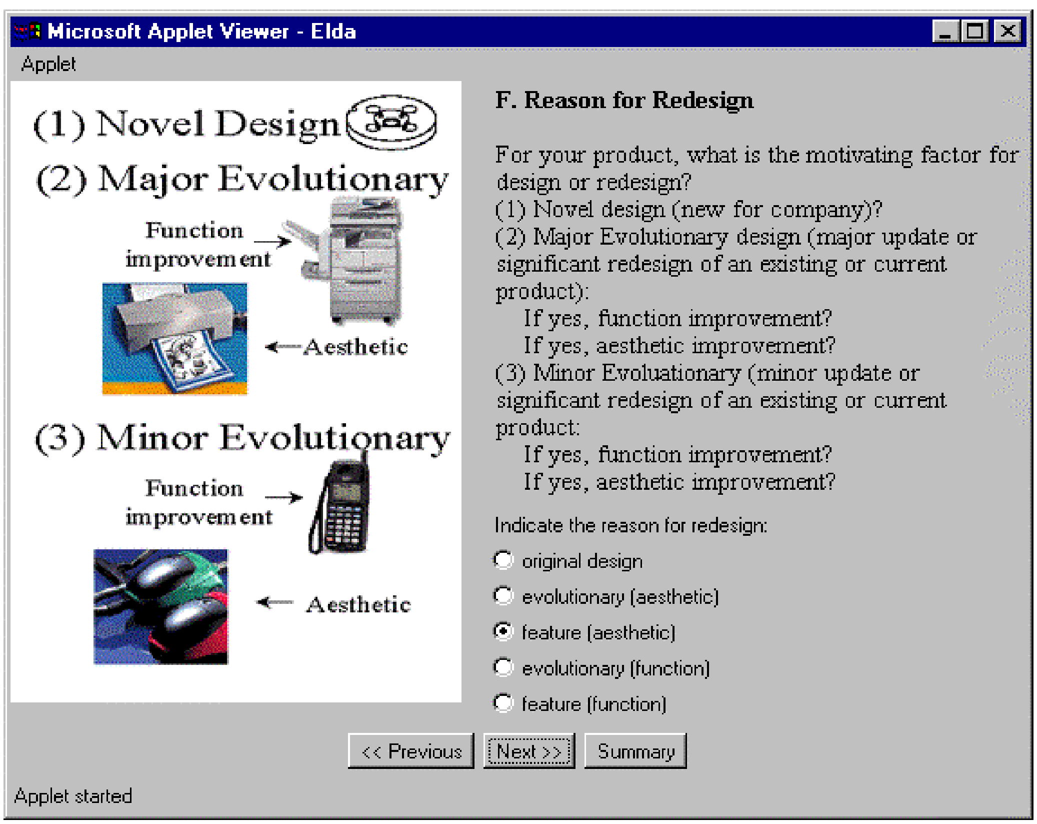

Figure IV-9. ELDA-reason for redesign

Summary Screen is the last screen for user to submit their choices. So "Next" and "Summary" buttons get disabled.

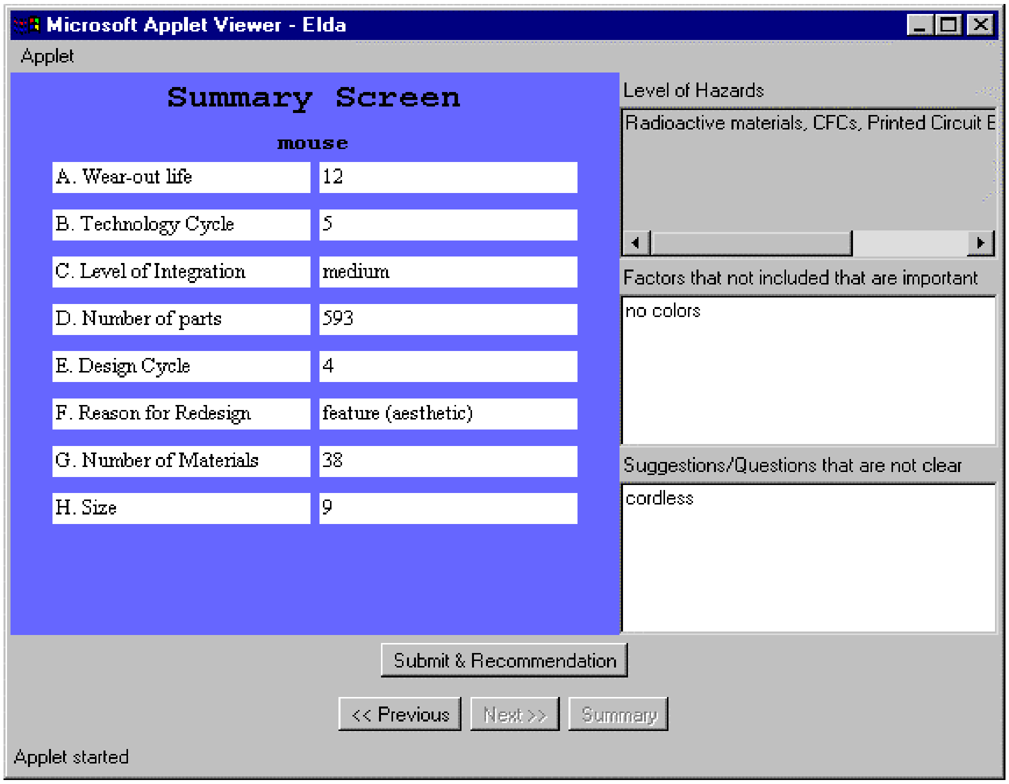

Figure IV-10. ELDA-summary screen

After clicking the "Submit and Recommendation" Button, the recommendation page appears as a second internet browser screen.

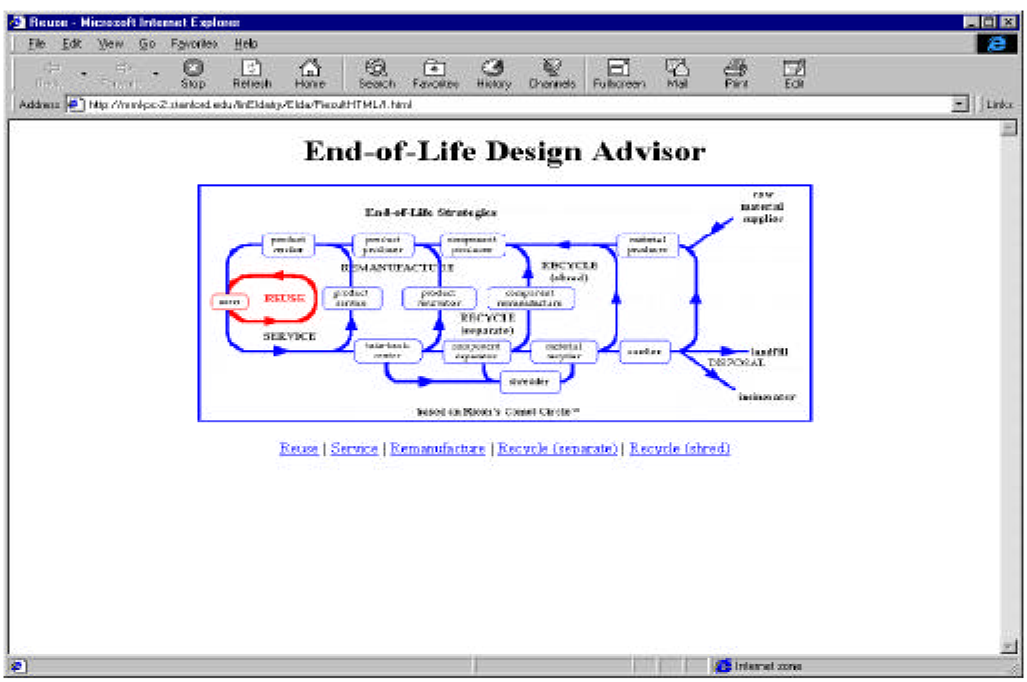

Figure IV-11. ELDA-example recommendation

Appendix V. Validation Data

The robustness of the classification method was analyzed. The following data was collected from nine product designers for cell phone, television and vacuum cleaner, respectively.

Table V-1. Data collected from designers for cell phone

CELL PHONE	1	2	3	4	5	6	7	8	9	LOW	HIGH	AVERAGE	ST.DEV
Technology cycle	2	1	15	3	3	4	1	1.5	0.5	0.5	15	3.4	4.5
Wear-out life	3	4	5	5	5	5	2.5	4.5	3	2.5	5	4.1	1.0
Wear-out/techcycle	1.5	4	0.3	1.7	1.7	1.3	2.5	3	6	0.3	6	2.4	1.7
Level of integration	high	med	high	high	high	high	high	high	med	med	high	high	N/A
Number of parts	20	15	5	50	50	20	200	25	32	5.0	200	46.3	59.6
Reason for redesign	bc	b	b	b	b	c	b	b	b	b	c	b	
Design cycle	1	0.5	2.0	3.0	3.0	0.3	0.5	1.0	1	0.3	3	1.4	1.1
ELDA classified end-of-life strategy	3	3	3	3	3	3	3	3	3	3.0	3	3.0	0.0

Table V-2. Data collected from designers for telephone

TELEVISION	1	2	3	4	5	6	7	8	9	LOW	HIGH	AVERAGE	ST.DEV
Technology cycle	5	7	30	10	10	35	7	30	4	4	35	15.3	12.5
Wear-out life	15	15	10	20	20	10	7	10	11	7	20	13.1	4.6
Wear-out/techcycle	3	2.1	0.3	2.0	2.0	0.3	1	0.3	2.8	0.3	3	1.5	1.1
Level of integration	med	low	high	low	low	high	med	med	low	low	high	med	N/A
Number of parts	100	70	10	50	50	25	50	25	100	10	100	53.3	31.9
Reason for redesign	c	d	d	d	e	d	d	d	d	c	e	d	
Design cycle	2	1	3	3	3	1.5	1.5	1.5	1	1	3	1.9	0.8
ELDA classified end-of-life strategy	4	5	3	3	4	3	3	3	4	3	5	3.6	0.7

Table V-3. Data collected from designers for vacuum cleaner

VACUUM CLEANER	1	2	3	4	5	6	7	8	9	LOW	HIGH	AVERAGE	ST.DEV
Technology cycle	10	10	50	30	30	50	15	30	10	10	50	26.1	16.2
Wear-out life	25	20	3	10	10	5	7.5	10	15	3	25	11.7	7.1
Wear-out/techcycle	2.5	2	0.1	0.3	0.3	0.1	0.5	0.3	1.5	0.1	2.5	0.9	0.9
Level of integration	low	low	med	low	low	med	med	med	med	low	med	low	N/A
Number of parts	50	45	25	50	50	100	30	25	20	20	100	43.9	24.3
Reason for redesign	b	d	e	d	d	d	e	e	e	b	e	d	
Design cycle	5	3	5.0	5.0	5.0	4.0	1.5	2.5	3	1.5	5	3.8	1.3
ELDA classified end-of-life strategy	3	3	3	3	3	3	3	3	5	3.0	5	3.2	0.7

Appendix VI. Sample Interview Questions

The following table outlines the questions used in interviews to collect more information about the Environmental Value Chain Analysis operating in a company. The particular questions are taken from the interview preparation for Philips Medical Devices.

Table VI-1. Example Questions for EVCA interviews

CATEGORY	QUESTIONS
Money Matters	What kind of incentive ($ profits) exist for pre-owned business? Do companies/hospitals get trade-in 'allowance' for product (what percentage of value)? What is the average (and range) of the product cost to manufacture? What is the average (and range) of the product selling price? How are the costs of returning and processing the product being financed?
Customers	Who owns products? What kind of ownership involved (owned or leased)? Who are 1st customers (institutions – private, academic, municipal; location - ?, size -?)? Who are 2nd customers (institutions – private, academic, municipal; location - ?, size -?)? How long do consumers keep the product (1st, 2nd, etc) How would customers 'dispose' of the product without you (can they sell it themselves)? What are the changes in customer preference over time?
Target Sales	Where are the sales? What percentage of sales are the pre-owned sales? What is the sales volume?
Service	What type of service contract do you provide for pre-owned products? Does it differ from new product service contract? Do Philips people provide 'service' for products? Are upgrades available (what type)? Is there a company-wide service organization or is that provided by product divisions? How many warranty returns to you get? Is the product disposed because of technical defects?
Metracom / Philips System	Where is refurbishing done? Where is original manufacturing done? What kind of 'middle-men' exist? Is the product processed in-house or by a third party?
External pressure	Are you regulated by the U.S. Food and Drug Administration, Ministry of Health etc? Does the U.S. EPA, or environmental regulation regulate you? How does legislation or regulation effect the pre-owned business? To what extent is the manufacturer responsible for the end-of-life phase? Does a take back obligation already exist for discarded products?

Company Reactivity	What have you learned along the way to profitability? What have been major challenges? What are the critical internal flows of communication? What gets 'reaction' from company (what moves, or pushes company to move quickly-for example, bad publicity?) How does it then move quickly (for example, once support received from CEO, does that assure success?)

The questions, given in Table V-2, target a particular product and seek to gather information about product functionality and technical characteristics.

Table VI-2. Example Questions for ELDA interview

CATEGORY	QUESTIONS
Technical Characteristics	How big is the product? What is the average life of the product? What is the product's weight? <ELDA> of example product (to be discussed later) How frequent, type, nature of redesigns?
Product Functionality	What amount of repurchase is motivated by design (change in function, etc) or motivated by product wear-out? What are major design changes? What would make consumer want to upgrade the product? What is the 'key' functionality of the product? Can you give quantifiable numbers to consumer preferences/functionality levels? How many product platforms, generations, etc –timing of product release? How long does it take for high end functionality to move through the whole product line? Do you have technology roadmaps for the product? Where is environmental positioning in the roadmap? Scorecard comparison? How do technology roadmaps differ across products (within division, within product category)? How to build technology roadmap for various products? What has been the technology evolution for products during the last 10 years? What were the 'best-sellers' of these products? How quickly was 'best-seller functionality' moved to lower end products? What functionality is changing: software? Interface? Production technology? Mechanical? (in other words, you need advances from which divisions to provide customer satisfaction) Is the product very sensitive to trends? Are there new products on the market that offer more features?

Appendix VII. Biographical Notes

Catherine Rose, born in Charlotte, North Carolina, is the youngest of four children of an engineer father and educator mother. Throughout her childhood, she continually pestered adults with the question ‘why?’. In the North Carolina State University College of Engineering newsletter, she was quoted saying, "I don't want to make my life impossible, but I like a challenge."

Catherine Rose graduated from North Carolina State University in 1996 summa cum laude, completing a B.S. in Mechanical Engineering, B.S. in Applied Mathematics and B.A. in Spanish Languages and Literature. She completed her masters degree in Mechanical Engineering in 1998 from Stanford University. Her PhD in Mechanical Engineering from Stanford University will be conferred in January 2001.

Her research interests include business aspects of end-of-life treatment of products as well as other environmental strategy concerns. In 1999, she was selected as one of forty National Science Foundation summer interns and worked at Japan’s Ministry of International Trade and Industry. As a Research Fellow at Delft University of Technology in the Netherlands, Catherine contributed her knowledge to their Design for Sustainability group.

Dr. Matt Schnaderbeck (Stanford '98, Chemistry), Catherine's fiancé, lives outside of Boston, MA. Catherine will join Matt in January 2001 and pursue opportunities combining business, engineering and environmental strategy.