12-1-2011

Determining a relationship between design characteristics and the end-of-life disposition of cellular phones

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Determining a Relationship between Design Characteristics and the End-of-Life Disposition of Cellular Phones

A Thesis

Submitted in partial fulfillment of the

requirements for the degree of

Master of Science in Sustainable Engineering

in the

Department of Industrial & Systems Engineering

Kate Gleason College of Engineering

by

Ashley DeVierno

December 2011

DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING

KATE GLEASON COLLEGE OF ENGINEERING

ROCHESTER INSTITUTE OF TECHNOLOGY

ROCHESTER, NEW YORK

CERTIFICATE OF APPROVAL

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Abstract

In recent years, the consumption of consumer electronics has increased rapidly in the United States and across the world. As the consumer electronics industry continues to innovate and turn over new products, older products become obsolete and enter the ever growing electronics waste stream, which was 2.3 million tons in 2007.The increasing volume of electronic waste (e-Waste) has gained the attention of consumers, media outlets, and policy makers across the world. This has put pressure on original equipment manufacturers (OEMs) of consumer electronics to manage their products in an environmentally responsible way at the end of their product lifetimes. It has also motivated OEMs to improve their product designs to become more suitable for end-of-life recycling and recovery processes in an effort to reduce their environmental impact.

Many sustainable design methods for end-of-life disposition have been developed “ad-hoc” from industry knowledge or “guess and check” methods. The published literature lacks a scientific method for determining the relevant design criteria useful for reducing the environmental impact of end-of-life disposition of consumer electronic products. The purpose of this study is to define the criteria or design characteristics of cellular phones that have a significant relationship with end-of-life disposition environmental impact and lend themselves to sustainable design practices.

To determine the significant design characteristics of cellular phones the following activities are performed: (1) a set of design characteristics that may be used to relate the product design and end-of-life environmental impact is defined, (2) the end-of-life disposition of consumer electronics is described, (3) the process for selecting end-of-life separation processes for materials or components is described, (4) the environmental impact is calculated using a one phase, end-of-life disposition life cycle assessment, (5) thirty-four cellular phones, including 10 smart phones are disassembled to evaluate their design characteristics and environmental impacts, and (6) linear regression analysis (LRA) is used to determine the cellular phone design characteristics that have the most significant relationship with end-of-life environmental impact.

The results of the research method demonstrate that it is possible to establish a relationship between cellular phone design characteristics and their end-of-life disposition environmental impact. The LRA concluded that *Volume* is the only significant design characteristic for a cellular phone’s end-of-life disposition environmental impact. A cellular phone’s end-of-life disposition environmental impact is dominated by components that are regulated by the WEEE protocol (batteries and printed circuit boards), so their environmental impact is driven by the size of these components and not their other design characteristics. This trend is consistent with the results of the one-phase end-of-life disposition life cycle assessments that evaluated the disassembled cellular phones.

With this information, designers can focus their sustainable design efforts on modifying and improving the design characteristics that have the strongest relationship with end-of-life disposition environmental impact.

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Dedication

To the loving memory of

Rochelle Nicolette Perry

(1985-2011).

Rochelle's passion for life, effervescent personality, and selflessness are truly missed.

Acknowledgements

This research would not have been a success without the help and support of my many people. Thank you to everyone who has supported this research. I especially would like to thank my thesis committee: my advisor, Dr. Brian Thorn, Dr. Andres Carrano, and Dr. Marcos Esterman for their patience and guidance throughout this research and my time at RIT.

I would also like to acknowledge Kyle Weins, President of ifixit.com, for providing bill of material data for the smart phones analyzed in this research. Special thanks also goes to the RIT Student Environmental Action League (SEAL), Sustainable Engineering Research Group (SERG), the Sustainable Print Systems Laboratory (SPSL) for providing cellular phones and tools to collect data for this research. Furthermore, I would like to give special thanks to Wendi Latko and Victoria DeYoung, from Xerox and John Kreuder for the countless hours they spent proofreading the thesis document.

Finally, I would like to extend my gratitude to my family, friends, colleagues, and co-workers. My research would not have been successful without you!

Chapter 1

INTRODUCTION

This chapter outlines the motivation for improving design for end-of-life (DfEOL) methods to minimize the environmental impact of consumer electronics disposal and electronic waste (e-waste). To begin, the current trends of consumer electronic waste in the United States are discussed, followed by their potential local and global environmental impacts. Then the responses of governments, non-government organizations (NGOs), and original equipment manufacturers (OEMs) to the current trends and impacts via legislation, extended producer responsibility, and design programs are discussed. Finally, cellular phones are described in relationship to design characteristics, current end-of-life trends, and environmental legislation.

1.1 Consumer E-waste Trends and Environmental Impacts

In 2007, consumers in the United States purchased more than 500 million consumer electronic products (Euromonitor, 2010). This is equivalent to approximately 24 consumer electronic products per American household (CEA, 2008). The following products are categorized as consumer electronics: televisions and monitors, video cameras, cellular phones, computers, computer peripherals, audio/stereo equipment, VCRs, DVD players, telephones, fax, and copying machines, video game consoles, and wireless devices (EPA, 2001).

As consumers purchase new products for their households, they store or dispose of the old electronic products they no longer want. E-waste describes consumer electronic products that are discarded and no longer needed for use (EPA, 2001). E-waste is growing at the fastest rate of all tracked municipal solid waste in the United States (Nimpuno, McPherson, & Sadique, 2009).

In 2007, 2.3 million tons of computers, laptops, televisions, and mobile phones became e-waste in the United States with 1.8 million tons sent to landfill and the rest, approximately 13.6%, sent to recycling facilities. This included the recycling of 18% of televisions, 18% of computers and peripherals, and 10% of cellular phones discarded in 2007 (EPA, 2009). Approximately 50-80% of recyclers in the U.S. send e-waste to developing nations like China, Nigeria, Pakistan, Vietnam, India, and the Philippines. Only about 15% of the waste sent to these nations can be reused or refurbished for resale (Biello, 2008).

The other 85% is foraged for salvageable materials using recycling processes that are damaging to the human health and environmental well-being of the community. A recycling center in the town of Guiyu, China employs the following harmful recycling processes: manual/unprotected removal of materials; open incineration of wires; removing gold components using acid baths; the use of children for labor; and toxic dumping in irrigation ditches, rivers, and fields (Hicks, Dietmar, & Eugster, 2005).

Incineration or dumping of consumer electronics in the irrigation ditches, rivers, and fields has the potential to release contaminants into the air, waterways, groundwater, and soil. These materials include toxic substances such as persistent bioaccumulative toxic chemicals (PBTs), including antimony, arsenic, beryllium, cadmium, and lead; brominated flame retardants used for the printed circuit boards and plastic housings of consumer electronics; lead used in solder, components, and coatings; and heavy metals such as copper, nickel, and zinc from batteries (Fishbein, 2002).

Understanding the environmental impact of disposing consumer electronics can be difficult. The master equation of industrial ecology, also known as IPAT (Equation 1.1), describes environmental impact as a function of population, affluence, and technology:

$$Enviornmental\ Impact = population \times \frac{GDP}{person} \times \frac{environmental\ impact}{unit\ of\ per\ capita\ GDP} \qquad (1.1)$$

Population and gross domestic product (GDP) will continue to grow, especially in developing countries. This trend increases the importance of the last term in the IPAT equation in relation to the mitigation of environmental impact. It describes the ability of technology to allow development without causing more environmental damage and the effectiveness of technology's implementation. Personal consumption in the United States continues to grow alongside the purchase of consumer electronics, such as laptops (Figure 1.1 and 1.2). With the IPAT definition of environmental impact and current trends, it might be inferred that improving the technology of consumer electronics does not always mitigate the environmental impact, but increases it over time as more computers and cellular phones are manufactured and discarded (T. E Graedel, 1996).

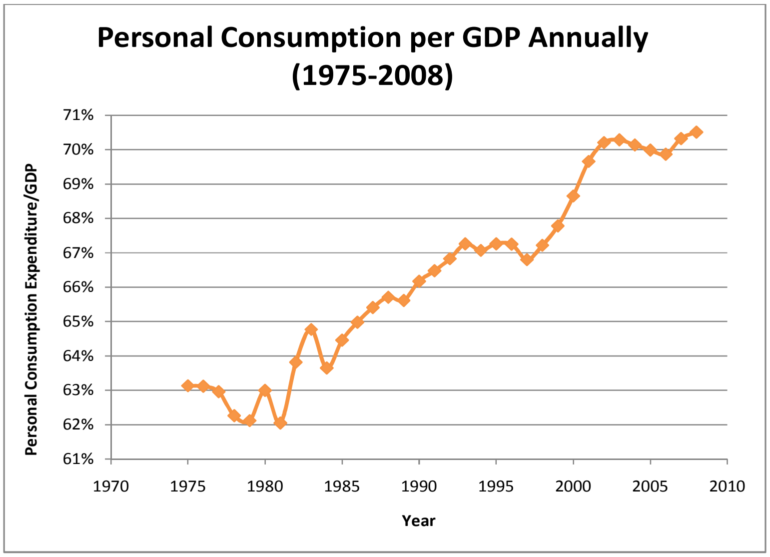


Figure 1.1: U.S. Personal Consumption per GDP over time Adapted from BEA. (2009). U.S. Beauru of Economic Analysis, 2009, from http://www.bea.gov/.

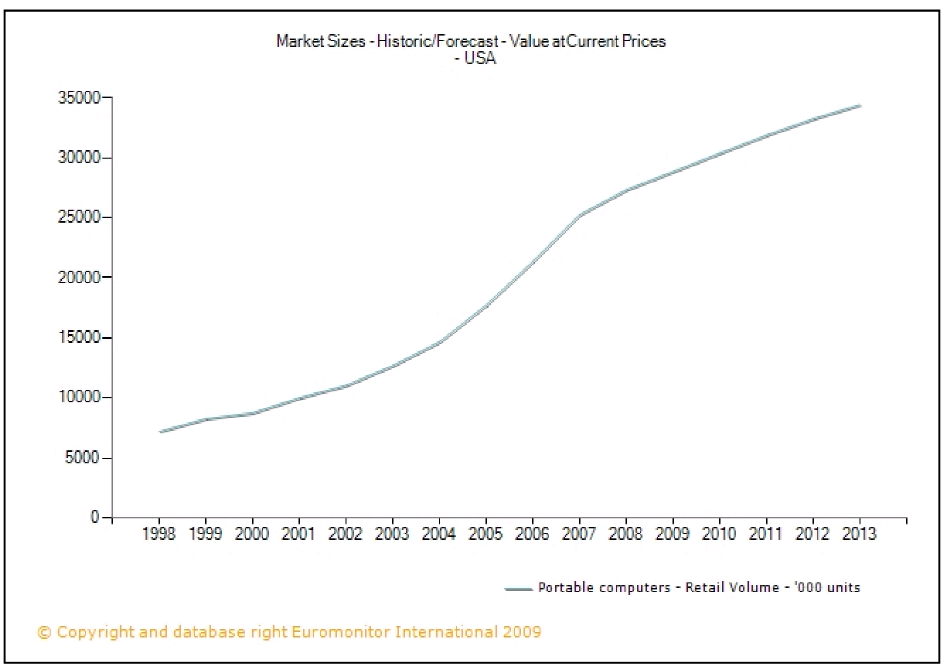


Figure 1.2: Retail Volume of Laptops in the U.S. in 1000s of units. Adapted from Euromonitor. (2010). U.S. Retail Volume of Consumer Electronics Euromonitor International.

1.2 Governments, NGOs, and OEMs Respond to E-Waste

1.2.1 Governments

The responses of governments, non-government organizations (NGOs), and original equipment manufacturers (OEMs) to the current trends and impacts have been numerous and varied. These responses include government legislation, NGO agreements and certifications, extended producer responsibility declarations, and OEM sustainable design programs.

In 1976, the United States created the Resource Conservation and Recovery Act (RCRA) to meet the following goals: "protect human health and the environment from the potential hazards of waste disposal, conserve energy and natural resources, reduce the amount of waste generated, and ensure that wastes are managed in an environmentally-sound manner." It is the primary law in the U.S., updated several times, that provides guidance for the control of hazardous waste from generation to disposal, which includes e-waste containing hazardous materials (EPA, 2010a).

In 2002, the European Union passed Directive 2002/95/EC on the Restriction of the Use of certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) and Directive 2002/96/EC on Waste Electrical and Electronic Equipment (WEEE) (Day, 2006). RoHS restricts the use of hazardous materials in electrical and electronic equipment. It restricts the maximum concentration of cadmium to be 0.01% by weight in homogenous materials and the maximum concentration of hexavalent chromium, lead, mercury, polybrominated biphenyls (PBB), and polybrominated diphenyl ethers (PBDE) to be 0.1% by weight in homogenous materials. WEEE requires original equipment manufacturers (OEMs) to take back electronic waste free of charge. It also requires safer substitutions to replace lead, mercury, cadmium, chromium and flame retardants such as polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) (Day, 2006).

In 2009, President Obama signed Executive Order (E.O.) 13514, "Federal Leadership in Environmental, Energy, and Economic Performance," which set goals for sustainability for the Federal Government in several areas, including electronics. The Federal Electronics Challenge program (FEC) promotes the environmentally sustainable purchasing, use, and disposal of electronics among government agencies (FEC, 2003).

1.2.2 Non-Government Organizations (NGOs)

In 1994, the Basel Convention passed an agreement, also known as the Basel Ban, to "ban the export of hazardous materials from richer to poorer countries." To date, 71 countries have ratified the amendment, not including the United States (2011). The Basel Action Network (BAN) is a charitable organization that promotes the Basel Ban and confronts those parties that defy the Basel Ban (BAN, 2010).

In 2006, the Green Electronics Council (GEC) became the host of the Electronic Product Environmental Assessment Tool (EPEAT). One month later, the Institute of Electrical and Electronics Engineers' (IEEE)'s standards board approved the EPEAT standard, IEEE 1680 (GEC, 2006b). The EPEAT standard helps companies that purchase computers, laptops, and monitors in large quantities evaluate and compare products based on environmental attributes, including design for end-of-life. Manufacturers then can secure market recognition for their efforts to mitigate environmental impacts (GEC, 2006a).

In 2006, Greenpeace International commissioned a study, which examined the impact of extended producer responsibility (EPR) on innovation and greening products. EPR laws include laws such as WEEE and the End-of-life of Vehicles (ELV). The study found that the environmental performance of products improved due to extended producer responsibility laws, especially in the areas of hazardous materials, recyclability, and recycling (Rossem, Tojo, & Lindhqvist, 2006).

1.2.3 Original Equipment Manufacturers (OEMs)

The EPR study also commended consumer electronics companies, such as Dell, HP, and IBM, for their take-back and recycling programs. HP was recognized for including WEEE and RoHS requirements in its design for the environment (DfE) program, which includes materials innovation and design for recycling (DfR) (Rossem et al., 2006). Greenpeace also publishes their Guide to Greener Electronics annually, which scores OEMs on their elimination of hazardous substances, take-back and recycling, and overall reduction of climate impacts, disclosed through life cycle assessments and/or carbon footprints. The top five companies in 2010 were Nokia, Sony Ericsson, Philips, Hewlett Packard, and Samsung (Greenpeace, 2010).

Researchers such as Graedel and Allenby and Otto and Wood suggest the design stage as having the largest effect on the environmental impact of products and services ((T.E. Graedel & Allenby, 1995; Otto & Wood, 2001). Most OEMs cite one of the following methods as an approach to combat e-waste: life cycle assessment (LCA), design for the environment (DfE), design for x (DfX),

and cradle-to-cradle design (Apple, 2010; Dell, 2010; HP, 2009; IBM, 2010). OEMS, such as Nokia, Ericsson, and Motorola, have design programs to lower impact and improve recyclability and disassembly (Russo, 2009).

1.2.3.1 Life Cycle Assessment (LCA)

The International Organization for Standardization states life cycle assessment "studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to- grave) from raw material acquisition through production, use, and disposal" (Figure 1.3) (ISO, 1997). An accurate life cycle assessment involves substantial detail about the materials used in the product, processes needed to make the product, the intended life of the product, transportation of the product, energy used by the product, and disposal of the product. Full life cycle assessments are usually completed after the final design of the product has been selected via computer software, such as Simapro or Gabi. Environmental indicators that are typically included in LCA are impact on human health from hazardous and toxic wastes, impact on eco-system from conventional pollutants and hazardous and toxic wastes, and impact on resources including energy use (Hendrickson, Lave, & Matthews, 2006).

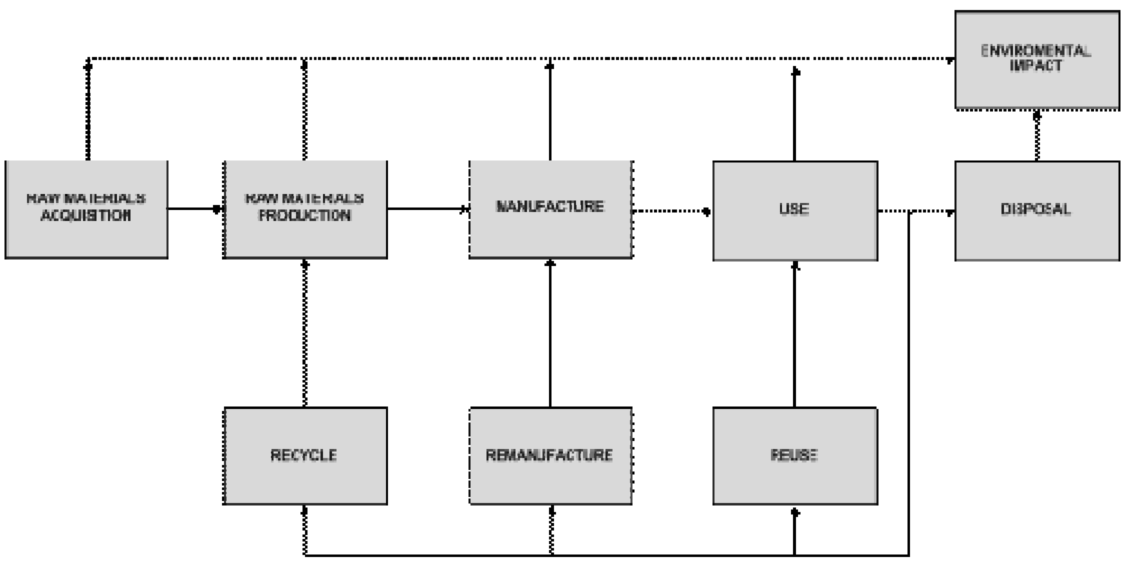


Figure 1.3: Typical Life Cycle Adapted from Hendrickson, C. T., Lave, L. B., & Matthews, H. S. (2006). *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach*. Washington, DC: Resources for the Future.

1.2.3.2 Design for the Environment (DfE)

According to the United States Environmental Protection Agency (EPA), DfE is "an approach companies use to make business decisions that consider environmental impacts along with

traditional business considerations of cost and performance" (EPA, 2002). Usually, the first step in the process is to implement several DfE guidelines using checklists for product structure, materials selection, labeling and finishing, and fastening. Then an initial assessment of the life cycle impact uses a bill of materials with estimated design and material proxies to describe the stage with the highest impact. Design for x techniques focus on the stage with the highest impact to make specific design changes. These techniques include "design to minimize material usage, design for disassembly, design for recyclability, design for remanufacturing, design to minimize hazardous materials, design for energy efficiency, and design to regulations and standards." After changes have been implemented, a full life cycle assessment is used to assess environmental impacts in more detail using the completed bill of materials of the product, which was described above (Otto & Wood, 2001).

1.2.3.3 Design for EOL (DfEOL)

Design for x (DfX) techniques that play a significant role in this research are those representing the end-of-life or final disposition of the products, commonly known as Design for End-of-Life (DfEOL). Typically, the end-of-life (EOL) of a product is described as the instance when the product does not satisfy the primary purchaser's needs (C. M. Rose, Stevels, & Ishii, 2000). According to the World Resources Institute (2010), the duration of the end-of-life stage is from the time when the consumer discards the product to the time it is allocated to another product's life cycle or returns to nature. They describe the following attributable processes as being associated with end-of-life:

- collection and transport of end-of-life products and packages,
- dismantling of components from end-of-life products,
- shredding and sorting,
- incineration and sorting of bottom ash,
- land filling and landfill maintenance, and
- transformation into recycled material, such as re-melting.

The International Organization for Standardization's (2006) ISO 14044 standard describes end-of-life in terms of reuse and recycling (includes material recovery and energy recovery). It separates them into two groups:

- Closed Loop- the reuse of the material does not require the material to leave the product life cycle or recycling does not change the inherent properties of material.

In this case, the material is replacing the use of virgin or primary material in the original life cycle and

- Open Loop- the reuse or recycling of the material requires the material to leave the product life cycle and it changes the inherent properties of the material. In this case, the material does not always replace the use of virgin or primary material in the original life cycle.

The concept of design for end-of-life has been around for many years. It is not only seen as beneficial to the environment and reduction of resource consumption, but as a way to reduce the costs from extracting and manufacturing new materials. Many approaches have been taken to consider the end-of-life of products at the design stage. One of the most recognized methods to evaluate product disassembly is design for assembly (DfA), which was created by Boothroyd and Dewhurst in the late 1970s. Other methods include design for disassembly, design for recyclability, and design for remanufacturing. Design for disassembly is used to improve any end-of-life that requires manual material separation for material recovery, such as remanufacturing and recycling with disassembly. There are two approaches to design for disassembly: following basic guidelines and checklists or developing a disassembly tree. Some basic disassembly guidelines are described below (Table 1.1).

Table 1.1: Disassembly Guidelines (Bras, 1998; T Dowie & Simon, 1994; Fiksel, 1995; GE, 1995; ICER, 1993; Otto & Wood, 2001; VDI, 1991).

Guideline	Reason
Minimize the number of fasteners.	Usually results in a lower disassembly time from faster removal.
Minimize the number of fastener removal tools needed.	Tool changing costs time.
Fasteners should be easy to remove.	Save time in disassembly.
Fastening points should be easy to access.	Awkward movements slow down manual disassembly.
Snap fits should be obviously located and able to be torn apart using standard tools.	Special tools may not be identified or available.
Try to use fasteners of compatible material with the parts connected.	Enables disassembly operations to be avoided.
If two parts cannot be compatible, make them easy to separate.	They must be separate to recycle.
Eliminate adhesives unless compatible with parts joined.	Many adhesives cause complete contamination of parts for materials recycling.
Minimize the number and length of interconnecting wires or cables used.	Flexible elements slow to remove; copper contaminates steel, etc.
Connections can be designed to break as an alternative to removing fasteners.	Fracture is a fast disassembly operation.

Design for recyclability will improve the collection and recycling (with or without disassembly) of products. Bras, et al's (1998) approach to design for recyclability provides a rating for recyclability and a rating for seperability. If the product scores lower than three for both ratings, then it is recyclable. The rating for a full assembly is represented as follows (Equation 1.2):

$$r_{assembly} = \sum_{components} r_i m_i \qquad (1.2)$$

with r_i as the rating for component, *i* and m_i as the mass of component *i*. The rating matrices and an example are given in Product Design by Otto and Wood (Bras, 1998).

Design for remanufacturing prepares the product for remanufacturing, which involves disassembly, sorting, cleaning, and inspection. Remanufactured components are usually tested and qualified "like new" components and used in new products. To improve the product for cleaning, labels and glue, printing on components, and closed angles should be avoided (Table 1.2). For

inspection, the assembly should have a base that allows parts to be removed easily and parts should have features that will show their quality at the time of inspection (Otto & Wood, 2001).

Table 1.2: Cleaning Guidelines (Andreu, 1995).

Guideline	Reason
Avoid using labels with glue. Try pop-outs, mold writing.	Preferable to disassemble than to contaminate.
Avoid printing writing on the components.	Printing material is incompatible.
Avoid having closed angles in the components.	Add difficulty to cleaning.

1.2.3.4 Cradle-to-Cradle Design

Life Cycle Assessment and Design for the Environment are effective methods for the mitigation of environmental impact, but they tend to operate on the notion of cradle-to-grave design. Cradle-to-grave design focuses on the product creation, product distribution, and product use. A truly sustainable system does not have a beginning, middle, and an end. Is has an endless cycle of inputs from one subsystem to another. The concept of waste is eliminated, because it does not exist. Every subsystem or sub process's output is an input to another subsystem or sub process. McDonough (2002) calls this concept cradle-to-cradle design, but it is not a new theory. Nature has been closing its loops for billions of years in prairies, coral reefs, and forests. For example, when a leaf falls to the ground, it is recycled in the bodies of microbes, turned into soil and water, and absorbed by the tree, which then makes a new leaf. Designers need to understand how to make products that are self-renewing and/or that create inputs for other subsystems (Benyus, 1997; McDonough, 2002). "Servicizing" is another concept often cited as a way to switch from a cradle-to-grave design approach to a cradle-to-cradle design approach. It describes meeting the customer needs without selling a product, but a service or solution. With the service model, it is cost effective for the manufacturer to design products that have a long life and to collect them when they are no longer needed (Hawken, 1999).

1.3 Cellular Phones

In this section, cellular phones are described in relationship to design characteristics, current end-of-life trends, and environmental legislation. A mobile phone or cellular phone's main function is to allow wireless communication using radio waves. They are typically in service for 1-2 years before they are disposed. If their life is extended with reuse or refurbishment, they last an additional 1-3 years (IEc, 2007). Mobile phones have a mean weight of 0.4 pounds (Chancerel & Rotter, 2009; IEc, 2007). The major components that typically compose a cellular phone are an

antenna, housing, battery, display, microphone, speaker, keyboard, and a motherboard or printed circuit board (Fishbein, 2002; Lambert & Gupta, 2005; Ram et al., 1999; Xiaoying & Schoenung, 2006). The materials that are found in these components typically include, but are not limited to, metals, such as copper, tin, nickel, zinc, iron, gold, silver, aluminum, antimony, cadmium, chromium, and lead; nonmetals, such as silica; and plastics such as PVC, organic BFRS (PBDEs and PBBs), and rubber (Bhuie, Ogunseitan, Saphores, & Shapiro, 2004; Chancerel & Rotter, 2009; Hageluken, 2006; IEc, 2007). The materials in cellular phones that RoHS and RCRA regulate are cadmium, chromium, lead, mercury, and organic BFRs. Antimony is regulated by RCRA (Santillo, Walters, Brigden, & Labunska, 2007). It is estimated by the U.S. EPA that 79% of mobile phones were sent to landfill, 19% were sent to the recycler, and 2% were incinerated in 2010 (IEc, 2007).

Chapter 2

PROBLEM STATEMENT

Electronic waste is very complex and contains a wide variety of materials, components, and configurations. Because of the intricacy of the products themselves, their recovery processes can also become very complicated depending on the desired output of end-of-life recovery. A product design can be created to decrease the environmental impact of consumer electronics and increase the effectiveness of disposal processes. Analysis and improvement of the entire design is very difficult and time consuming, so the producer typically uses their knowledge and experience to simplify the criteria selection. This arbitrary selection of criteria does not always capture the intended goal of the producer or the lowest environmental impact.

The purpose of this thesis is to define the criteria or design characteristics of cellular phones that have the most significant contribution to the end-of-life disposition environmental impact and lend themselves to sustainable design practices. The potential design characteristics and end-of-life disposition processes should be easily quantifiable to be useful to design development and comparison.

Sustainable design practices, such as design for the environment (DfE) describe the potential end-of-life disposition processes in terms of a set of quantitative and qualitative design criteria. These techniques are integral to the methods described in this study. End-of-life disposition processes are described by component type and life cycle impact analysis methods. Finally, linear regression analysis is used to determine if there is a relationship between design characteristics and the environmental impact of end-of-life disposition, which design characteristics are significant to end-of-life disposition environmental impact, and which significant design characteristics contribute the most to this environmental impact.

The main hypotheses under investigation are:

1. There exists a set of design characteristics that may be used to relate the product design and end-of-life environmental impact,
2. A method can be used to determine which of the design characteristics are significant with respect to end-of-life environmental impact, and that

3. A method can be used to determine the relative importance of the significant design characteristics with respect to end-of-life environmental impact.

The main objectives, which will be used to investigate the hypotheses, are:

1. Determine the design characteristics that may have a contribution to the environmental impacts arising from end-of-life disposition processes, and to
2. Use linear regression analysis to determine the most significant design characteristics lending themselves to sustainable design practices.

Defining the significant design characteristics by end-of-life disposal scenario and product type can provide a scientific approach to choosing the criteria for the reduction of the environmental impact of consumer electronic products and has the potential to expand into other waste electrical and electronic equipment (WEEE).

Chapter 3

LITERATURE REVIEW

The following chapter addresses the current state of research of design for end-of-life of small consumer electronics. The relationship between consumer electronic design characteristics and their environmental impact during end-of-life disposition processes is the focus of this study. This will be accomplished by reviewing studies that:

(1) Relate design characteristics to end-of-life retirement or environmental impacts;

Design characteristics refer to attributes that can be used to describe or classify the product model. These attributes are (1) physical, such as number of parts, number of fasteners, etc. or they are (2) technical, such as obsolescence, failure, level of integration, etc. End-of-life retirement refers to the action(s) taken when the consumer decides to end their use of a product, such as storage, reselling, reusing, recycling, landfill disposal, or incineration. Environmental impacts refer to the potential damage to human health, ecosystems, or resource availability.

(2) Describe the end-of-life design characteristics for consumer electronics and describe the metrics to measure them;

Metrics refer to the equations or otherwise quantitative representation of the design characteristics, which enable the design characteristics to be measured and analyzed.

(3) Describe the available end-of-life disposition processes of consumer electronics; and

End-of-life disposition processes refer to (1) end-of-life disposition processes described through interviews with electronics recyclers and (2) models of end-of-life disposition processes created by researchers in the literature to represent existing end-of-life systems.

(4) Describe methods used to measure the environmental impact of end-of-life disposition processes.

Methods refer to (1) techniques to model the benefits and impacts of end-of-life disposition processes and (2) life cycle impact analysis methods to quantify those benefits and impacts.

3.1 Relating design characteristics to end-of-life retirement

The following is a review of the current research linking design characteristics to end-of-life. These studies propose interactions between design characteristics of consumer electronics and end-of-life policies, scenarios, or environmental impacts.

Chancerel and Rotter (2009) used statistical methods to identify the recycling-oriented attributes of 23 consumer electronic products that had a significant contribution to the

implementation of a recycling infrastructure. The recycling-oriented attributes will be reviewed in detail in Section 3.2. The recycling infrastructure had to be compliant with the weight-based recycling targets set forth by the Waste Electrical and Electronic Equipment (WEEE) protocol. They measured the mechanical properties, material composition, plastic composition, and chemical composition of products with mean, median, quartiles, and standard deviation. They also measured the calculated recovery rate (CRR) to represent the impact of component properties on material and energy recovery. Chancerel and Rotter (2009) found that plastic composition and improper sorting of products with high grade PCBs-for recycling-had a large influence on the CRR and the ability to meet WEEE weight based recycling targets. They also stressed that more research needs to be focused into the classification of electronics to improve end-of-life recycling processes.

Rose (2001) used a classification and regression tree (CART) to identify the design characteristics that influenced the end-of-life scenarios of a general group of products (Figure 3.11). Rose's (2001) design characteristics will be reviewed in detail in Section 3.2. The classification and regression tree (CART) used cluster analysis to group the design characteristics into categories. Rose (2001) chose design characteristics arbitrarily based on recycling industry observations, product development knowledge, and governmental initiatives. The following characteristics were useful in determining appropriate end-of-life scenarios such as reuse, recycling and landfill disposal: wear-out life, technology cycle, level of integration, number of parts, design cycle, and reason for redesign.

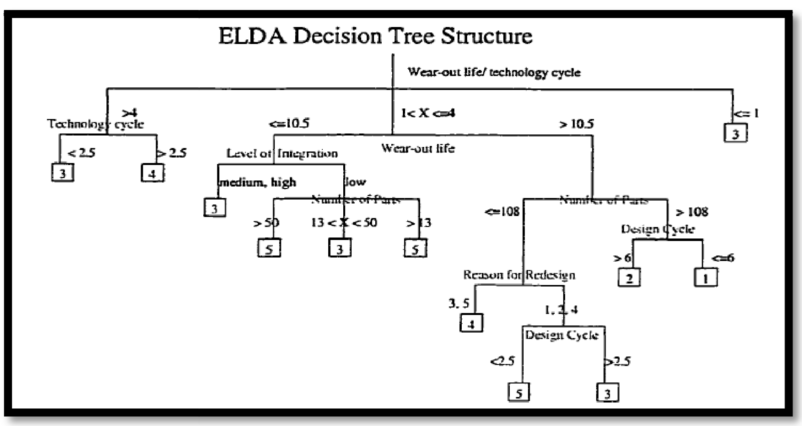


Figure 3.1: CART of the End-of-life Design Advisor. Adapted from Rose, Catherine Michelle. 2001. Design for environment: A method for formulating product end-of-life strategies, Stanford University, United States -- California.

Van Nes and Cramer (2006) used empirical research to categorize the relative importance of product characteristics on end-of-life scenarios. Their focus was on the end user's decision to

replace products when they are no longer needed. Their empirical research included a literature search, a qualitative investigation, and a quantitative survey. They found wear and tear to be the most important factor motivating consumers to replace their products because it was mentioned frequently as playing a large role in sustainability decision making.

Atlee and Kirchain (2006) defined guidelines for creating sustainability metrics and evaluating recycler performance. Mass, value, energy, and environmental impact indices were compared and trade-offs were identified. Each index explained a portion of the recycling system, with a positive or negative environmental impact, such as resource conservation. It was discovered that recycling system sustainability is dependent on the product's recycling value, recycling energy, and recycling environmental impact, in addition to mass. Mass and value are reviewed as design characteristics in Sections 3.2.1 and 3.2.7. Recycling energy and environmental impact calculations are reviewed in Section 4.1.6.

3.1.1 Discussion

Design characterization is typically conducted in two ways (1) using a quantitative analysis such as standard statistical analysis or regression or (2) using an empirical analysis such as qualitative benchmarking or surveying. Both approaches have their benefits, but many researchers prefer design tools that utilize a quantitative approach. In the next section, the design characteristics and their metrics that have potential to be used in the methodology's design characterization will be reviewed.

3.2 End-of-life design characteristics and their metrics

The following section offers a review of design characteristics that are used to describe consumer electronics for end-of-life analysis. This section affinitizes potential design characteristics into the following categories: weight, geometry, fasteners, contaminated parts, number of wires, material concentration, plastic concentration, hazardous materials, value, ability to disassemble, obsolescence, modularity, failure, testing, design cycle, level of integration, and redesign. Each subsection describes how potential design characteristics have been defined and how they have been measured or represented quantitatively. The design characteristics and metrics outlined in this section will be evaluated for their ability to be used in the methodology in Sections 4.1.2 and 4.1.3.

3.2.1 Weight

The weight of the product determines the amount of material that must be handled during end-of-life disposal. It is defined with English or metric units in pounds or kilograms, respectively. Xanthopoulos and Iakovou (2009) cited weight as significant criteria for evaluating the appropriateness of a component for end-of-life management. Iakovou, et al (2009) described weight as a critical factor because the Waste Electrical and Electronic Equipment (WEEE) directive sets weight limits for end-of-life management. Huisman and Stevels (2006) investigated the WEEE directive's weight-based recycling targets using their QWERTY method and found that the associated environmental impact of e-waste does not have a direct relationship with the weight of the materials, especially for precious metals (Figure 3.22). For example, products like cellular phones may have a low amount of precious metals, but those precious metals may contain the highest burden at end-of-life. On the other hand, Chancerel and Rotter (2009) evaluated the characteristics of WEEE and found that the fractional weight of material in a product was relevant to manual disassembly. They also noted that within an equipment type, changing the design to decrease the differences in absolute weight does not improve the manual disassembly of those components with a defined electric or electronic function, such as a printed circuit board.

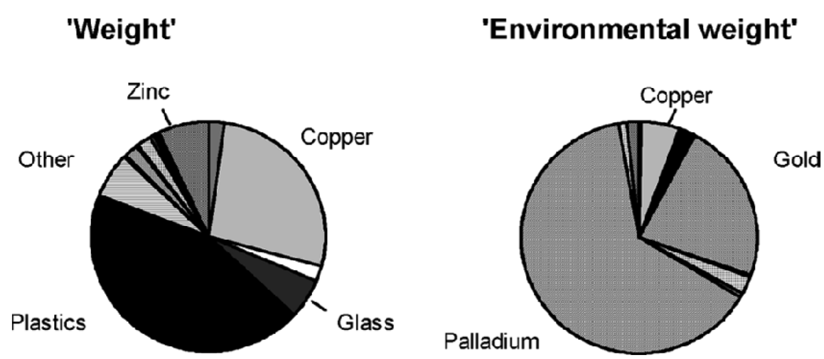


Figure 3.2: Weight versus environmental weight for a cellular phone. Adapted from Huisman, J., and L. N. Stevels. 2006. Eco-efficiency of take-back and recycling, a comprehensive approach. *Electronics Packaging Manufacturing, IEEE Transactions on* 29 (2):83-90.

3.2.2 Geometry

Product dimensions are described as the measured length, width and height of a product in inches or millimeters. Herrman, et al (2006) cite product dimension as a recycling-relevant product property.

3.2.3 Fasteners, Contaminated Parts, and Wires

The fasteners, contaminated parts, and wires characteristics describe the different methods that are used to connect components in a product. The fasteners characteristic describes screws, snap-fits, levers, etc. It is defined as the total number of these fasteners used or counted in a product. Fishbein (2002) describes number of fasteners as one of the key product design features that could enable or thwart closed loop recycling. Ying, et al (2005) linked the types of connections with electronics recycling in their environmental benchmarking method.

The contaminated parts characteristic is used to describe parts that contain adhesives, labels, or paint that increase the difficulty of reusing or recycling those parts. It can be described as the number of parts that contain adhesives, labels, or paint. In a study conducted by the American Plastics Council (2000) two-thirds of plastic parts collected through Hennepin County's Consumer Electronics Collection program were rejected for: (1) metalized coatings, paint, or glass filler, (2) lamination or labels that were difficult to remove, (3) composite plastics, (4) high density-variable structural foam, or (5) comingled plastics.

The wires characteristic describes the cables or wires that are used to transfer information between printed circuit boards. It can be defined as number of wires. Verein Deutscher Ingenieure (1991), The British Industry Council for Electronic Equipment Recycling (1993), Dowie (1994), Fiksel (1995), Bras (1998), and General Electric Plastics (1995) cited fastening guidelines and labeling guidelines to reduce environmental impact (Table 1.1 and Table 3.1)

Table 3.1: Design for the Environment labeling guidelines (Bras, 1998; T Dowie & Simon, 1994; Fiksel, 1995; GE, 1995; ICER, 1993; Otto & Wood, 2001; VDI, 1991).

Guideline	Reason
Ensure compatibility of ink where printing is required on parts.	Maintain maximum value of recovered material.
Eliminate incompatible paints on parts- use label imprints or even inserts.	Many label-removal operations for paints cause part deterioration.
Use unplated metals that are more recyclable than plated.	Some plating can eliminate recyclability.
Use electronic part documentation.	These parts can be reused.

3.2.4 Material Concentration

The material concentration describes the diversity of materials contained in a product for end-of-life disposal. It is defined as the mass fraction of materials, mass percentage of materials, or number of materials. Boks and Ab (2001) evaluated an environmental score based on the material

composition of a product and the recovery characteristics of recycling processes in their product material recycling cost model (PMRCM). They describe the material composition by the mass percentage of each material, such as plastic. Dahmus and Gutowski (2007) used information theory to count the mass fraction of materials or material mixing, H, of a product in bits (Equation 3.1). The more diverse the materials are in a product, the more difficult it is to separate and salvage materials at end-of-life.

$$H = c_i \log c_i \tag{3.1}$$

The concentration, c_i is defined with m_i as the mass of the material, i and m_{tot} as the sum of the masses of each material (Equation 3.2).

$$c_i = \frac{m_i}{m_{tot}} \tag{3.2}$$

Products with an H less than 0.5 are more likely to be recycled. Chancerel and Rotter (2009) used a relative weight, $X_{ij,k}$ of a material, j in an equipment type, k to describe a mass fraction of materials in a device (Equation 3.3). In the relative weight, $X_{ij,k}$, X is the mass fraction and m is the mass with indices i for equipment, j for material, and k for equipment type.

$$X_{ij,k} = \frac{m_{ij,k}}{mi,k} \tag{3.3}$$

They also used an average relative material composition per equipment type, $\overline{X_{J,k}}$, which gives a higher weighting to heavier electronics (Equation 3.4). The weighted arithmetic mean, $\overline{X_{J,k}}$, is the relative weight of material, j in equipment, k and m is the mass with indices i for equipment, j for material, and k for equipment type.

$$\overline{X_{J,k}} = \frac{\sum_{i=1}^{n} m_{ij,k}}{\sum_{i=1}^{n} m_{i,k}} \tag{3.4}$$

Chancerel and Rotter (2009) discovered that in small appliances such as coffee makers, the relative weight of plastics overshadows the other material types, making them less suitable for material recovery.

3.2.5 Plastics Concentration

The concentration of plastics in an electronic product influences their end-of-life disposition. The American Plastics Council (2000) found that the electronics industry purchased at least 16 different kinds of plastics, not including wires, in 1995. Polystyrene (PS) was the highest,

followed by acrylonitrile butadiene styrene (ABS), polypropylene (PP), polyurethane (PU), and phenol formaldehyde (PF). The Association of Plastic Manufacturers in Europe, APME (2001) mentions 15 different plastics types in waste electronic and electronic equipment (WEEE) in Western Europe, including PS, high-impact polystyrene (HIPS), acrylester styrene acrylonitrile (ASA), styrene acrylonitrile (SAN), and ABS.

Electronics recyclers such as Sunnking (K. Romeo, personal interview, September 27, 2009) cite comingled plastics as a major issue. Murphy, et al (2001) found that the cost of sorting plastics from consumer electronics is driven by the supply and demand of plastic. Plastics sorting also influences the purity of the recycled material in the output stream. Williams, et al (2006) and Blyler, et al (2003) defined a plastics recovery rate (PRR) to determine the benefit of recovering plastics from consumer electronics (Equation 3.5). The PRR was derived from Coulter, et al's (1996) value removal rate (VRR) and material removal rate (MRR). They found that products with a higher PRR for a particular plastic are more effective at meeting the recycled material demands for that plastic.

$$PRR_{plastic\ type} = \frac{total\ weight\ of\ each\ plastic\ type\ (g)}{total\ disassembly\ time\ per\ product\ (\mathrm{min})} \tag{3.5}$$

Few references in the literature have a metric for the plastics concentration in a product. Since the plastics concentration is a more detailed view of the materials concentration, it can be defined similarly to the materials concentration design characteristic. The materials concentration design characteristic is defined as the mass percentage of plastics, mass fraction of plastics, or number of plastics. Rios, et al (2003) found that recycling processes with disassembly were not impacted environmentally or economically by the diversity of plastics in consumer electronic products.

3.2.6 Hazardous Materials

The hazardous materials characteristic describes a product's potential to be toxic or harmful to humans, animals, or plants in end-of-life (EOL) disposition analysis. In the literature, this characteristic is described as the number of hazardous materials in a component, the number of components containing hazardous materials, the number of hazardous materials in a product, or the percentage of hazardous materials in a component or a product. Ying, et al (2005) found the relationship between electronics recycling and hazardous materials, such as halogenated flame-retardants in plastics, to be important. They included hazardous material criteria in their environmental benchmarking method. Chancerel and Rotter (2009) found almost 100% of the

products they investigated contained components that were in Annex II of the Waste Electrical and Electronic Equipment (WEEE) directive. Annex II of WEEE provides a populated list of components that contain hazardous materials. In Table 3.2, research studies that have defined and measured hazardous materials in consumer electronic products are summarized.

Table 3.2: Research studies that defined and measured hazardous materials in consumer electronics.

Research Study	Definition of Hazardous Material	Metric
Iakovou, et al (2009)	Number of components that contain hazardous materials.	Measured the environmental burden with Eco-Indicator 99 and the components that are ranked highest, are assumed to be removed for special processing.
Atlee and Kirchain (2006), Doctori Blass, et al (2008), Most (2003), Fishbein (2002), the American Plastics Council (2000), and Hageluken (2006)	Describe hazardous materials in a product by the components that contain them.	Listed the Printed Circuit Boards (PCBs), Liquid Crystal Displays (LCDs), Mercury Relays, and Nickel-Cadmium (Ni-Cd) batteries, etc. contained in the product.
Chancerel and Rotter (2009)	Describe hazardous materials in a product by the components that contain them	Used Annex II of the WEEE-Directive to classify which components contained hazardous materials
Bhuie, et al (2004)	Describe the hazardous materials in a product by their percentage by weight in a product.	Measured the percentage by weight of hazardous materials in a product.

Hazardous materials are regulated and require special disposal at end-of-life, which can increase costs. They can also contaminate the recycling stream if they are not sorted properly.

3.2.7 Value

Value determines the profitability of discarding or recovering components in end-of-life disposition analysis. It is defined as a commodity value in dollars per pound of material or as a resale value in dollars per component. Ying, et al (2005) linked value with electronics recycling in their environmental benchmarking method. Xanthopoulos and Iakovou (2009) cited the residual value as being a significant criterion for evaluating the appropriateness of a component for end-of-life recovery. Dahmus and Gutowski (2007) used a commodity value calculation to separate those products that had a large value at end-of-life and those that did not. They used this to determine a cut-off point or boundary for recycling. This illustrated that products that contained materials in

high demand at end-of-life disposition had a higher recycling rate than those that were in low demand. Atlee and Kirchain (2006) found that materials such as plastic that were heavy and recyclable were not recycled, because they had a low residual value at end-of-life disposition. Research studies that have defined and measured value in consumer electronic products are summarized (Table 3.3).

Table 3.3: Research studies that defined and measured value in consumer electronics.

Research Study	Definition of Value	Metric
Iakovou, et al (2009)	Residual value.	The market value of the component at the time of disposal that justifies investment in reuse or recycling capital from the original equipment manufacturer (OEM).
Atlee and Kirchain (2006)	The market value of secondary and primary material.	Value of the material per the weight of material ($/kg)
Bhuie, et al (2004)	The profit made from recycling.	The revenues from selling recycled material minus the recycling cost. Recycling cost is a function of labor, transportation, and residual disposal costs.
Coulter, et al (1996)	Value removal rate (VRR) (Equation 3.6) and material removal rate (MRR) (Equation 3.7). $V.R.R. = \frac{Material\ Value\ (\$)}{Time\ (min)} > Labor\ Cost\ (\$/min)$ (3.6) $M.R.R. = \frac{Material\ Mass\ (lb)}{Time\ (min)} > 5\ lbs/min$ (3.7)	The VRR describes the time it takes to recover the commodity value of a recycled material whereas the MRR describes the time it takes to recover a material assuming the value of the material doesn't change drastically.

3.2.8 Ability to disassemble

The ability to disassemble design characteristic describes the process of deconstructing a product into components in terms of recoverability, difficulty, time, sequence, and precedence. Sunnking (K. Romeo, personal interview, September 27, 2009) and Maven Technology (T. R. Wheaton, personal interview, April 15, 2010) rely heavily on the dismantling of products for their reuse and refurbishing business model. Sunnking (K. Romeo, personal interview, September 27, 2009) reuses approximately 90% of the electronic products that they collect and shred 10%, which are mostly hard drives. Xanthopoulos and Iakovou (2009) cited the recoverability of each component as being significant criteria for evaluating the appropriateness of a component for end-

of-life recovery. Ishii (1996) proposed that planning for design for product recovery (DfPR) needs to be improved.

Kroll (1995) described disassembly difficulty in terms of the number of disassembled parts, the number of disassembly tasks, the number of non-value added tasks, the number of tool and hand manipulations, the disassembly of parts not theoretically required, or the number of tools used. Iakovou, et al (2009) defined the ease of disassembly with disassembly time as a function of destructive disassembly, tools, fixtures, access to components, force, etc. Ying, et al (2005) linked disassembly time of components with electronics recycling in their environmental benchmarking method. Kroll and Carver (1999) used standard work measurement to estimate the time it took to do several disassembly tasks.

Kroll's (1995) disassembly time formula described the disassembly for the entire product (Equation 3.8). *Disassembly time* is a function of the following variables: *total*, *# of task repetitions*, and *# of tool and hand manipulations*. *Total* is the sum of the disassembly difficulty ratings (*accessibility, positioning, force, base time, and special*) from each chart multiplied by the number of task repetitions. *Accessibility* is the ease at which a part can be reached. *Positioning* is the degree of precision needed to remove a fastener or part. *Force* is an estimation of force needed to remove a component. *Base time* is the time needed to remove a part easily. *Special* is a penalty for any task that the method does not accommodate.

$$Disassembly\ Time\ (sec) =$$
$$\left(\sum Total - 5 \times \sum \#\ of\ task\ reps\right) \times 1.04 + (\#\ of\ tool\ and\ hand\ manipulations) \times 0.9 \quad (3.8)$$

The number of task repetitions, *# of task reps* is defined as the number of times the same task is performed in a row. Kroll's (1995) formula required the use of more than fifteen charts, which is complicated. The disassembly time obtained was too broad because it yielded only the total time to disassemble a product instead of providing the disassembly time per each component in the product. Without the disassembly time per component, components cannot be differentiated for recycling or disassembly.

Dowie (1994) created charts to describe theoretical disassembly times for common fasteners and operations. They describe disassembly time as the time per component removed using three charts. Williams, et al (2006) expanded on Kroll (1995) and Dowie (1994)'s methods to include "presorting, tooling selection, decision analysis, and plastics identification". These

additional metrics are generic, indicating that they do not vary with the type of product being analyzed.

Ishii and Lee (1996) developed a reverse fishbone diagram to document the disassembly of products and evaluate parameters such as number of recycling sort bins. Number of sort bins is a function of the repetitive components in a product family, the variety of materials in a product, and the number of sequence dependent disassembly steps on the reverse fishbone diagram. Hammond (1996) adapted Boothroyd and Dewhurst's design for assembly to describe the disassembly efficiency with a disassembly index (Equation 3.9). The disassembly index, μ *disassembly* is a function of the variables: *# Ideal* and *time,* where *# Ideal* is the theoretical minimum number of parts and *time* is the measured disassembly time in seconds. The metric, theoretical number of parts relies on the expertise of the analyst to determine if parts can be removed to improve disassembly. This is determined by understanding if two assembly parts need to be the same material, have the same relative motion, or need to be disassembled so they do not obstruct the disassembly of other parts. This judgment makes the results of the disassembly index ambiguous and hard to duplicate.

$$\mu\, disassembly = \frac{(\#\, Ideal)(1.5\text{ sec})}{time} \tag{3.9}$$

3.2.9 Obsolescence

In end-of-life disposition analysis, obsolescence determines the how rapidly a technology is changing, which could make upgrading and reuse more difficult and increase electronic waste. It can be defined as the technology cycle, the technology cycle time (TCT), the technology adoption cycle (TAC), or the economic life. Rose (2001) defined the technology cycle as the time before the main functions' mechanisms become obsolete in a product or the time before it becomes less desirable because a new technology is released. To measure technology cycle, Rose (2001) estimated a range for each technology from aggregate data. The data analyzed varied according to designers' interpretations. For example, mobile devices varied from 1 to 15 years with a mean of 4.3 years and a standard deviation of 5.4 years.

Cheng, et al (2010) and Kayal and Waters (1999) used the technology cycle time (TCT) to describe the progress of the semiconductor industry's technology. Chen, et al (2007) measured TCT by finding the technology's patent and calculating the median age of the citations of the patent and comparing it to the current date. The shorter the TCT, the more rapidly the technology is changing. Some products list the patent numbers on their products or in their user guides, but the

majority of products do not. For example, the Sprint (2005) lists patent numbers under the Patent and Trademark Information section of its manual for the Nextel i560. Finding patent numbers becomes more difficult when looking for patent information for subcomponents like memory.

Meade and Rabelo (2004) quantified the technology adoption cycle to calculate the technology marketing stage where the product currently resides. There are six marketing stages: (1) innovation, (2) chasm, (3) tornado, (4) main street, (5) decline, and (6) obsolescence (Figure 3.3). In the innovation and chasm phases, the product has not been accepted by the market. The tornado phase is when the product has the steepest acceptance. The main street phase is when the majority of the consumer population has adopted the product. Finally, the decline phase is when the technology begins to phase-out and other technologies have begun to take its place. Meade and Rabelo (2004) determined the technology marketing phase that contains the product technology by classifying products based on inflection rate and center point. The inflection rate or slope determines when the life cycle phase changes. The center point determines when the product technology crossed the chasm phase. To calculate the inflection rate and center point, marketing information is used. The publically available marketing information differentiates product classes, such as cellular phones versus computers, but it does not differentiate product models, such as cellular phone A versus cellular phone B. To understand the significance of obsolescence on end-of-life environmental impact, the method needs to differentiate product models.

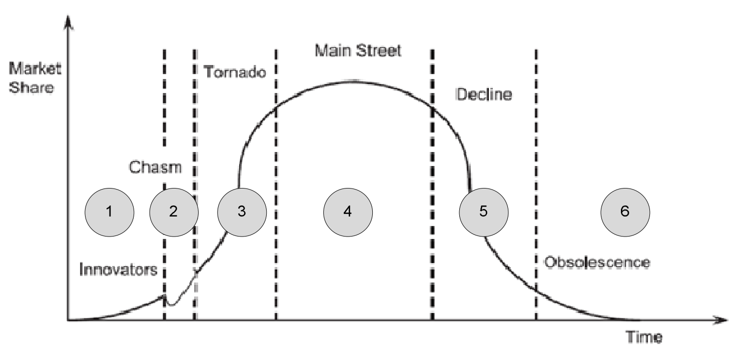


Figure 3.3: Technology Adoption Life Cycle Phases. Adapted from Meade, Phillip T., and Luis Rabelo. 2004. The technology adoption life cycle attractor: Understanding the dynamics of high-tech markets. *Technological Forecasting and Social Change* 71 (7):667-684.

Fishbein (2002) defined economic life as the age at which the owner chooses to replace a product. This is typically one and a half years for cellular phones. The economic life is difficult to measure if the length of time the device was in the last user's possession is unknown. Tucker

(2010) states that some recyclers can measure the time in which the product was last turned on using the BIOS login data from the device. BIOS data may not be accurate if the user last turned on the device to determine if it was functional before taking the device to the recycler in an attempt to determine the functionality of the device.

3.2.10 Design Cycle

The design cycle determines the frequency of design changes to a product for end-of-life disposition analysis. It is usually defined by time in months or years. Rose (2001) defined the design cycle as the time between successive generations of the product. Some product release dates are listed on specification sheets for products sold online, but it is not always readily available. For example, (juggle.com) reviews products and lists the HP DeskJet 5650's product release date as July 2003. For most products, the OEM would have to be willing to supply the product release dates.

3.2.11 Modularity

Modularity describes the internal component structure of a product for end-of-life disposition analysis. It is described by the number of parts or modules, number of components, number of assemblies, number of duplicates, or number of ideal parts. Iakovou, et al (2009) found the quantity of a particular component in a product to be important at end-of-life, because of economies of scale. Rose (2001) defined modularity in her end-of-life design advisor (ELDA) as the number of parts from the product's bill of materials. Ishii (1998) defined modularity in terms of a functional design attribute (FD) or functional complexity (FC). FD is the number of functions in a module and FC is the flexibility of the functions, such as language or technology life cycle required in a module. Xanthopoulos and Iakovou (2009) cited the multiplicity of each component as being significant criteria for evaluating a component for end-of-life recovery. Hammond (1996) expanded upon Boothroyd and Dewhurst's ideal or theoretical minimum number of parts to describe modularity in remanufacturability. Ideal parts are those that satisfy large ranges of motion, contain only the materials required to achieve design requirements, satisfy assembly or disassembly, and low value parts that protect other parts from wear. Increasing the number of modules increases the disassembly time of a product, which in turn makes reuse a less attractive option for end-of-life disposal.

3.2.12 Level of Integration

Level of Integration describes the complexity of a design. It is defined as functionality per module or functional complexity. Rose (2001) defined a functionally complex product as a product

with highly dependent modules that support a variety of functions. On the other hand, a simple product has modules that independently support different functions. Ishii (1998) found that products with a high level of integration and low level of modularity were more difficult to sort into modules and materials at end-of-life. This could increase the environmental impact of the product.

3.2.13 Failure and Testing

The failure and testing characteristics describe the inability of the product to perform its desired functions, thus becoming eligible for end-of-life disposal. Failure is defined as wear-out life or number of replaced parts. Rose (2001) defined wear-out life as the length of time until the product does not meet its original function. Testing is defined as number of inspections, testing time, or cleaning. Sunnking (K. Romeo, personal interview, September 27, 2009) and Maven Technology (T. R. Wheaton, personal interview, April 15, 2010) cite testing as an important part of their recycling process. Testing leads to the reuse and resale of products, which generates the most revenue for recyclers' businesses. Hammond (1996) measured failure and testing in relation to refurbishing or remanufacturing with inspection and testing indices (Equation 3.10 and 3.11). He measured testing with the cleaning index as well (Equation 3.12).

The inspection index, $\mu_{Inspections}$ is a function of *# Ideal inspections*, *# Parts*, and *# Replacements*. *# Ideal inspections* represents the "theoretical minimum number of parts that do not need to be replaced during refurbishing." *# Parts* is the total number of parts in the product. *# Replacements* is the parts that need to be replaced during refurbishment

$$\mu_{Inspections} = \frac{\#\,Ideal\ Inspections}{\#\,Parts - \#Replacements} \tag{3.10}$$

The testing index, $\mu_{Testing}$ is a function of *# Tests*, and $Time_T$. *# Tests* represents the action of "checking the products performance against a criteria." $Time_T$ is the total time it takes to perform all testing for the product in seconds.

$$\mu_{Testing} = \frac{(\#\,Tests)(10\ sec)}{Time_T} \tag{3.11}$$

The cleaning index, $\mu_{Cleaning}$ is a function of *# Ideal* and *Cleaning Score*. *# Ideal* is the minimum number of parts that need to be cleaned and *Cleaning Score* is the effort required for cleaning the parts.

$$\mu_{Cleaning} = \frac{(\# \, Ideal)(1)}{Cleaning \ Score} \quad (3.12)$$

3.2.14 Redesign

Redesign describes the purpose for the design of the product. This is defined as reason for redesign. Rose (2001) listed original design, evolutionary design, or feature change as reasons for redesign. This objective of this research is to improve design for end-of-life, so the reason for redesign would be to minimize end-of-life environmental impact.

3.2.15 Discussion

Potential design characteristics and their metrics were affinitized into 14 categories. They will evaluated for their ability to be used in the methodology in Sections 4.1.2 and 4.1.3. Once the design characteristics and their metrics are selected, they will be used to describe the designs of cellular phones for the analysis. In the next section, end-of-life disposition processes of consumer electronics will be reviewed. In the methodology, end-of-life disposition processes will be structured in such a way that their environmental impact can be calculated using appropriate methods.

3.3 End-of-life disposition processes of consumer electronics

This section reviews the end-of-life disposition processes of consumer electronic products. End-of-life disposition processes refer to (1) the actual end-of-life disposal processes described through interviews with electronics recyclers and (2) models of end-of-life disposal processes created by researchers in the literature to represent the actual end-of-life systems. Rose, et al (2000) described the end-of-life of a product as the instance when the product does not satisfy the primary purchaser's needs. They defined end-of-life using the end-of-life hierarchy. The end-of-life hierarchy orders end-of-life systems in order of least to greatest environmental impact: reuse, service, remanufacture, recycle, recycle with disassembly, and disposal. Reuse and recycling are cited most frequently as the end-of-life systems for consumer electronic equipment. The Main-Recycling System (Figure 3.4), created from interviews and studies discussed in this section, includes all or some of the following processes: sorting, dismantling, size reduction, and separation into output fractions at a high level. Once in their respective output fractions, materials may undergo further processing, such as metallurgical processes. This section will review the current state of research on (1) reuse and recycling processes and (2) output fraction recovery processes that were used to create the Main Recycling System (Figure 3.4).

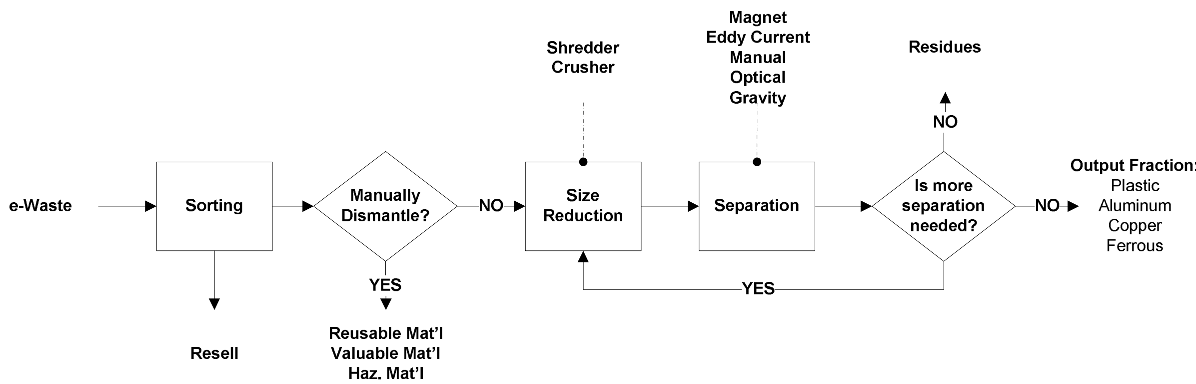


Figure 3.4: Main-Recycling System.

3.3.1 Reuse and recycling processes

Sunnking (K. Romeo, personal interview, September 27, 2009) and Maven Technology's (T. R. Wheaton, personal interview, April 15, 2010) recycling models follow that of the Main-Recycling System, except they have a third party manage their output fractions and residues. Kang and Schoenung (2005) suggested that reuse and recycling are the most feasible end-of-life systems for electronic products. They included collection and transportation in addition to the processes in the main-recycling system. Atlee and Kirchain (2006) include collection, refurbishment, and smelting in addition to the processes in the main-recycling system. Chancerel and Rotter (2009) describe end-of-life disposition processes similarly to the main-recycling system with pre-sorting, mechanical pre-processing, recovery, and disposal. Huisman (2003) defined end-of-life systems in terms of their recycling processes for (1) electronics with cathode ray tubes (CRTs), (2) electronics without CRTs, (3) cellular phones, and (4) metal dominated electronics.

(1) Electronics with CRTs are sorted into their housing, cathode ray tube, and other materials. Housings are sent to a mechanical shredder to recover the plastic material. The cathode ray tube is sent to a mechanical shredder, then to a cleaning process. A sieve is used to separate the glass from the unwanted or hazardous lead material. The other material is sent to a mechanical shredder. A magnet is used to sort out the ferrous metals. Then an eddy current is used to remove the aluminum material. The remaining material is resent through a shredder and then a magnet to remove more ferrous material. The second eddy current specifically targets the material made of copper. Finally, a sifter is used to capture the residue material.

(2) Electronics without CRTs are sent directly to a mechanical shredder, and then a magnet is used to separate out the ferrous metals material. Non-ferrous metals are sent through an eddy current to remove the aluminum. The remaining material is resent through a shredder and then a magnet to remove more ferrous material. The second eddy current specifically targets the material made of copper. Finally, a sifter is used to capture the residue material.

(3) Cellular phones are sent directly to a mechanical shredder, and then to a magnet to be sorted into ferrous metals and copper.

(4) Metal dominated electronics are sent directly to a mechanical shredder, and then a magnet is used to separate out the ferrous metals material. Finally, non-ferrous metals are sent through an eddy current to separate the aluminum and the copper.

Hageluken (2006) described recycling of metals from electronics using a mechanical process that is similar to the typical reuse and recycling system with manual disassembly of housings, cables, batteries, and PCBs, size reduction via shredding, and separation into output fractions via magnetic, eddy current, manual, optical, or gravitational separation techniques. Knight and Sodhi (2000) defined their bulk recycling separation process similarly to the typical reuse and recycling system, but they also include air and density separation processes.

3.3.2 Output fraction recovery processes

The final step in the Main Recycling System is recovering materials from the separation processes' output fractions. After separation and sorting, CSS (2007) and Hischier, et al (2005) send some materials or components, such as PCBs, to output fraction recovery processes for further refinement. Kang and Schoenung (2005) described the recovery processes for lead, copper, precious metals, and plastics. The lead, copper, and precious metals enter pretreatment, liberation, separation and upgrading, and purification processes. Pretreatment includes some combination of the mechanical recycling processes described in the previous section. Liberation includes a smelting process that displaces foreign material. For lead, a reverberating furnace is used. Separation and upgrading includes the separation of unwanted materials and the addition of pure material to improve chemical properties. This is typically done using a blast furnace. The purification process includes a refining process, which continues in the blast furnace or using another process, such as electrolytic refining. Hageluken (2006) described the metallurgical

recycling of metals as when the metals are separated with a smelting process, and then they are sorted using their chemical properties. Then, they mix with the metal in the collector (blast furnace), become slag, or escape the collector in a volatized or dust form. Kang and Schoenung (2005) treat thermoplastics in a plastics recovery process where the plastic is melted with an extruder and then formed into pellets with a pelletizer. Hischier and Gallen (2007) send other plastics to incineration for energy recovery. Hischier, et al (2005) send dust or other residues from size reduction and separation that cannot be recovered to the landfill.

3.3.3 Discussion

End-of-life disposition processes were reviewed for consumer electronics with the Main Recycling System. This included reuse, recycling, and output fraction recovery processes. In the next section, methods to calculate the environmental impact of these end-of-life disposition processes will be reviewed.

3.4 The environmental impact of end-of-life disposition processes

Methods to measure the environmental impact of end-of-life disposition processes are reviewed in this section. The methods refer to (1) life cycle impact analysis (LCIA) methods to quantify the benefits and impacts of end-of-life disposition and (2) techniques to model the benefits and impacts of end-of-life disposition processes. Videira, et al (2010) described tools and methods that have been developed to estimate the environmental impact of products and services, such as ecological footprint, material flow analysis, and life cycle assessment (LCA). LCA is one of the main tools used by designers for end-of-life analysis. Xanthopoulos and Iakovou (2009) cited the life cycle environmental burden as being significant criteria for evaluating the appropriateness of a component for end-of-life recovery. Iakovou, et al (2009) define environmental burden using the eco-indicator 99 LCA methodology from the Gabi 4 software: the higher the eco-indicator 99 score, the higher the environmental impact. The following section will discuss LCA methods that are used to estimate the environmental impact of end-of-life disposition processes.

3.4.1 Life cycle assessment methods for end-of-life disposition processes

Life Cycle Assessment is a methodology to calculate the environmental impact of a system from its creation to its end-of-life disposal. ISO 14044 (2006) structures the life cycle assessment methodology with four main steps: goal and scope, life cycle inventory, life cycle impact assessment, and interpretation. The goal and scope describe the purpose of the LCA study, the functional unit or metric of comparison, and the system boundaries. The life cycle inventory

describes the data collected or sourced from premade databases. The LCIA step includes the calculation and assessment of environmental impact. Global warming potential, cumulative energy demand, and human toxicity are examples of impact categories. The interpretation step describes the evaluation of results against the goal and scope. It also includes sensitivity analysis to assess variability in data and parameters. Carbon footprints are a subset of life cycle assessments that focus solely on the global warming potential of the system throughout its life cycle.

Standards have been created to guide life cycle practitioners on how to conduct life cycle analyses or carbon footprints, such as IS0 14044 and the World Resource Institute's Greenhouse Gas Protocol Initiative. In these standards and throughout the literature, the end-of-life or disposal life cycle stage is modeled using closed-loop or open loop recycling. ISO 14044 (2006) uses closed-loop recycling methods when processing is not required to return material back into another life cycle stage. For example, in a closed-loop recycling system, components that are reused at end-of-life are returned back into to the manufacturing stage for assembly without processing. ISO 14044 (2006), The World Resource Institute (2010), ILCD (2010) handbook, Frischknecht (2010), Nicholson, et al (2010), McEwen (2010), Weidema (2003), and Ekvall and Tillman (1997) model open-loop recycling using allocation methods such as (1) avoided burden, (2) cut-off, (3) 50/50, (4) economic allocation, (5) market model for system expansion (6) loss of quality, and (7) substitution. ISO 14044 (2006) and the World Resource Institute (2010) recommend avoiding allocation whenever possible, but if necessary to use physical properties, economic value, and then number of uses of recycled material as allocation criteria. Ekvall and Tillman's (1997) life cycle cascade (Figure 3.5) is typically referred to when open-loop recycling methods are calculated.

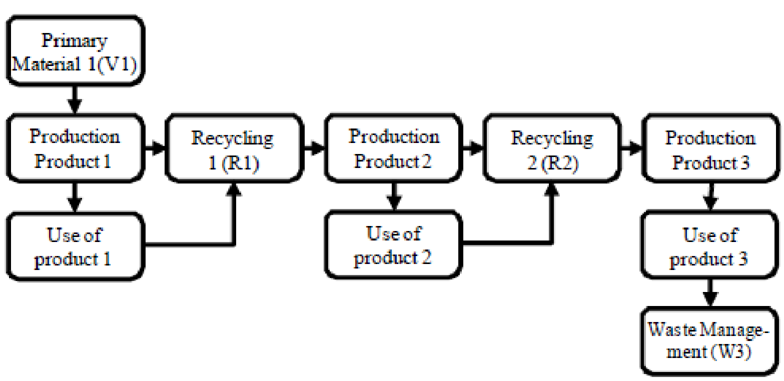


Figure 3.5: Open-Loop life cycle cascade for three life cycles (Ekvall & Tillman, 1997).

The cascade describes the environmental impact of end-of-life disposition with life cycle stage nomenclature, used throughout this section. Primary Material 1 *(V1)* is the environmental impact

of extracting virgin material in the first life of the product *(L1)*. Production Product 1is the environmental impact of manufacturing in the first life of the product *(L1).* Use of Product 1 is the environmental impact of using the product in its first life *(L1).* Recycling 1 *(R1)* is the environmental impact of recycling the product in its first life *(L1).* Production Product 2 is the environmental impact of manufacturing in the second life of the product *(L2).* Use of Product 2 is the environmental impact of using the product in its second life *(L2).* Recycling 2 *(R2)* is the environmental impact of recycling the product in its second life *(L2).* Production Product 3 is the environmental impact of manufacturing in the third life of the product *(L3).* Use of Product 3 is the environmental impact of using the product in its third life *(L3).* Waste Management 3 *(W3)* is the environmental impact of the final treatment the product in its third, usually final, life *(L3).*

3.4.2 Avoided Burden method

The avoided burden method, otherwise known as System Expansion, 0/100 Output Method, End of Life Recycling, or 100% Virgin Material, is used to model open loop recycling using a closed-loop allocation. It is used to represent a system where the environmental burden of virgin materials *(V1)* is being replaced by recycling materials *(R1, R2).* The avoided burden method is commonly used when the manufacturer would like to promote end-of-life recycling. The Metals Industry (2007) supported the End-of-Life Recycling approach (avoided burden approach) for modeling recycling in LCA, because it encourages metals recycling. Nicholson, et al (2010) also argued that the 100% Virgin Material method (avoided burden method) encourages the development of recyclable products. The Environmental Protection Agency (EPA) (2010) uses the avoided burden method in their Waste Reduction Model (WARM). The WARM Model was created to assist companies with collecting greenhouse gas (GHG) information from waste management practices. Ashby (2009) uses the avoided burden method to model the end-of-life in his eco-audit tool. The eco-audit measures the embodied energy of materials throughout the life cycle of products.

When modeling the avoided burden method, McEwen (2010), Nicholson, et al (2009), and ISO 14044 (2006) give each life of the product *(L1, L2, L3)* an equal environmental burden *(V1 + (R1+R2) + W3)* depending on the number of times recycling occurs *(n)* (Equation 3.13).

$$L1 = L2 = L3 = \frac{V1+(R1+R2)+W3}{n} \tag{3.13}$$

For carbon footprinting, the World Resources Institute (2004) defines avoided burden or the 0/100 Output Method as when the net virgin material equals the difference of the virgin material input

(V1) and the recycled material *(R1, R2).* The ILCD (2010) handbook comparatively describes this method in their recyclability substitution approach.

3.4.3 Cut-off method

The cut-off method, also known as Recycled Content, 100/0 Output Method, and 100% Recycled Material, is used to model open-loop recycling when only those end-of-life environmental burdens directly caused by the product are included in the life cycle analysis. Nicholson, et al (2010) argued that the 100% recycled material method encourages the use of recycled material. The EPA (2010b) used the cut-off method to model recycling in their recycled content tool (ReCon). It is used to assist companies with collecting greenhouse gas (GHG) information from manufacturing or buying materials containing post consumer content. The ecoinvent v2.0 (2010) database used the cut-off recycling method to represent their life cycle inventory data. It placed the burden of recycling processes into the recycled materials processes or inputs.

In the cut-off recycling method, McEwen (2010), Frischknecht (2010), and ISO 14044 (2006) gave an environmental burden for the virgin materials *(V1)* used in the first life of the product *(L1)* and an environmental burden for the refurbishing processes *(R1)* of the materials used to make the new product in the second life *(L2).* An environmental gain is given for the percentage of material recycled. Finally, the environmental burdens of the disposal of the recycled materials *(R2 + W3)* in the third life *(L3)* are not included (Equation 3.14, 3.15, 3.16). For carbon footprinting, the World Resources Institute (2004) also defines cut-off or the 100/0 Output Method as when the recycling processes *(R1)* are allocated to the recycled material input in the second life (L2).

$$L1 = V1 \tag{3.14}$$

$$L2 = R2 \tag{3.15}$$

$$L3 = R2 + W3 \tag{3.16}$$

3.4.4 50/50 method

Nicholson (2009) used the 50/50 method, also known as Average Burden, to represent the supply and demand of recycled materials. Nicholson, et al (2010) argue that the 50/50 method encourages the development of recyclable products and use of recycled materials. It is modeled as the average environmental burden between the virgin material *(V1)* and the recycling processes *(R1+R2)* (Equation 3.17, 3.18, and 3.19).

$$L1 = \frac{V1+R1+W3}{n-1} \quad (3.17)$$

$$L2 = \frac{R1+R2}{n-1} \quad (3.18)$$

$$L3 = \frac{V1+R2+W3}{n-1} \quad (3.19)$$

3.4.5 Economic Allocation method

The economic allocation method is used to allocate recycling in terms of the recycled material market value and the cost of recycling processes. When McEwen (2010) modeled the economic allocation method, the environmental burdens of recycled material and virgin material are proportional to the market value of the recycled material and the value of the material stream (Equation 3.20). Each of the product's lives are allocated the environmental burdens from recycling processes and the environmental credits from not wasting material. ISO 14044 (2006) supported economic value as recycling allocation criteria, but did not give more specific details on how it should be modeled.

$$\frac{recycled\ material\ burdens}{virgin\ material\ burdens} = \frac{recycled\ material\ market\ value}{entire\ process\ value} \quad (3.20)$$

3.4.6 Market Model for System Expansion method

The market model for system expansion method is used to model recycling with two types of markets, fully utilized or underutilized. In the fully utilized market, all scrap that is available is being used, so the process that produces less scrap receives more of the environmental burden. Weidema (2003) and McEwen (2010) modeled a fully utilized market by allocating the environmental burden of the virgin materials *(V1)* and the refurbishing processes *(R1, R2)* to the first life. They include potential changes to future processing in addition to benefits from virgin material avoided in the product's second life.

In an underutilized market, available scrap is not being used, so the process that uses less scrap receives more of the environmental burden. Weidema (2003) and McEwen (2010) modeled an underutilized market by allocating the environmental burden of the virgin materials *(V1)* and the refurbishing processes *(R1, R2)* to the first life. They included the benefits from waste avoided in the third life.

3.4.7 Loss of Quality method

Nicholson (2009) and Ekvall and Tillman (1997) used the loss of quality method to represent the loss of material quality in recycling *(R1, R2)* and the processes necessary to regain the quality that was lost (Equation 3.21). In the loss of quality method, Q_i is the material quality metric that can be described with market pricing data.

$$Li = \frac{Q_i}{\sum_{i=1}^{n} Q_i} \times (V1 + R1 + R2 + W3) \qquad (3.21)$$

3.4.8 Substitution method

Nicholson (2009) utilized the substitution method to describe a recycling system that replaces the burden of virgin material extraction with recycling. In this method, each life *(L1, L2, and L3)* has an equivalent environmental burden. Recycling materials substitute 100% of virgin material minus the loss from recycling processes. Each life also gets a burden for the recycling processes *(R1)*, virgin materials *(V1)*, and waste treatment processes *(W3)* (Equation 3.22). In the substitution method, *r%* is the percentage of material lost in recycling processes that has to be replenished by virgin material.

$$L1 = L2 = L3 = (100\% - r\%) \times (R1) + \ r\% \ \times (V1 + W3) \qquad (3.22)$$

3.4.9 Discussion

LCIA methods to quantify the environmental impacts and benefits of all life cycle stages were reviewed. Then eight techniques to frame the environmental impacts and benefits at end-of-life disposition were reviewed. In Section 4.1.6, LCIA methods and end-of-life disposition modeling techniques will be selected to calculate the environmental impact of end-of-life disposition.

3.5 Discussion

In chapter 2, two hypotheses are presented. The first hypothesis describes the ability to determine a set of design characteristics that may be used to relate the product design and the end-of-life disposition environmental impact. It is supported in the review of design for the environment (DfE) methods and end-of-life studies (Section 3.2). The studies are diverse in their selection of design characteristics for end-of-life disposition analysis. This diversity supports the designer's need for guidance when selecting product attributes to improve upon in DfE. The studies and checklists were also limited in their documentation of how the environmental impact was measured, which motivates the review of available literature on methods to calculate the environmental impact of end-of-life disposition (Section 3.4).

The second hypothesis describes the ability of the method to determine which of the design characteristics are significant with respect to end-of-life environmental impact. This hypothesis is supported by the qualitative and quantitative metrics described by Atlee and Kirchain (2006), Van Nes and Cramer (2006), Chancerel and Rotter (2009), and Rose (2001) (Section 3.1). The focus of this thesis will be to use a quantitative model, such as statistical or regression analysis, to provide a set of significant design characteristics or criteria to designers to support sustainable design practices.

The literature review uncovered up to twenty-three design characteristics that could potentially drive the environmental impact of cellular phones at end-of-life disposition. The literature review uncovered up to twenty-three design characteristics that could potentially drive the environmental impact of cellular phones at end-of-life disposition. In Chapter 4, the methodology is defined to:

- Select design characteristics;
- Select design characteristic metrics;
- Model the end-of-life disposition of cellular phones;
- Calculate the environmental impact of cellular phones at end-of-life disposition; and to
- Determine cellular phones' significant design characteristics that contribute to end-of-life disposition environmental impact.

The ability of the methodology to satisfy the thesis objectives will be tested through sensitivity analysis.

Chapter 4

METHODOLOGY

The objective of this thesis is to analyze the relationship between end-of-life environmental impact and technical design characteristics of consumer electronics, specifically cellular phones, to assist with design for end-of-life decision-making. Understanding the relationship between the product design characteristics and the environmental impact of recovering product components at end-of-life will enable design decision making and prioritization.

4.1 Methodology Components:

To meet the stated objective, the following activities take place:

(1) Current methods that describe a relationship between consumer electronics' product design, and their end-of-life disposition or environmental impact are identified in the literature review;

(2) Potential design characteristics that describe designing consumer electronics for end-of-life disposition are extracted and selected from the available literature;

(3) Potential metrics to quantify the selected design characteristics are extracted from the available literature;

(4) Consumer electronics end-of-life disposition processes are outlined;

(5) The framework for selecting end-of-life disposition separation processes for materials or components is outlined;

(6) The framework for estimating the environmental impact of consumer electronics' end-of-life disposition is outlined;

(7) Linear regression analysis is used to determine if there is a relationship between design characteristics and the environmental impact of end-of-life disposition;

(8) Data collection is described;

(9) The design characteristic metrics and end-of-life disposition environmental impact is verified and the linear regression analysis is validated;

(10) A sensitivity analysis is conducted; and

(11) Conclusions are extracted.

These activities are briefly described below:

4.1.1 Relating Product Design and End-of-Life Disposition or Environmental Impact

Current methods that describe a relationship between consumer electronics' product design and their end-of-life disposition or environmental impacts are identified in the literature review. Methods are preferred if they meet the following criteria:

(1) They connect consumer electronic design to environmental impact;

(2) They connect consumer electronic design to end-of-life disposition;

(3) They describe electronic products in terms of design characteristics or

(4) They use design metrics to measure environmental impacts.

Gaps or differences between the current research and the thesis objective are identified for each study. For example, the end of life design advisor (ELDA), developed by Rose, et al (2000) is reviewed, because it used design characteristics to predict the potential environmental impacts of electronic products. There are research gaps in ELDA pertaining to the selection of design characteristics and the definition of environmental impacts. Rose, et al (2000) selected design characteristics based on industry knowledge instead of their impact on end-of-life disposition. Environmental impacts were defined in terms of a discrete end-of-life environmental hierarchy where reuse had the lowest environmental impact and incineration had the highest. This is not ideal because end-of-life disposition for consumer electronics includes a combination of reuse, recycling, landfill, or incineration. Methods relating product design and end-of-life disposition or environmental impact are described in more detail in the literature review in Chapter 3.

4.1.2 Extracting and Selecting Potential Design Characteristics

Potential design characteristics that describe designing consumer electronics for end-of-life disposition are extracted and selected from the available literature. They are extracted from

studies on design for the environment, optimization, and life cycle assessment, among others. Design characteristics are selected if they meet the following criteria:

(1) They describe end-of-life disposition after collection, transportation, inspection, or testing;

(2) They can be applied to the architecture (materials, fasteners, components, etc.) of cellular phones;

(3) They can differentiate between small consumer electronic product models and product families; and

(4) They can be described by the available data and tools.

Design Characteristics are not selected if:

(1) They are needed to describe other design characteristics;

(2) They are needed to select the end-of-life disposition separation process; or

(3) They are needed to calculate the end-of-life environmental impact.

For example, "The reason for redesign" cannot differentiate between product models and product families, so it is not selected as a design characteristic. All products under evaluation have the same reason for redesign, which is to improve material recovery at end-of-life disposition. The extraction and selection of design characteristics is described in more detail in Chapter 5.

4.1.3 Selecting Potential Metrics

Potential metrics to quantify the selected design characteristics are extracted from the available literature. Metrics are selected if they meet the following criteria defined by Altee and Kirhain (2006):

(1) They are useful: if they are simple, not ambiguous, and address the clear goal of the design characteristic;
(2) They are robust: if they are easy to calculate and are reproducible; and
(3) They are feasible: if there is data readily available to complete the calculations.

Metrics are not selected if:

(1) They are needed to calculate other metrics;

(2) They are needed to select the end-of-life disposition separation process; or

(3) They are needed to calculate the end-of-life environmental impact.

For example, counting the number of fasteners in a product is a clear metric that is easy to interpret. It is straightforward to describe a fastener, so it is distinguishable from other parts, which also makes the calculation simple to replicate. Since products can be examined for fasteners with a bill of materials or through pictures or videos, data collection is feasible. The selection of metrics is described in more detail in Chapter 6.

4.1.4 Consumer Electronics End-of-Life Disposition

The consumer electronics end-of-life disposition is outlined. Flow charts are created from case studies in the available literature and interviews with electronics recyclers. They represent the end-of-life disposition of each material or component type that is used to make cellular phones. The flowcharts include processes such as sorting, manual dismantling, mechanical recycling, discarding to landfill, and incineration. Consumer electronics disposition is described in more detail in Chapter 7.

4.1.5 Selecting End-of-Life Disposition Separation Processes

The process for selecting end-of-life disposition separation processes for materials or components is outlined. In consumer electronics end-of-life disposition, materials or components are separated with manual dismantling or mechanical recycling. The main factors influencing the selection of separation processes are value, reusability, and hazardous material regulations. Selecting end-of-life disposition separation processes for materials or components is described in more detail in Chapter 8.

4.1.6 The Environmental Impact of Consumer Electronics' End-of-Life Disposition

The process for describing the environmental impact of consumer electronics end-of-life disposition is outlined. To describe the environmental impact of the end-of-life disposition of consumer electronics, a life cycle approach is used. This approach follows the ISO14040-44 (2006) life cycle assessment framework, which includes: (1) Goal and Scope, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation. The process for describing the environmental impact of consumer electronics end-of-life disposition is described in more detail in Chapter 9.

4.1.7 Determining a Relationship between Design Characteristics and End-of-Life Disposition Environmental Impact

Linear regression analysis is used to determine if there is a relationship between design characteristics and the environmental impact of end-of-life disposition. It determines the following:

(1) Is there a relationship between design characteristics and the environmental impact of end-of-life disposition?;

(2) If there is a relationship, which design characteristics are significant?;

(3) Do interactions exist between the design characteristics?; and

(4) What is the relative importance of the significant design characteristics to the environmental impact of end-of-life disposition? i.e. what combination of design characteristics and their interactions explain the end-of-life disposition environmental impact the best?.

Determining if there is a relationship (and if so, the nature of the relationship) between design characteristics and the environmental impact of end-of-life disposition is described in more detail in Chapter 10.

4.1.8 Data Collection

Data is collected from disassembling actual cellular phones. Cellular phones are acquired at their end-of-life or for newer products teardowns from OEMS and ifixit.com are used. Data is also extracted from case studies in the literature to verify results.

Data collection is described with six data collection methods: (1) the reverse fishbone diagram, (2) the bill of materials, (3) the product specifications, (4) the disassembly time spreadsheet, (5) the FCC ID and average lifespan, and (6) the function tree diagram. Each method provides the data needed to describe the design characteristic metrics and the end-of-life disposition environmental impact. Data collection is described in more detail in Chapter 12.

4.1.9 Verification

The design characteristic metrics and the end-of-life environmental impact calculations are verified. The design characteristic metrics are verified with partial data from case studies. When duplicated product model data is available, it is compared to confirm the accuracy of the metric calculations. Verification is described in more detail in Chapter 12.

4.1.10 Validation

The design characteristic metrics and the end-of-life environmental impact calculations are validated. The one phase end-of-life disposition LCA is validated with the ecoinvent manual, Disposal of Electric and Electronic Equipment (e-Waste). Then, the linear regression model is validated by comparing the signs of the regression coefficients with the predicted correlation between design characteristics and end-of-life disposition environmental impact. Validation is described in more detail in Chapter 8.

4.1.11 Sensitivity Analysis

A sensitivity analysis is conducted understand its uncertainty and variation in the linear regression analysis. Variation may exist in the design characteristic metric calculations, the environmental impact calculations, data collection and sampling, and the selection of end-of-life disposition separation processes. The sensitivity analysis is explained in more detail in Chapter 13.

4.1.12 Conclusions

Conclusions are drawn from the results and analysis on (1) the ability of the method to solve the problem and meet the thesis objective; (2) the strengths and weaknesses of the chosen modeling activity; and (3) the applicability of the method to real life design activity. The conclusions are reviewed in Chapter 14.

4.2 Discussion

This chapter provided an overview of the methodology that will be used to solve the problem and meet the thesis objective. The following chapters will provide more detail on the methods and tools used, which describe the relationship between design characteristics and the environmental impact of their end-of-life disposition. The chapters are organized as follows:

Chapter 5: Extracting and selecting potential design characteristics;

Chapter 6: Selecting potential metrics;

Chapter 7: Consumer electronics end-of-life disposition;

Chapter 8: End-of-life separation process selection for materials or components;

Chapter 9: Estimating the environmental impact of the end-of-life disposition of consumer electronics;

Chapter 10: Determining a relationship between design characteristics and end-of-life disposition environmental impact;

Chapter 11: Data Collection;

Chapter 12: Verification and Validation;

Chapter 13: Sensitivity Analysis;

Chapter 14: Results and Analysis; and

Chapter 15: Conclusions.

Chapter 5

EXTRACTING AND SELECTING POTENTIAL DESIGN CHARACTERISTICS

In this chapter, the potential design characteristics are extracted from the available literature. Then, they are selected if they meet the following criteria:

(1) They describe end-of-life disposition after collection, transportation, inspection, or testing;

(2) They can be applied to the architecture (materials, fasteners, components, etc.) of cellular phones;

(3) They can differentiate between small consumer electronic product models and product families; and

(4) They can be described by the available data and tools.

Design Characteristics are not selected if:

(1) They are needed to describe other design characteristics;

(2) They are needed to select the end-of-life disposition separation process; or

(3) They are needed to calculate the end-of-life environmental impact.

The twenty-three design characteristics are categorized into affinity groups and their definitions are given (Table 5.1). If they do not meet the given criteria (above), they are not selected and an explanation or "reason removed" is provided.

Table 5.1: Potential Design Characteristics.

Potential Design Characteristics	Definition	Reason Removed	Source(s)
Weight			
Weight	The amount of material in the product.	It is needed to select the end-of-life disposition separation process.	Xanthopoulos and Iakovou (2009), Iakovou, et al (2009) Huisman and Stevels (2006), Chancerel and Rotter (2009)
Product Dimensions			
Volume of a Rectangular Prism	The volume of the product.	n/a	Herrman, et al (2006)
Fasteners, Contaminated Parts, Wires			
Number of connections such as fasteners or wires	Types of connections in a product, such as screws, snap fits, wires, etc.	n/a	Fishbein (2002), Ying, et al (2005)
Parts that contain adhesives, labels, or paint that increase the difficulty of reusing or recycling that part	Adhesives, glues, stickers, labels, ink, paint, etc. that make the part difficult to remove or contaminate recycling.	n/a	American Plastics Council (2000)
Material Concentration			
Material mixing	The diversity and amount of materials measured by their binary disassembly steps.	n/a	Dahmus and Gutowski (2007)
Material composition	Mass percentage of materials in a product.	It is needed to describe material mixing, which is more relevant to recycling and recovery.	Boks and Ab (2001)
Plastics Concentration			
Plastics Concentration	The diversity and amount of plastics in a product.	n/a	The American Plastics Council (2000)

Potential Design Characteristics	Definition	Reason Removed	Source(s)
Hazardous Materials			
Number of components containing hazardous materials	Components containing hazardous materials, usually provided in lists, tables, or standards.	n/a	Atlee and Kirchain (2006), Doctori Blass, et al (2008), Most (2003), Fishbein (2002), the American Plastics Council (2000), Hageluken (Hageluken, 2006), Iakovou, et al (2009), Chancerel and Rotter (2009)
Percentage of hazardous materials in a component or a product	Percentage by weight of material in a component or a product.	n/a	Bhuie, et al (2004)
Value			
Commodity Value	The market value of material at end-of-life.	It is needed to select the end-of-life disposition separation process.	Dahmus and Gutowski (2007)
Component Resale Value	The market value of components at end-of-life.	It is needed to select the end-of-life disposition separation process.	Xanthopoulos and Iakovou (2009)
Ability to Disassemble			
Disassembly time	Time it takes to disassemble a product as a function of destructive disassembly, tools, fixtures, access to components, force, etc.	It is needed to select end-of-life disposition separation processes.	Iakovou, et al (2009), Ying, et al (2005)

Potential Design Characteristics	Definition	Reason Removed	Source(s)
Difficulty/Ease/Recoverability	The amount of effort that needs to be applied to disassemble components or products.	n/a	Xanthopoulos and Iakovou (2009), Iakovou, et al (2009)
Sequence & Precedence	The order in which components are removed during disassembly.	n/a	Ishii and Lee (1996)
Obsolescence			
Technology cycle	The time before the main functions' mechanisms become obsolete in a product or the time before it becomes less desirable because a new technology is released.	n/a	Rose (2001)
The technology cycle time (TCT)	The median age of the citations of a technology's patent compared to the current date.	It cannot be described by available data and tools.	Cheng, et al (2010) and Kayal and Waters (1999)
The technology adoption cycle (TAC)	The technology marketing stage where the product currently resides: (1) innovation, (2) chasm, (3) tornado, (4) main street, (5) decline, or (6) obsolescence.	It cannot differentiate between small consumer electronic product models and product families.	Meade and Rabelo (2004)
Economic life	The age at which the owner chooses to replace the product.	n/a	Fishbein (2002)
Design Cycle	Frequency of design changes to a product	It cannot be described by available data and tools.	Rose (2001)

Potential Design Characteristics	Definition	Reason Removed	Source(s)
Modularity			
Number of parts, components or modules	The quantity of a particular component in a product or the number of parts from the product's bill of materials.	It is needed to describe level of integration., which describes the functions per part or number of extraneous modules.	Iakovou, et al (2009), Rose (2001)
Multiplicity of components	The duplication of components in a product.	n/a	Xanthopoulos and Iakovou (2009)
Failure			
Wear-out life	The length of time until the product does not meet its original function.	n/a	Rose (2001)
Testing			
Testing	The process by which products are checked for their performance, so they can be reused or resold.	It describes end-of-life disposition during collection, transportation, testing, or inspection.	SunnKing (2009) and Maven Technologies (2010)
Level of Integration			
Functionally complex product	A product with highly dependent modules that support a variety of functions.	n/a	Rose (2001)
Redesign			
Reason for redesign	Purpose of the redesign of the product, such as original design, evolutionary design, or feature changes.	It cannot differentiate between small consumer electronic product models and product families.	Rose (2001)

5.1 Discussion

Twenty-five potential design characteristics are extracted from the available literature. After screening the potential design characteristics against a set of criteria (described above), 14 were selected. Those rejected are weight, material composition, percentage of hazardous materials in a component or a product, commodity value, component resale value, disassembly time, technology cycle time, technology adoption cycle, design cycle, number of parts, components or modules, testing, and reason for redesign.

Chapter 6

SELECTING POTENTIAL METRICS

In this chapter, potential metrics to quantify the selected design characteristics are selected from the available literature. They are selected if they meet the following criteria:

(1) They are useful: if they are simple, not ambiguous, and address the clear goal of the design characteristic;
(2) They are robust: if they are easy to calculate and are reproducible; or
(3) They are feasible: if there is data readily available to complete the calculations;

Metrics are not selected if:

(1) They are needed to calculate other metrics;

(2) They are needed to select the end-of-life disposition separation process; or

(3) They are needed to calculate the end-of-life environmental impact.

The fourteen selected design characteristics are quantified with thirty-two potential metrics (Table 6.1). The metrics are described qualitatively or mathematically (with a formula). If they do not meet the given criteria (above), they are not selected and an explanation or "reason removed" is provided.

Table 6.1: Potential Metrics to Measure Design Characteristics.

Potential Design Characteristic Metrics	Description/Formula	Reason Removed	Source(s)
Product Dimensions			
Volume of a Rectangular Prism	The Volume of a rectangular prism, in $in^3 = l \times w \times h$.	n/a	Herrman, et al (2006)
Fasteners, Tools, Wires, Contaminated Parts			
Number of fasteners	The number of fasteners in the product.	n/a	Verein Deutscher Ingenieure (1991), The British Industry Council for Electronic Equipment Recycling (1993), Dowie (1994), Fiksel (1995), Bras (1998), and General Electric Plastics (1995)
Number of tools	The number of tools needed for disassembly.	n/a	Verein Deutscher Ingenieure (1991), The British Industry Council for Electronic Equipment Recycling (1993), Dowie (1994), Fiksel (1995), Bras (1998), and General Electric Plastics (1995)
Number of wires	The number of wires in the product.	n/a	Verein Deutscher Ingenieure (1991), The British Industry Council for Electronic Equipment Recycling (1993), Dowie (1994), Fiksel (1995), Bras (1998), and General Electric Plastics (1995)

Potential Design Characteristic Metrics	Description/Formula	Reason Removed	Source(s)
Parts with adhesives, labels, or paint	The number of parts with adhesives, labels, or paint in the product.	n/a	Verein Deutscher Ingenieure (1991), The British Industry Council for Electronic Equipment Recycling (1993), Dowie (1994), Fiksel (1995), Bras (1998), and General Electric Plastics (1995)
Material Concentration			
Material Mixing	$H = c_{j_i} log c_{j_i}$, where $c_{j_i} = \frac{m_{j_i}}{m_j}$ $\forall\ materials, i, in\ product, j$	n/a	Dahmus and Gutowski (2007)
Plastics Concentration			
Mass percentage of plastics	$\sum_1^i \frac{mp_{j_i}}{mp_j}, where\ mp_{j_i} =$ $weight\ of\ plastic, i$ $\forall\ plastics, i\ in\ product, j$	n/a	Rios, et al (2003)
Variety of plastics	The number of different plastic materials in the product.	n/a	Ishii and Lee (1996)
Plastics Removal Rate	$PRR_{type,i} = \frac{\sum_1^i mp_i}{prod.disassembly\ time}$	It is needed to select an end-of-life disposition separation process.	Williams, et al (2006) and Blyler, et al (2003)
Hazardous Materials			
Components with highest environmental burden (using Eco-Indicator 99) contain hazardous materials.	Calculate the Environmental burden using the EcoIndicator 99 method.	It is needed to calculate the environmental impact of end-of-life disposition scenarios.	Iakovou, et al (2009)
Refer to Annex II of WEEE	Count the components in the table of components containing hazardous materials.	n/a	Chancerel and Rotter (2009)
Number of components/materials containing hazardous materials	Count the components on the list of components containing hazardous materials.	It is combined with the previous metric, which is an externally recognized list that is	Atlee and Kirchain (2006), Doctori Blass, et al (2008), Most (2003), Fishbein (2002), the American

Potential Design Characteristic Metrics	Description/Formula	Reason Removed	Source(s)
		continually updated.	Plastics Council (2000), Hageluken (2006) Ying, et al (2005)
Percentage of hazardous materials in a product	$\sum_{1}^{i} \frac{mhp_{j_i}}{mhp_j}, where\ mph_{j_i} = weight\ of part\ with\ hazardous\ material, i\ \forall\ parts\ with\ hazardous\ material, i\ in\ product, j$	n/a	Bhuie, et al (2004)
Ability to Disassemble			
Number of disassembled parts	The number of parts removed for disassembly.	n/a	Kroll (1995)
Number of disassembly tasks	The number of tasks needed to dismantle the product.	n/a	Kroll (1995)
Number of non-value added tasks	The number of tasks that do not result in a disassembled part or component.	n/a	Kroll (1995)
Number of tool and hand manipulations	The number of times a component is picked up or put down and the number of times a tool is picked up or put down.	It is not useful, because the results are subjective and varied.	Kroll (1995)
Disassembly of parts not theoretically required	The number of non-ideal parts removed for disassembly.	It is not useful, because the results are subjective and varied.	Kroll (1995)
Number of tools used	The number of different tools used for disassembly.	It is repeated in the fasteners, tools, wires, contaminated parts category.	Kroll (1995)
Disassembly index	$\mu\ disassembly = \frac{(\#ideal)(1.5sec)}{time_\tau}$	It is not useful, because the results are subjective and varied.	Hammond (1996)
Variety of materials or plastics	The number of parts with different materials or plastics in	n/a	Ishii and Lee (1996)

Potential Design Characteristic Metrics	Description/Formula	Reason Removed	Source(s)
	the product.		
Number of sequence dependent disassembly steps	The number of disassembly steps that must follow a precedence sequence.	n/a	Ishii and Lee (1996)
Repetitive components	The number of components that have more than one duplicate.	n/a	Ishii and Lee (1996)
Obsolescence			
Technology Cycle	Estimate the time between technology releases.	It is not feasible.	Rose (2001)
BIOS login data	The date the user last turned on the electronic device, which is stored on the hard drive.	It is not feasible.	Tucker (2010)
Product's failure compared to its product family's average failure.	$(disassem.yr - mfg.yr) - product\ family's\ avg.life\ (yrs)$	n/a	EPA (2007)
Modularity			
Multiplicity of components	The number of components that have one or more duplicates.	It is repeated in the ability to disassemble category as repetitive components.	Xanthopoulos and Iakovou (2009)
Functional design attribute	The number of functions in a module.	It is repeated in the level of integration category.	Ishii (1998)
Functional complexity	The flexibility required in a function.	It is not feasible.	Ishii (1998)
Ideal Parts	Parts that: satisfy large ranges of motion; contain only the materials required to achieve design requirements; satisfy assembly or disassembly; or are low value and protect other parts from wear.	It is not useful, because the results are subjective and varied.	Hammond (1996)

Potential Design Characteristic Metrics	Description/Formula	Reason Removed	Source(s)
Failure			
Wear-out life	The time until the critical part (providing function) wears out or fails; the time until the complete product fails (losing all functions); or the mean time failure.	Data is not readily available to complete the calculations.	Rose (2001)
Inspection Index	$\mu\ inspections = \frac{\#\ ideal\ inspect}{\#parts - \#replaced}$	It describes end-of-life disposition during collection, transportation, testing, or inspection.	Hammond (1996)
Testing Index	$\mu\ testing = \frac{(\#tests)(10\text{sec})}{time_{\tau}}$	It describes end-of-life disposition during collection, transportation, testing, or inspection.	Hammond (1996)
Level of Integration			
Highly dependent modules that support a variety of functions.	The number of functions per module.	n/a	Rose (2001)

6.1 Discussion

Thirty-two potential metrics are extracted from the available literature. After screening the potential metrics against a set of criteria (described above), 18 were selected. Among those rejected are plastics removal rate (PRR), components with the highest environmental burden (calculated using Eco-Indicator 99) contain hazardous materials, number of tool and hand manipulations, disassembly of parts not theoretically required, disassembly index, technology cycle, BIOS login data, functional complexity, ideal parts, wear-out life, inspection index, and testing index. Several metrics were repetitive, so they are consolidated, including number of tools, hazardous materials, and level of integration.

Chapter 7

CONSUMER ELECTRONICS END-OF-LIFE DISPOSITION

At the end of its useful life, collected electronic waste (e-Waste) is transported to a recycling center (Kang & Schoenung, 2005). At the recycling center, the e-Waste enters the Main Recycling System, which includes sorting, separation, and recovery or refining processes (Figure 3.4) (Jaco Huisman, 2003). From the main recycling system, materials and components branch off into specialized systems depending on their characteristics. First, the e-Waste is sorted into functioning and non-functioning products. Functional products are resold as used or refurbished products. Non-functional products are sent to a separation process. There are two separation processes: manual dismantling or mechanical recycling (Hageluken, 2006). Products are manually dismantled if their components or materials qualify as reusable, valuable, or hazardous. Otherwise, they are sent to the mechanical recycling separation process.

Components that may be functioning independently of the product's ability to function, such as disk drives and hard drives, are considered reusable and are manually dismantled (Figure 7.1). Then, they go to a refurbishing process to be reused. Cellular phones do not include functionally independent components, so cellular phone components will not adhere to the Manually Dismantling sub-model and will not be reused.

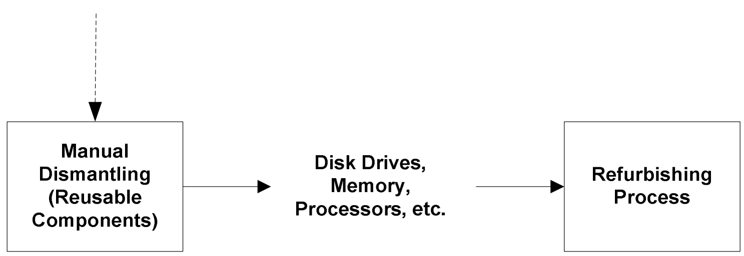


Figure 7.1: Manually Dismantling Reusable Material.

If the revenue generated from recovering materials and components is greater than the cost of recovery, those materials and components are considered valuable and are manually dismantled (Figure 7.2). Determining the value of materials or components is discussed in more detail in section 8.2. Ferrous and nonferrous metals go to a mechanical recycling separation process after disassembly. In the mechanical recycling process, materials are shredded or crushed. Then they

are sorted until their particles are the correct size for smelting and refining. Dust or other residues from size reduction and separation that cannot be recovered go to the landfill (R. Hischier et al., 2005). Thermoplastics, such as ABS, PC, and PS, go to a plastics recovery process after disassembly. In the plastics recovery process, the plastic is melted with an extruder and then formed into pellets with a pelletizer (Kang & Schoenung, 2005). Printed circuit boards (PCBs) go to copper or precious metal smelting and refining processes after disassembly (CSS, 2007; R. Hischier et al., 2005). In the copper or precious metal smelting and refining process, materials are separated, recovered, and upgraded or refined (Kang & Schoenung, 2005).

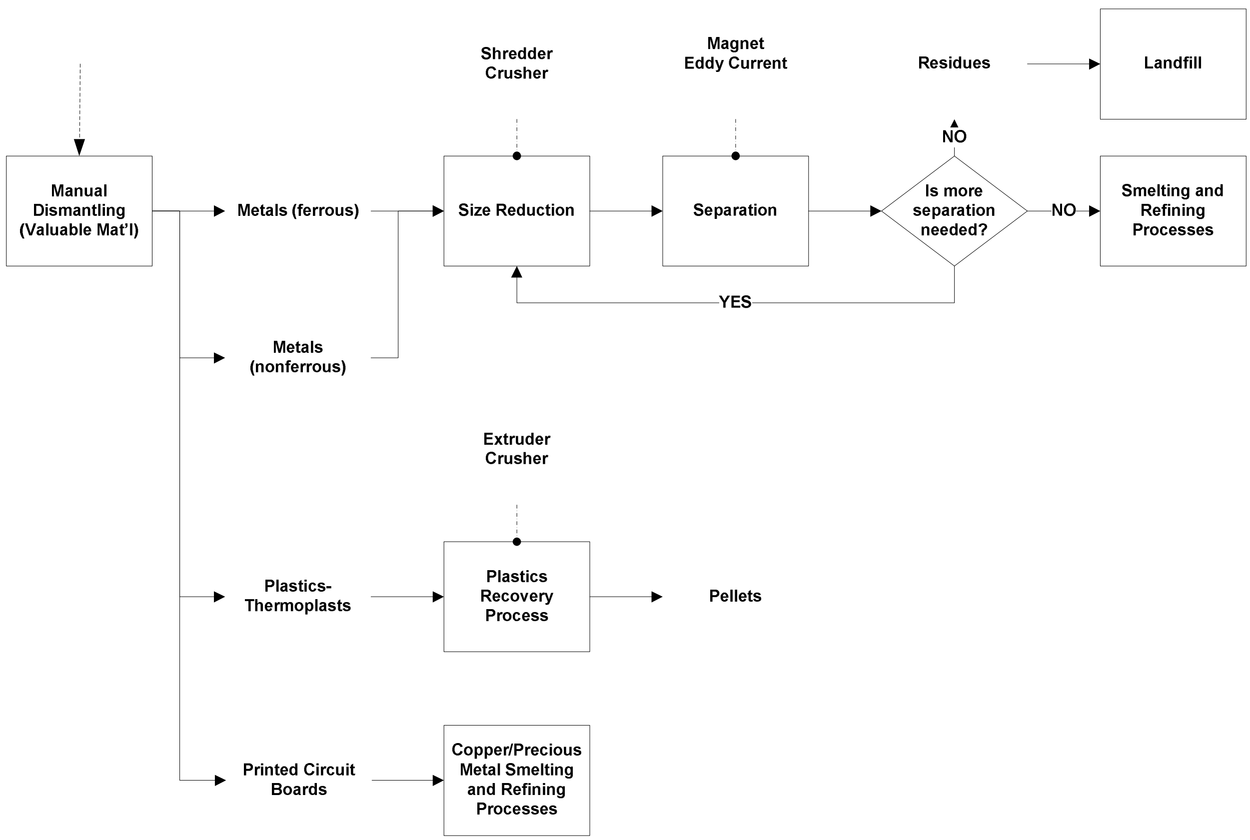


Figure 7.2: Manually Dismantling Valuable Material.

If regulations, such as the Restriction of Hazardous Substances (www.rohs.eu), designate materials or components as harmful, then they are considered hazardous and are manually dismantled, according to the Waste Electrical and Electronic (WEEE) protocol (EP & EU-27, 2003) (Figure 7.3). Batteries go to a battery recycling process that is a mixture of hydrological and pyrometallurgical processes after disassembly (Roland Hischier & Gallen, 2007). Freegard, et al (2006) cite ABS, PC, ABS/PC, and HIPS as the most frequent plastics containing brominated flame-

retardants (BFRs). All plastics labeled as ABS, PC, ABS/PC or HIPS are assumed to contain BFRs and go to incineration for energy recovery after disassembly (defra, 2006). Mobile phone PCBs and PCBs with a surface area greater than 10 cm^2 go to copper or precious metal smelting and refining processes after disassembly (CSS, 2007; EP & EU-27, 2003; R. Hischier et al., 2005). In the copper or precious metal smelting and refining process, materials are separated, recovered, and upgraded (Kang & Schoenung, 2005). Liquid Crystal Displays (LCDs) with a surface area greater than 100 cm^2 go to incineration after disassembly (EP & EU-27, 2003; Martin, Simon-Hettich, & Becker, 2008). All LCDs with gas discharge lamps must have the lamps disassembled and go to mechanical recycling after disassembly (defra, 2006). The lamps are shredded and separated into glass, metal, and powder containing mercury, and then the material is used in other industrial processes or purified to make new lamps (Technology, 2006).

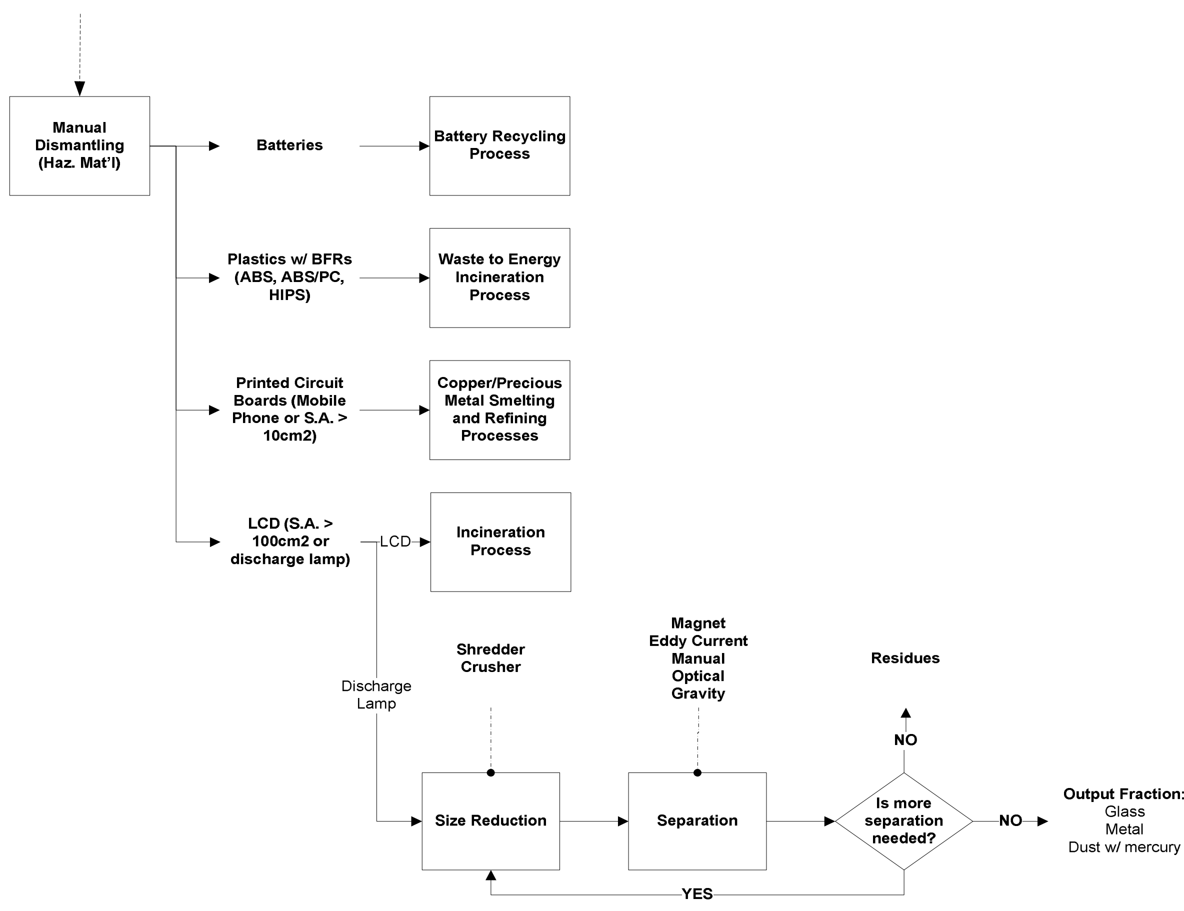


Figure 7.3: Manually Dismantling Hazardous Materials.

Materials and components that are not manually dismantled are mechanically recycled (Figure 7.4). All materials go through size reduction and separation processes. Then, the metals go to smelting and refining processes that separate, recover, and upgrade materials for reuse. Alternatively, the plastics go to incineration for energy recovery (Roland Hischier & Gallen, 2007; Kang & Schoenung, 2005).

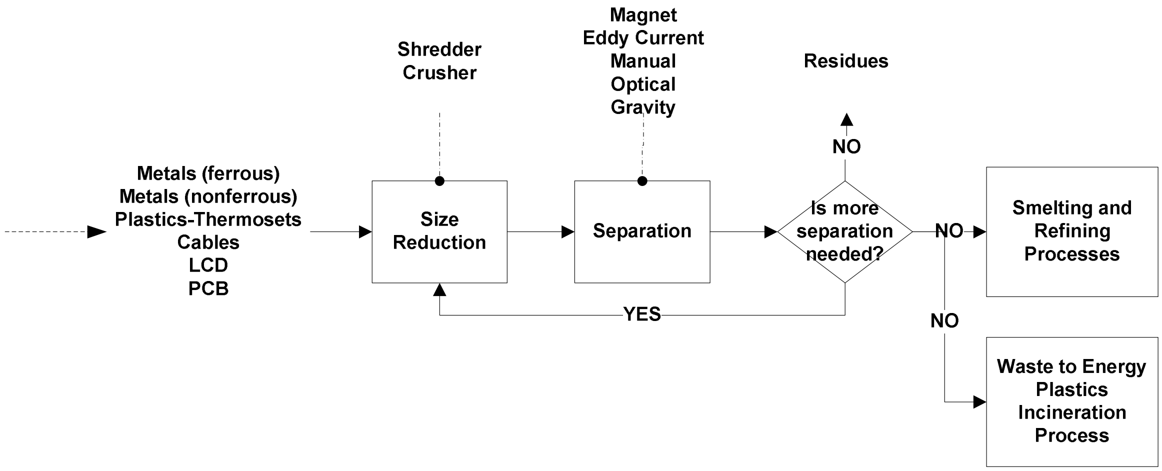


Figure 7.4: Mechanically Recycling Materials.

7.1 Discussion

Describing the main recycling system (Figure 3.4) and its subsystems (Figure 7.1- Figure 7.4) provides a framework for determining the environmental impact of end-of-life disposition. With this framework, products and their components are described with their potential end-of-life disposition processes. To determine the end-of-life disposition processes of components or materials, their separation processes (manually dismantling or mechanical recycling) are selected. Value, reusability, and hazardous material regulations are the main factors influencing the selection of separation processes.

Chapter 8

END-OF-LIFE SEPARATION PROCESS SELECTION FOR MATERIALS OR COMPONENTS

The process for selecting end-of-life disposition separation processes for materials or components is outlined. In consumer electronics end-of-life disposition, materials or components are separated with manual dismantling or mechanical recycling. Some materials or components are separated using both separation processes. The main factors influencing the selection of separation processes (manual dismantling vs. mechanical recycling) are value, reusability, and hazardous material regulations. The material removal rate (MRR) and the value removal rate (VRR) determine if the materials or components in a product are valuable enough to be manually dismantled. The MRR describes the rate at which the materials or components are removed during end-of-life disposition processing:

$$MRR = \frac{material\ or\ component\ weight\ (lb)}{material\ or\ component\ disassembly\ time\ (min)} \qquad (8.1)$$

If the MRR is high, more materials or components are removed in less time, which decreases the cost of end-of-life disposition and increases revenue. Materials or components with an MRR greater than or equal to 5 lbs/min are removed for manual dismantling, as suggested by Coulter et al (1996).

The VRR describes the rate at which valuable materials or components are removed during end-of-life disposition processing:

$$VRR = \frac{material\ or\ component\ value\ (\$)}{material\ or\ component\ disassembly\ time\ (min)} \qquad (8.2)$$

If the VRR is high, more valuable materials or components are removed in less time. Materials or components with a VRR greater than the cost of labor will be removed for manual dismantling, as suggested by Coulter et al (1996). The cost of labor in the United States is $7.25/hr or $0.12/min (DOL, 2010).

To calculate the MRR and VRR, the material or component disassembly time and the material or component value must be determined (Equation 8.1 and Equation 8.2). Estimating the

disassembly time is described in more detail in section 8.1. Estimating material or component value is described in more detail in section 8.2.

8.1 Estimating Material or Component Disassembly Time

To calculate the MRR and VRR, the disassembly time must be determined. Disassembly time is estimated using tables created by Dowie (1994), because disassembly time can be calculated per module. The tables contain estimated times for manual disassembly operations and disassembly operations performed with power tools, such as a drill (Table 8.1). Williams, et al (2006) expanded on Dowie's (1994) methods to include estimates for "presorting, tooling selection, decision analysis, and plastics identification." These processes were not included, because they provided the average disassembly times by product type only and not by tasks or modules.

Disassembly time depends on the type of removal method and the difficulty of removal. A spreadsheet tool was created from the tables to collect disassembly data and estimate the disassembly time per material or component (Table 8.2).

Table 8.1: Disassembly Time Tables (T. Dowie, 1994).

Disassembly Part Removal Times (sec)				
Degrees of Freedom	Horizontal Removal		Vertical Removal	
	1 hand	2 hands	1 hand	2 hands
2	0.3	0.5	0.6	1
1	0.5	2	1	2.5
Time to Move Parts/tools	(seconds)			
Pick up	0.7			
Put Down	0.7			

Separation times of two fastened parts		
Fastener	Removal Method	Time
Screws (sec/rev)	manual	0.6
	power screwdriver	0.15
Snap Fits (sec/snap)	manual breaking	1.5
	breaking with tool	3
Clips (sec/clip)	manual	1
	tool	2
Glues, etc. (sec)	manual breaking, 1 hand	3
	manual breaking, 2 hands	1
	breaking with tool	2
Cutting cords (sec)	tool	0.5
cutting wire (sec)	tool	0.25
Disconnect wire (sec)	manual	1.5

Modifiers to fastener removal times (removal difficulties)					
motion obstructions					
	easy to access (sec)	more than one direction, around an obstruction (sec)	more than one direction around an obstruction, with restricted vision (sec)	extended reach (sec)	severely obstructed access (sec)
No resistance	0	3	9	12	17
holding down part	6	9	15	18	23
corroded	9	12	18	21	26

Table 8.2: Disassembly Time Spreadsheet.

Part #	Part Name	Material	Quantity	lb/component	lbs	Step/Task	Degrees of freedom (1 or 2) [linear in x-dir, y-dir, or z-dir, rotation around x, y, or z]	Direction (L/R/up/dwn)	Horizontal or Vertical Removal (h/v)	#hands (1 or 2)	Pick up or put down (up/dwn) (# of times)	Fastener (n/a, screw, snapfit (lever/latch), clips, glues, cut cords, cut wire, disconnect wire)	Removal Method (manual/power/tool)	Tool Name	# of Repetitions	Motion Obstructions (easy access/1+ directions around obstruction(1plus)/1+ dir and obstruction with restricted vision(1+v)/ extended reach/severely obstructed)	No resistance/holding down part/corroded	How many times did product need to be reoriented (rotate/flip/hold in hand)?
1	Battery Door	unlabeled plastic	1	0.013	0.013	lever/ latch, remove	1	dwn	v	2	3	snapfit	manual		1	easy access	holding down part	0
2	Battery	Li-Ion 3.7V	1	0.063	0.063	remove	1	R	H	2	2	n/a	manual		1	easy access	holding down part	0
3	Torx (T4)	ferrous	4	0.000	0.000	unscrew, remove	1	up	v	2	3	screw	tool	torx	1	easy access	holding down part	0
4	Button panels	unlabeled plastic	2	0.003	0.006	remove	1	R	H	2	2	n/a	manual		1	easy access	holding down part	0
5	Backcover	>PC+ABS<	1	0.000	0.000	remove	1	R	H	2	2	n/a	manual		1	easy access	holding down part	0
6	keyboard	unlabeled plastic	1	0.016	0.016	remove	1	up	v	2	2	n/a	manual		1	easy access	holding down part	0
7	Front Frame	>PC+ABS<	1	0.028	0.028	remove	1	R	H	2	2	n/a	manual		1	easy access	holding down part	0
8	Speaker Frame	>PA+GF50<	1	0.016	0.016	w/p, remove	1	R	H	2	3	n/a	tool	fh	1	1plus	corroded	0
9	Speaker	ferrous	2	0.000	0.000	Remove	2	UP/R	H	1	2	n/a	manual		1	easy access	no resistance	0
10	Motherboard	PCB	1	0.056	0.056	Remove	1	R	H	2	2	n/a	manual		1	easy access	holding down part	0
11	Display	LCD (20.8 mm2)	1	0.025	0.025	bend, remove	1	R	H	2	3	n/a	manual		1	easy access	holding down part	0
12	keyboard connecter	unlabeled plastic	1	0.003	0.003	PP, remove	1	up	v	2	3	glues	tool	fh	1	easy access	holding down part	0
13	Center Frame	nonferrous	1	0.041	0.041	remove	2	UP/R	H	1	2	n/a	manual		1	easy access	no resistance	0

8.2 Estimating Material or Component Value

Recovering materials for reuse and recycling at the end-of-life disposition of consumer electronic products typically occurs in two forms (1) recovering whole components and (2) recovering materials. Because the processes differ, the quality of the recovered materials or components also differ, changing their value. For this method, the value of recovering components is denoted as the component value or V_c, and the value of recovering the materials is denoted as the materials value or V_m. Each module in the product is represented only by their V_c or their V_m. The value of the entire product is then the sum of all the values of the modules with component values V_c and the modules with material values V_m.

In Chapter 7, the Main Recycling System (Figure 3.4) and its subsystems (Figure 7.1-Figure 7.4) were created from interviews with electronics recyclers and literature information. For the Main Recycling System and its subsystems, the method for estimating the component value or material value is described. The components that are manually dismantled are represented with a component value V_c if they are not a homogeneous or single material (

Figure 8.1). If the materials are mono materials or are mechanically recycled, they are represented with a material value V_m (

Figure 8.1).

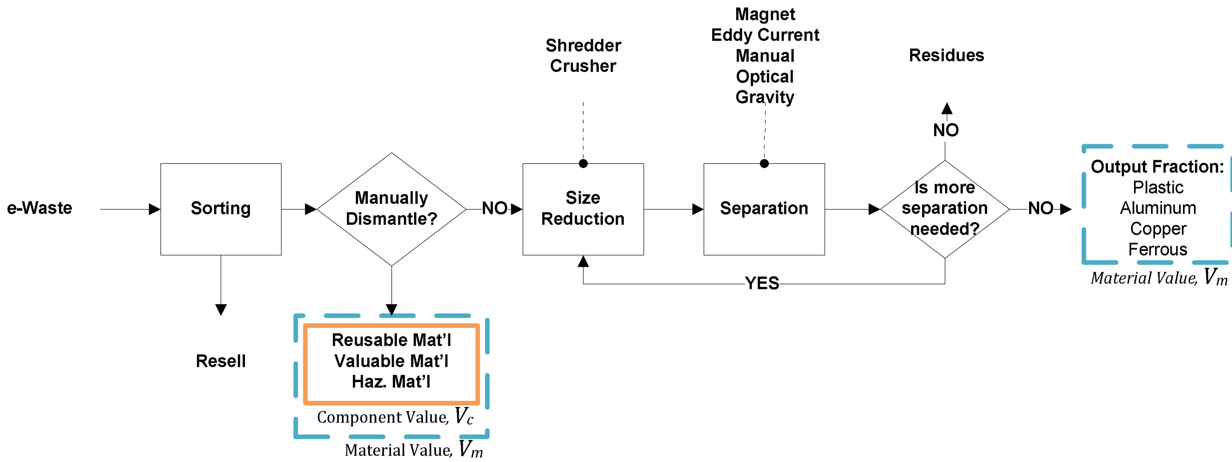


Figure 8.1: Describing the Value of Reuse and Recycling in the Main Recycling System.

Disk drives, memory, and processors from laptop computer and desktop computer computers are reusable components that are manually dismantled (Chapter 7). These reusable components are represented with a component value $V_{c.}$ (Figure 8.2).

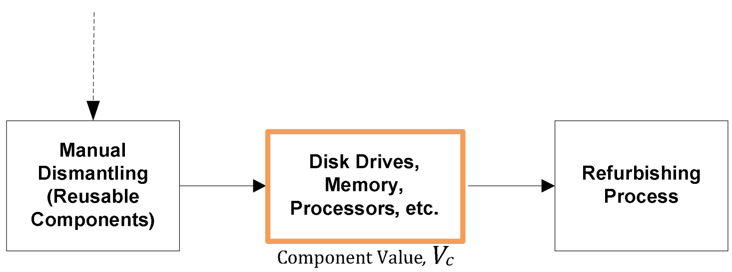


Figure 8.2: Describing the Value of Reusable Material.

Materials that are valuable are manually dismantled and go to a pure or single material recycling stream (Chapter 7). They are represented with a material value, V_m. (Figure 8.3). Printed circuit boards are manually dismantled and go to precious metal refining and smelting processes (Chapter 7). If they are valuable, they are represented with a component value $V_{c.}$ (Figure 8.3).

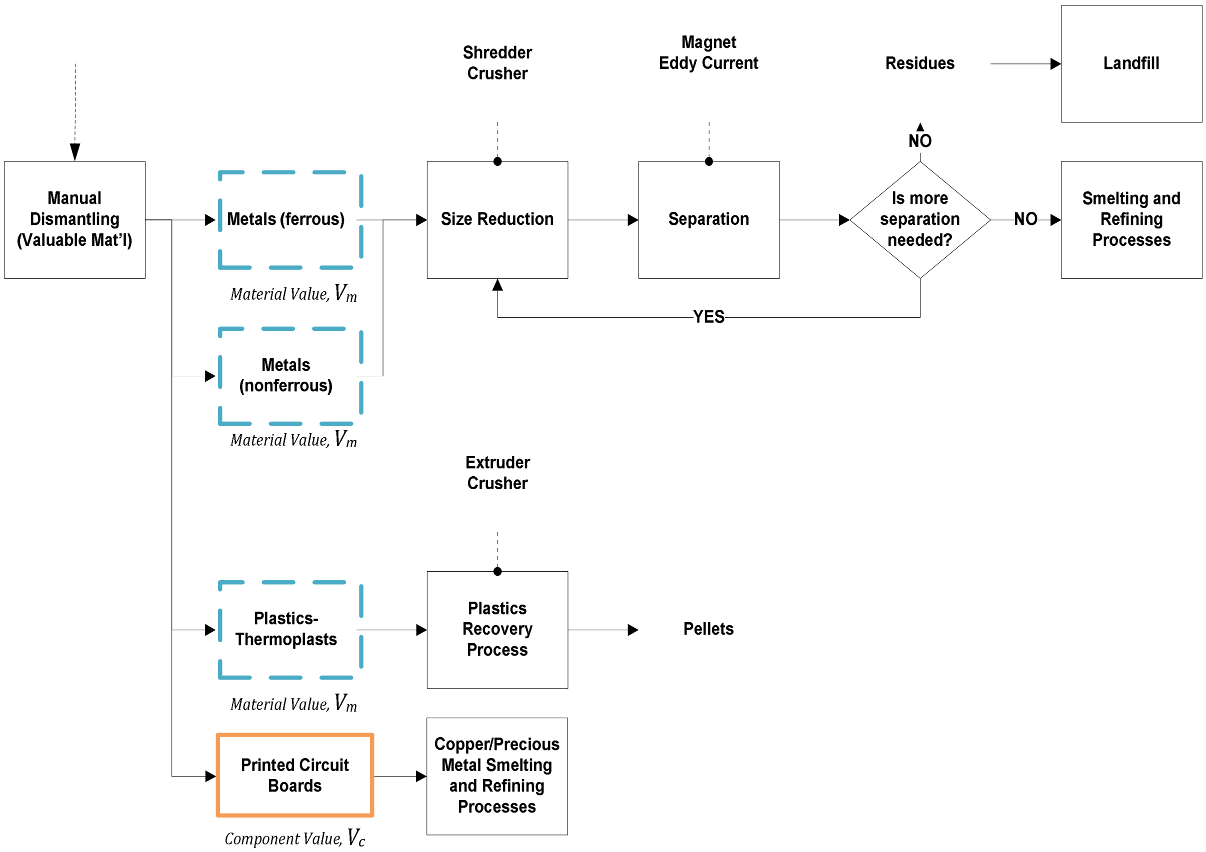


Figure 8.3: Describing the Value of dismantling Valuable Material.

Hazardous materials are manually dismantled and go to their designated recovery processes (Chapter 7). Materials or components that are classified as hazardous material by the Waste Electric and Electronic Equipment Protocol (WEEE) or other legislation, such as batteries, PCBs, and LCDs, are represented with a component value V_c (Figure 8.4). Plastics containing BFRs are represented with a material value, V_m (Figure 8.4).

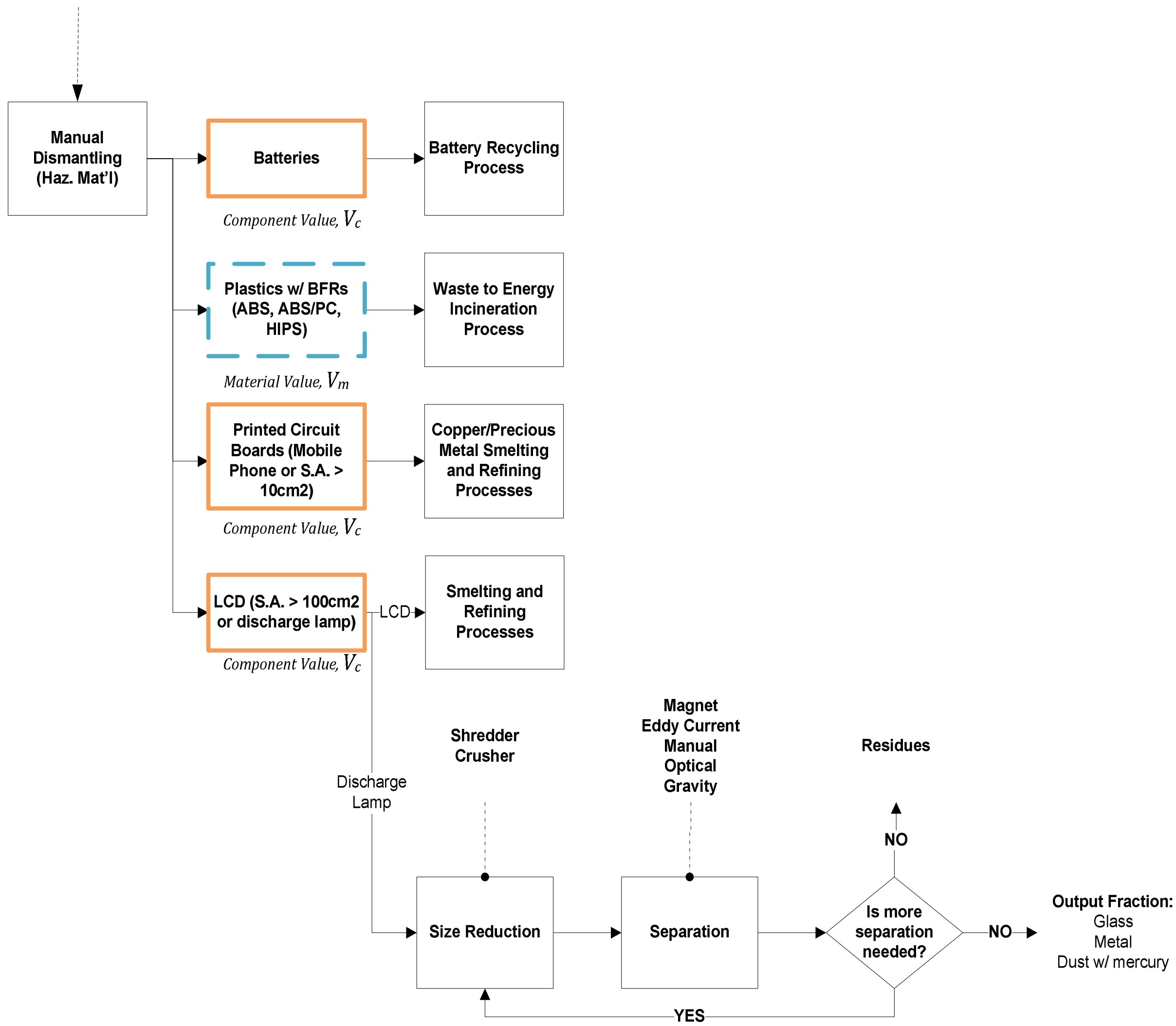


Figure 8.4: Describing the value of dismantling hazardous materials.

Ferrous and nonferrous metals, thermosetting plastics, cables, LCDs, and PCBs are sent through mechanical recycling for size reduction, sorting, and material recovery (Chapter 7). The materials that are not manually dismantled, because they are not reusable, valuable, or hazardous, are represented by their material value V_m. (Figure 8.5).

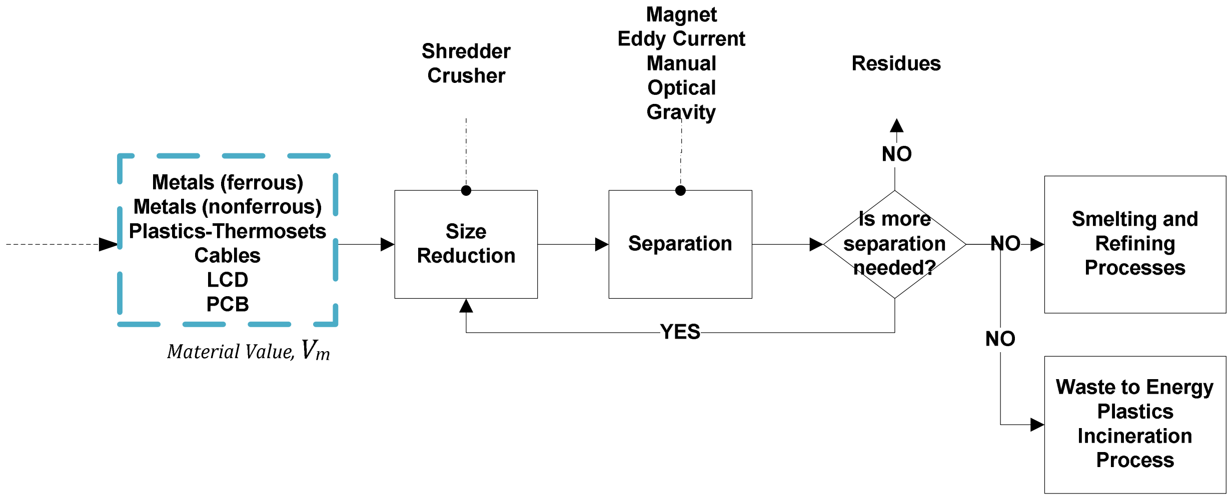


Figure 8.5: Describing the value of mechanical recycling.

To describe the material and component values of the materials in cellular phones, bulk recycling values are used (Table 8.3). The majority of the material and component values are derived from Recycle NET (http://www.recycle.net). The material values for gold, silver, and palladium found in PCBs, are derived from Metallix Direct Gold's (http://www.metallixdirectgold.com) gold, silver, and palladium calculators. To capture the value of sending plastics to a waste to energy incineration process, plastics are assigned an energy value of 17,900 BTU/lb of plastic, which is approximately 5.24 kWh/lb of plastic (SPI, 2009). With the average cost of electricity in the U.S. at $0.10 (EIA, 2011), the value of recovering a pound of plastic is approximately $0.52. To represent the value of cables, the material composition of a cable is multiplied by the value of the materials found in a cable (Table 8.4).

To represent the value of PCBs, the material composition of a PCB is multiplied by the value of the materials found in a PCB (Table 8.5). The material composition of a PCB is represented as the average of the output fraction of pre-shredded printed circuit boards less than 8 mm on each side and shredded printed circuit boards less than 2.5 mm on each side (Chancerel & Rotter, 2009). To represent the value of LCDs, the material composition of a LCD is multiplied by the value of the materials found in a LCD (Table 8.6). These values are evaluated in the sensitivity analysis.

Table 8.3: Material and Component Values for Cellular Phones.

Components/Materials	End-of-Life Disposal Process	Component or Material Value ($/lb)		Value Source(s)
Batteries (NiMH)	Disassembly, Recycling	$	0.46	http://www.recycle.net
Batteries (LiIon)	Disassembly, Recycling	$	1.50	http://www.recycle.net
Metals (Ferrous)	Disassembly, Recycling, Smelting/Steel Refining	$	0.10	http://www.recycle.net
Metals (Nonferrous-Al)	Disassembly, Recycling, Smelting/Al Refining	$	0.00	http://www.recycle.net
Metals (Nonferrous-Cu)	Disassembly, Recycling, Smelting/Al Refining	$	1.05	http://www.recycle.net
Plastics (BFRs: ABS, ABS/PC, HIPS)	Disassembly, Incineration	$	0.52	EIA (2011), SPI (2009)
Plastics (Disass)-Thermoplasts (ABS, PC, HIPS, PS, PET)	Disassembly, Plastics Recovery/Extruder, Injection Molding			
	ABS	$	0.12	http://www.recycle.net
	PC	$	0.65	http://www.recycle.net
	ABS/PC also unlabelled plastic	$	0.09	http://www.recycle.net
	HIPS	$	0.29	http://www.recycle.net
	PS	$	0.21	http://www.recycle.net
	PET	$	0.18	http://www.recycle.net
Plastics (Mech)-Thermosets, Foam, Rubber	Recycling, Incineration	$	0.52	EIA (2011), SPI (2009)
Cables (Plastic)	Recycling, Incineration	$	0.49	Atlee (2005), EIA (2011), SPI (2009)
Cables (Steel, Cu, Al)	Recycling, Smelting/Refining	included above		http://www.recycle.net, Atlee (2005)
Printed Circuit Boards (Mobile Phone or S.A. > 10cm)	Disassembly, Copper/Precious Metal Smelting/Refining	$	2.43	http://www.recycle.net
Printed Circuit Boards	Disassembly, Recycling, Copper/Precious Metal Smelting/Refining	$	1.72	http://www.metallixrefining.com, Chancerel and Rotter (2009), Atlee (2005), Hageluken (2006), Norgate (2004)
Drives, Memory, Processors	Reuse			
	Hard Drive ($/Unit)	$	4.00	http://www.recycle.net
	DVD Drive ($/Unit)	$	2.50	http://www.recycle.net

Components/Materials	End-of-Life Disposal Process	Component or Material Value ($/lb)	Value Source(s)
	CD Drive ($/Unit)	$ 4.50	http://www.recycle.net
	Floppy Drive ($/Unit)	$ 2.50	http://www.recycle.net
LCD (S.A. > 100cm or discharge lamp)	Disassembly, LCD Smelting/Refining, Shredding/Separate Discharge Lamp and remove mercury dust	$ 3.75	http://www.recycle.net
LCD	Recycling, Smelting/Refining	$ 1.06	http://www.recycle.net, Brady (2003), Martin (2008), Li (2009)
Glass	Recycling	$ 0.75	http://www.recycle.net, Brady (2003), Martin (2008), Li (2009)
LED	Recycling	$ 0.10	http://www.recycle.net, Brady (2003), Martin (2008), Li (2009)

Table 8.4: Material Composition and Value of Cables.

	Material in Cables	lb Material	$/lb Material	$/lb Cable	Source(s)
Cables (plastic)	Plastic (with waste to energy incineration)	0.38	$ 0.52	$ 0.20	Atlee (2005), EIA (2011), SPI (2009)
Cables (metal)	Steel	0.04	$ 0.10	$ 0.00	Atlee (2005), http://www.recycle.net
	Cu	0.27	$ 1.05	$ 0.28	Atlee (2005), http://www.recycle.net
	Al	0.27	$ 0.00	$ 0.00	Atlee (2005), http://www.recycle.net
Other	Other	0.04	$ -	$ -	
			Total	$ 0.49	

Table 8.5: Material Composition and Value of Printed Circuit Boards (PCBs).

Material in PCB	$/lb Material	lb material/ lb PCB	$/lb PCB	Source(s)
Silver	$ 393.65	0.0005	$ 0.21	Chancerel and Rotter (2009), http://www.metallixdirectgold.com
Gold	$ 10,236.84	0.0001	$ 1.05	Chancerel and Rotter (2009), http://www.metallixdirectgold.com
Palladium	$ 7,512.02	0.00003	$ 0.25	Chancerel and Rotter (2009), http://www.metallixdirectgold.com
Copper	$ 1.05	0.183	$ 0.19	Atlee (2005), Hageluken (2006), Norgate (2004), http://www.recycle.net
Thermoset Plastic	$ 0.10	0.265	$ 0.03	Atlee (2005), Hageluken (2006), http://www.recycle.net
Other	$ -	0.551	$ -	
		Total	$ 1.72	

Table 8.6: Material Composition and Value of Liquid Crystal Displays (LCDs).

Material in LCD	lb material	$/lb LCD	Source(s)
PC	0.09	$ 0.09	http://www.recycle.net, Brady (2003), Martin (2008), Li (2009)
PMMA, Plexiglass	0.09	$ 0.10	http://www.recycle.net, Brady (2003), Li (2009)
PET	0.09	$ 0.18	http://www.recycle.net, Li (2009)
PCB	0.09	$ 2.50	http://www.recycle.net, Li (2009)
CFFL	0.01	$ -	http://www.recycle.net, Martin (2008), Li (2009)
LED	0.01	$ 0.10	http://www.recycle.net, Martin (2008), Li (2009)
Glass	0.45	$ 0.75	http://www.recycle.net, Brady (2003), Martin (2008), Li (2009)
Indium tin oxide	0.10	$ 5.00	http://www.recycle.net, Martin (2008), Li (2009)
Liquid crystals	0.10	$ -	Martin (2008), Li (2009)
	Total	$ 1.06	

8.3 Discussion

In this method, selecting the end-of-life disposition separation processes for materials or components in a product is dependent on value, reusability, and hazardous materials. To determine if a material or component will be manually dismantled based on their values, the MRR and VRR are calculated. To calculate the MRR and VRR, the disassembly time and material or component value must be estimated. The impact of estimating disassembly time and value on the selection of end-of-life disposition separation processes is investigated in the sensitivity analysis. A component will be manually dismantled based on its reusability. The component is reusable if it is functioning independently of the product's ability to function, such as disk drives, hard drives, memory, and processors. A material or component will be manually dismantled if they are hazardous. They are hazardous if WEEE or other legislation classifies them as hazardous material. With the material or component type, and the end-of-life disposition separation process, the end-of-life disposition of the material or component is modeled and the environmental impact is calculated.

Chapter 9

THE ENVIRONMENTAL IMPACT OF THE END-OF-LIFE DISPOSITION

To describe the environmental impact of the end-of-life disposition of consumer electronics a life cycle approach is used. Life cycle assessment is used to determine the environmental impact of a product or service from material extraction through product end-of-life disposition. ISO14040-44 (2006) defines life cycle assessment in four stages: (1) Goal and Scope, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation. This method defines the proposed life cycle approach accordingly.

9.1 Goal and Scope

A single or one phase life cycle assessment is used to focus on the environmental impact of the end-of-life disposition of a single consumer electronic product. The environmental impact of end-of-life disposition is calculated using the avoided burden recycling method. The avoided burden recycling method evaluates the sum of the impacts from end-of-life disposition processes, such as sorting, manual dismantling, mechanical recycling, and waste, and subtracts the benefits of avoiding the production of primary materials (A. L. Nicholson et al., 2009). It does not include the environmental burdens of manufacturing, distribution, or use (Figure 9.1). As a starting point, the model assumes the following recovery rates: (1) 100% of primary materials production environmental impact is avoided through reuse, (2) 55% of primary materials production environmental impact is avoided through recycling, refining, and recovery, and (3) 5% of electricity production is avoided through waste to energy (WtE) incineration. It also assumes that the reuse and recycling processes cannot recover 10% of materials, which are sent to the landfill. The impact of the recovery rate is investigated in the sensitivity analysis, explained in more detail in Chapter 13. The percentage of materials that cannot be recovered with reuse or recycling or process loss will also be investigated in the sensitivity analysis in Chapter 13.

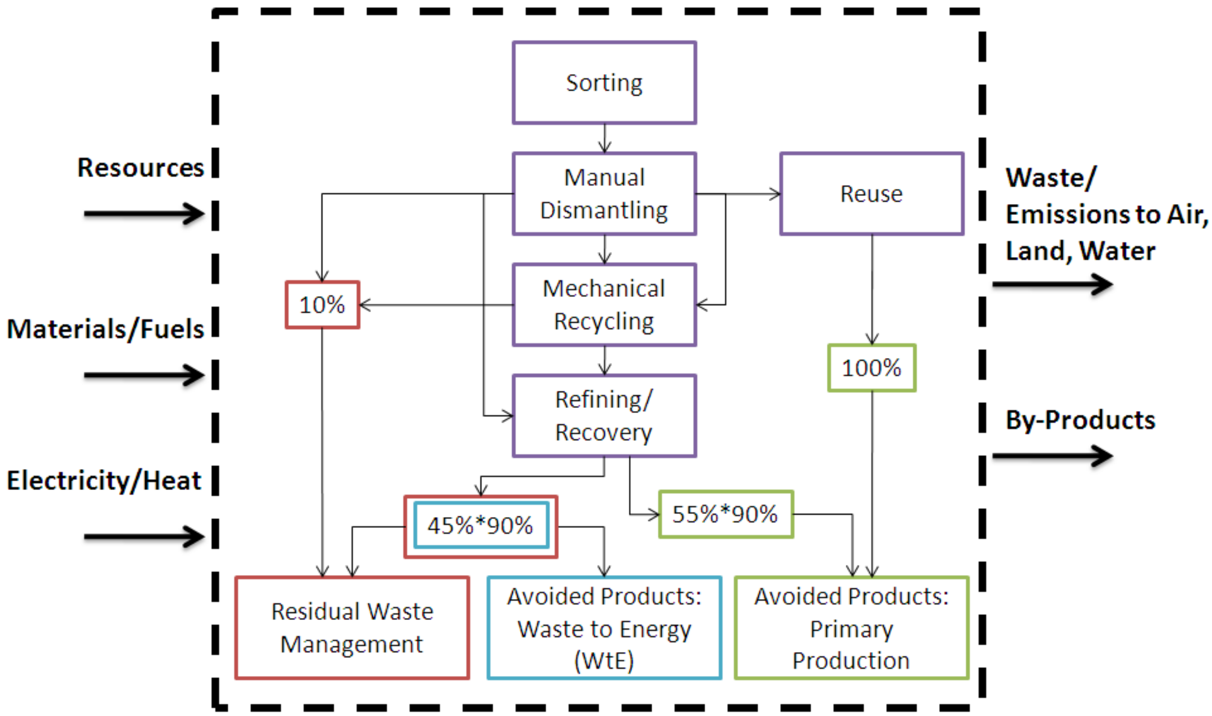


Figure 9.1: System Boundary of End-of-life Disposition

9.2 Inventory Analysis

Teardowns of cellular phones provide the material composition data for the consumer electronics at end-of-life disposition. Teardowns and data collection are described in more detail in Chapter 11. Primary life cycle inventory data for the materials and end-of-life disposition processes is not available, so secondary data from the ecoinvent v2.2 database (www.ecoinvent.org) is used (Table 9.1 and Table 9.2). At the time of this research, the ecoinvent v2.2 database has the largest amount of current electronic device data that is accessible to the researcher. If needed inventory data for materials or processes is not available in the ecoinvent v2.2 database, data from another source, such as IDEMAT (www.idemat.nl) is used (Table 9.1 and Table 9.2).

Table 9.1: Consumer Electronics Components and Materials and their ecoinvent Inventory Data

Components/Materials	ecoinvent v2.0 Materials/Processes
Batteries (NiMH)	Battery, NiMH, rechargeable, prismatic, at plant/GLO U
Batteries (LiIon)	Battery, LiIo, rechargeable, prismatic, at plant/GLO U
Metals (Ferrous)	Steel, electric, un- and low-alloyed, at plant/RER U
Metals (Nonferrous-Al)*	Aluminium, secondary, from old scrap, at plant/RER U
Metals (Nonferrous-Cu)*	Copper, secondary, from electronic and electric scrap recycling, at refinery/SE U
Plastics-Thermoplastics	
ABS	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER U
PC	Polycarbonate, at plant/RER U
ABS/PC	50%*Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER U+50%*Polycarbonate, at plant/RER U
PA-20GF	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U
PC-20GF (IDEMAT Database)	Modified PC 30% glass fibre I to 80% PC I and 20% Glass fibre I
Unlabeled Plastic	Polystyrene, high impact, HIPS, at plant/RER U
Plastics-Thermosets, Foam, Rubber	
Foam	Polyurethane, flexible foam, at plant/RER U
Rubber	Synthetic rubber, at plant/RER U
Cables (Steel, Cu, Al)	Copper, secondary, from electronic and electric scrap recycling, at refinery/SE U
Printed Circuit Boards- Surface Mounted Technology (SMT)	Printed wiring board, surface mounted, unspec., Pb free, at plant/GLO U
Printed Circuit Boards- Through Hole Technology (THT)	Printed wiring board, through-hole mounted, unspec., Pb free, at plant/GLO U
LCD	LCD module, at plant/kg/GLO U
Glass	LCD glass, at plant/GLO U

Table 9.2: Consumer Electronics End-of-Life Disposition Processes and their ecoinvent v2.0 Inventory Data.

End-of-Life Disposition Processes	ecoinvent v2.0 Waste Treatments
General Sorting and Manual Dismantling	Manual treatment plant, WEEE scrap = 2500 tonne/yr for 25 yr= 62.5 M kg
General Mechanical Dismantling	Dismantling, shredder fraction from manual dismantling, mechanically, at plant/GLO U
Metals, Manually Dismantling	Manual treatment plant, WEEE scrap = 2500 tonne/yr for 25 yr= 62.5 M kg Dismantling, shredder fraction from manual dismantling, mechanically, at plant/GLO U
LCD, Manually Dismantling and Refining/Recovery	Disposal, LCD module, to municipal waste incineration/CH U with 0% WtE
LCD, Mechanically Dismantling and Refining/Recovery	Electricity, medium voltage, production UCTE, at grid/UTCE U Mechanical treatment plant, WEEE scrap/GLO/IU =50,000 tonne/yr for 25 yr = 12.5B kg Disposal, LCD module, to municipal waste incineration/CH U with 0% WtE
Plastics- Thermosets (rubbers, foam, etc.), Mechanically Dismantling and Incineration	Electricity, medium voltage, production UCTE, at grid/UTCE U Mechanical treatment plant, WEEE scrap/GLO/IU =50,000 tonne/yr for 25 yr = 12.5B kg Disposal, plastic, industr. electronics, 15.3% water, to municipal incineration/CH U with 0% WtE
Li-ion Battery (WEEE), Manually Dismantling and Refining/Recovery	Disposal, Li-ions batteries, mixed technology/GLO U (Hischier and Gallen (2007))
NiMH Battery (WEEE), Manually Dismantling and Refining/Recovery	Disposal, NiMH batteries/GLO U (Hischier and Gallen (2007))
PCB (WEEE), Manually Dismantling and Refining/Recovery	Disposal, treatment of printed wiring boards/GLO U
Copper, Refining/Recovery	Included in Copper, secondary, from electronic and electric scrap recycling, at refinery/SE U (Classen, et al (2009))
Nonferrous Metals, Refining/Recovery	Included in Aluminium, secondary, from old scrap, at plant/RER U (Classen, et al (2009))
Ferrous Metals, Refining/Recovery	Included in Steel, electric, un- and low-alloyed, at plant/RER U (Classen, et al (2009))
Plastics Recovery- Thermoplasts: Manual Dismantling Extruder Pelletizer	Manual treatment plant, WEEE scrap = 2500 tonne/yr for 25 yr= 62.5 M kg Extrusion, plastic film/RER U 0.038 kWh/kg plastic Electricity, medium voltage, production UCTE, at grid/RER U (Hischier and Gallen (2007))

End-of-Life Disposition Processes	ecoinvent v2.0 Waste Treatments
Plastics Incineration- waste to energy-WtE (WEEE- plastics with BFRs)	Disposal, plastic, industr. electronics, 15.3% water, to municipal incineration/CH U with 5% Electricity, medium voltage, production UCTE, at grid/RER U avoided electricity (Net energy produced in MSWI: 4MJ/kg waste electric energy) Interview with Gabor Doka, Author of ecoinvent datasets on incineration (May 2, 2011)
Residual Waste Management	Landfill/CH U

9.3 Impact Assessment

The SimaPro life cycle assessment software package (PRe, 2008) is used to conduct the life cycle impact assessment. The ReCipe endpoint life cycle impact assessment method is used to quantify the environmental impacts, because it has the ability to aggregate the impact of human health, ecosystems, and resource availability into a single environmental impact score. The single environmental impact score enables the design characteristics to be related to an inclusive environmental impact using linear regression, explained in more detail in Chapter 10. The ReCipe endpoint method has three versions of normalization and weighting set combinations: egalitarian, hierarchist, or individualist. They each have two normalization geographies: Europe or World and two weighting set types: average or perspective (egalitarian, hierarchist, or individualist). The European normalization geography normalizes the damage (human health, ecosystems, and resource availability) environmental impact to the environmental impact of the European population and the World normalization geography normalizes the damage environmental impact to the environmental impact of the World population. The egalitarian perspective applies the precautionary principle and all possible relationships with environmental impact are included for a long-term period. The hierarchist perspective includes those relationships widely accepted by the LCA community to describe environmental impact. The individualist perspective includes only proven cause-effect relationships to describe environmental impact in a short-term period. The default method is hierarchist with a European normalization and an average weighting set. For this method, the baseline impact assessment uses the hierarchist perspective with a world normalization and an average weighting set. The impact of using the other combinations: (1) the egalitarian version with a world normalization and an average weighting set or (2) the individualist version with a world normalization and an average weighting set is evaluated in the sensitivity analysis.

9.4 Interpretation

The 34 cellular phones in the study were each evaluated for their environmental impact with a one-phase end-of-life disposition LCA. The output is described in terms of eco-indicator points. One eco-indicator point describes one one-thousandth of the impact of a world resident. First, the results of the damage assessment (human health, ecosystems, and resource availability) are normalized to the world's environmental impact per capita. Then the normalized scores are weighted with weightings of 400 times human health, 400 times ecosystems, and 200 times resource availability. Finally, the weighted scores are aggregated into a single score. The single score describes the aggregated eco-indicator points divided by 1000 or one eco-indicator point describes one one-thousandth of the impact of a world resident (Goedkoop et al., 2009).

The components that make up the cellular phone, such as the battery, printed circuit boards, and display, are also evaluated for environmental impact. For all cellular phones, including smart phones, the battery and printed circuit boards provided the greatest benefit when recycled (Figure 9.2 and Figure 9.3). This validates the WEEE protocol, which requires the removal of the batteries and printed circuit boards.

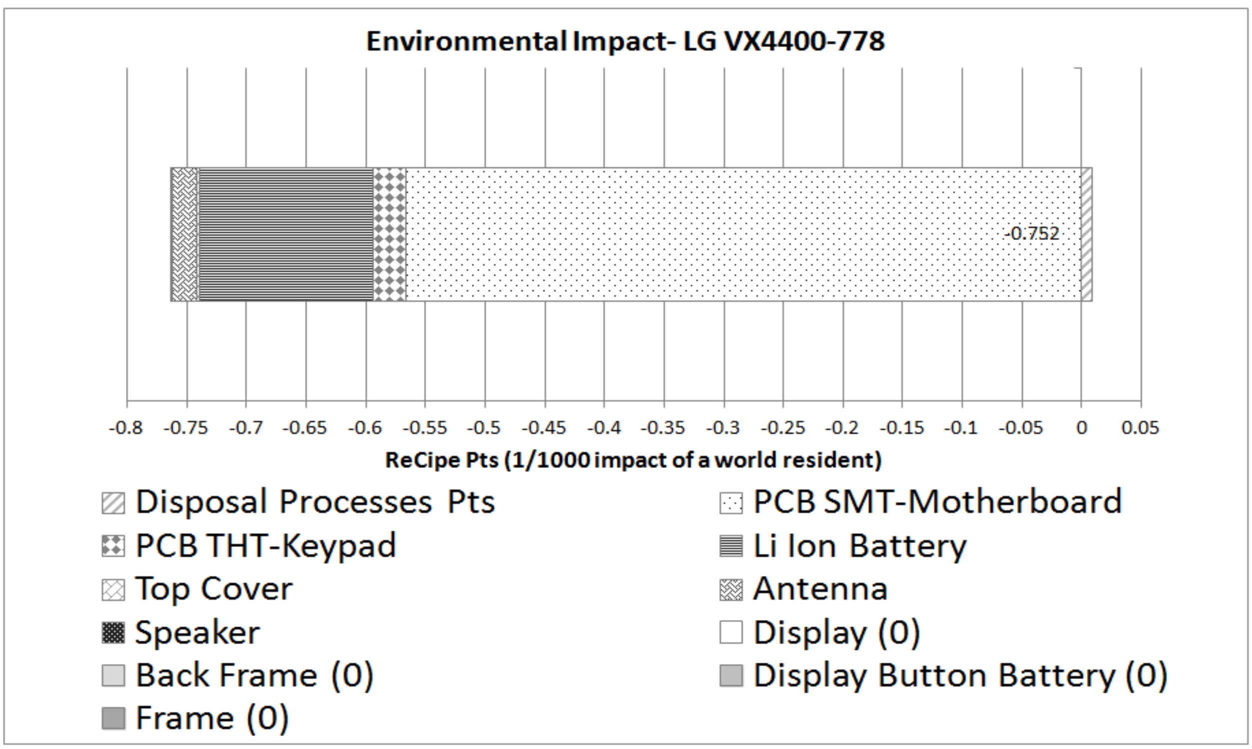


Figure 9.2: The one-phase end-of-life disposition environmental impact of the LG VX4400-778.

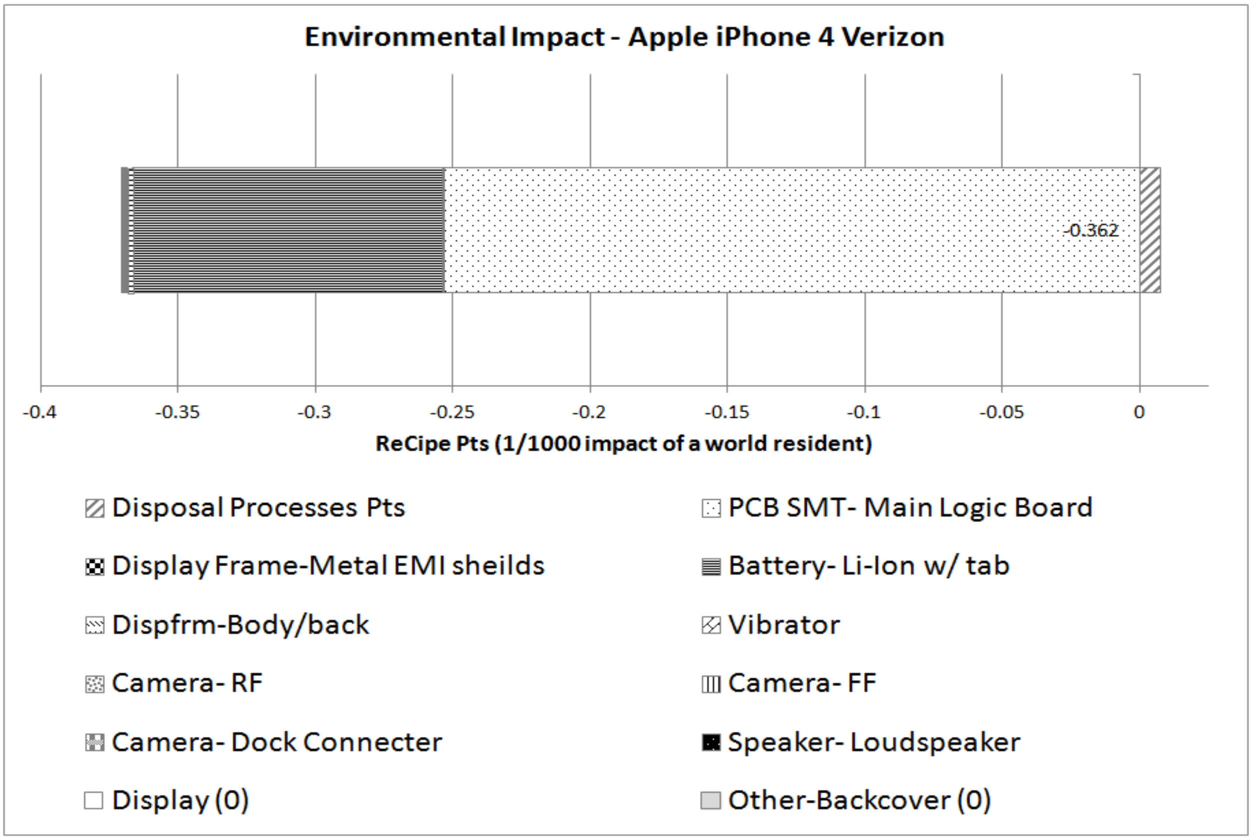


Figure 9.3: The one-phase end-of-life disposition environmental impact of the Apple iPhone 4 Verizon.

The IMPACT 2002+ damage oriented life cycle impact assessment method was used to test the sensitivity of the selection of ReCipe as the primary life cycle impact assessment method. Similar to the ReCipe method the battery and the PCB had the highest environmental benefit when recycled (Figure 9.4 and Figure 9.5). For the IMPACT 2002+ method, the battery's benefit was 10% more than that of the ReCipe method and the PCB's benefit was 10% less. This can be attributed to the difference in characterization factors between the methods.

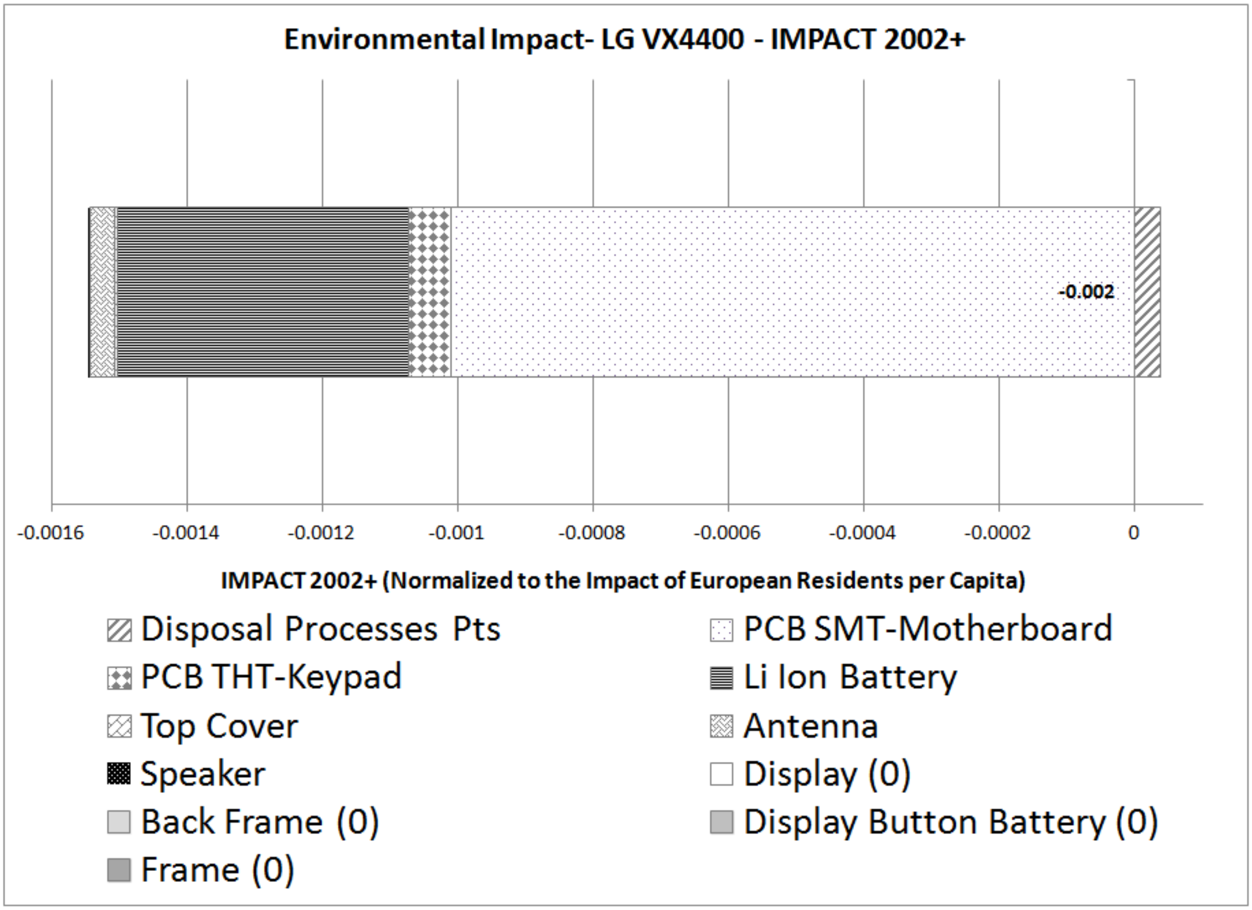


Figure 9.4: The one-phase end-of-life disposition environmental impact of the LG VX4400-778 with IMPACT 2002+.

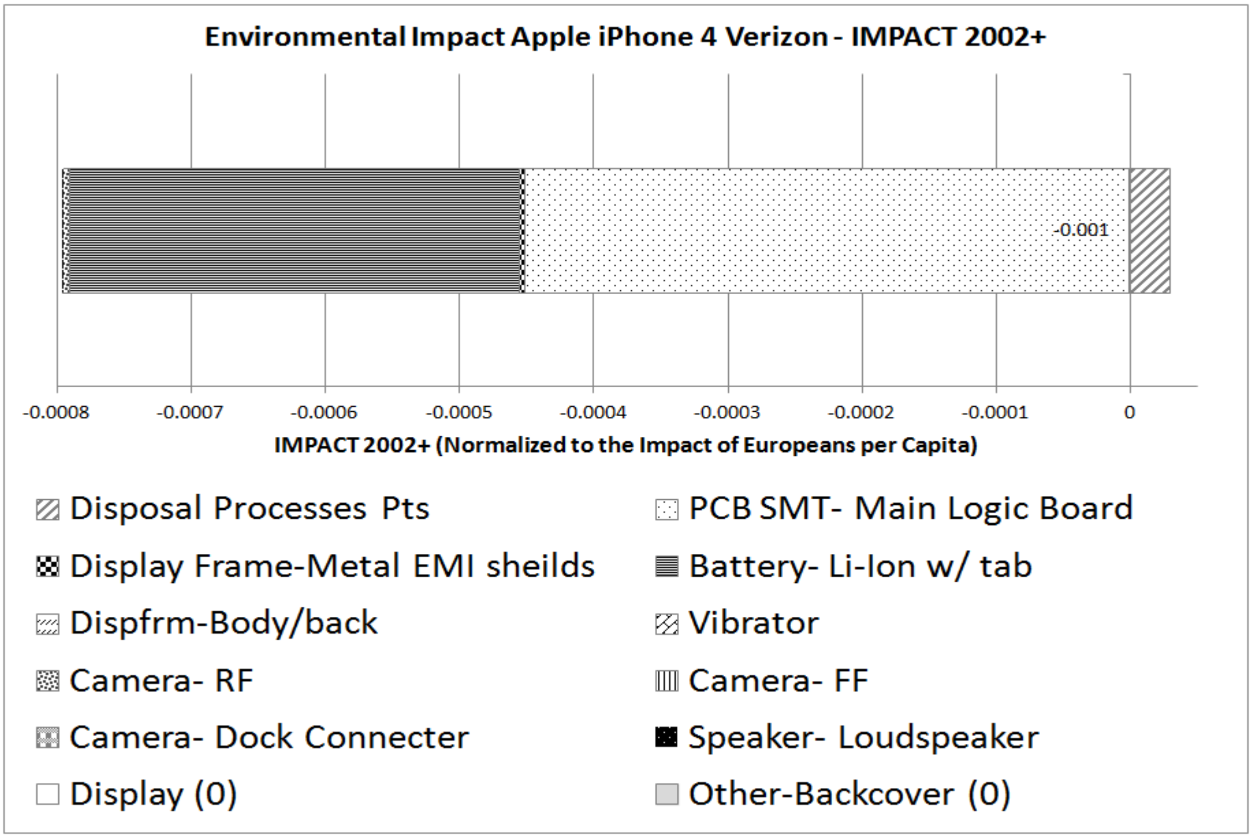


Figure 9.5: The one-phase end-of-life disposition environmental impact of the Apple iPhone 4 Verizon with IMPACT 2002+.

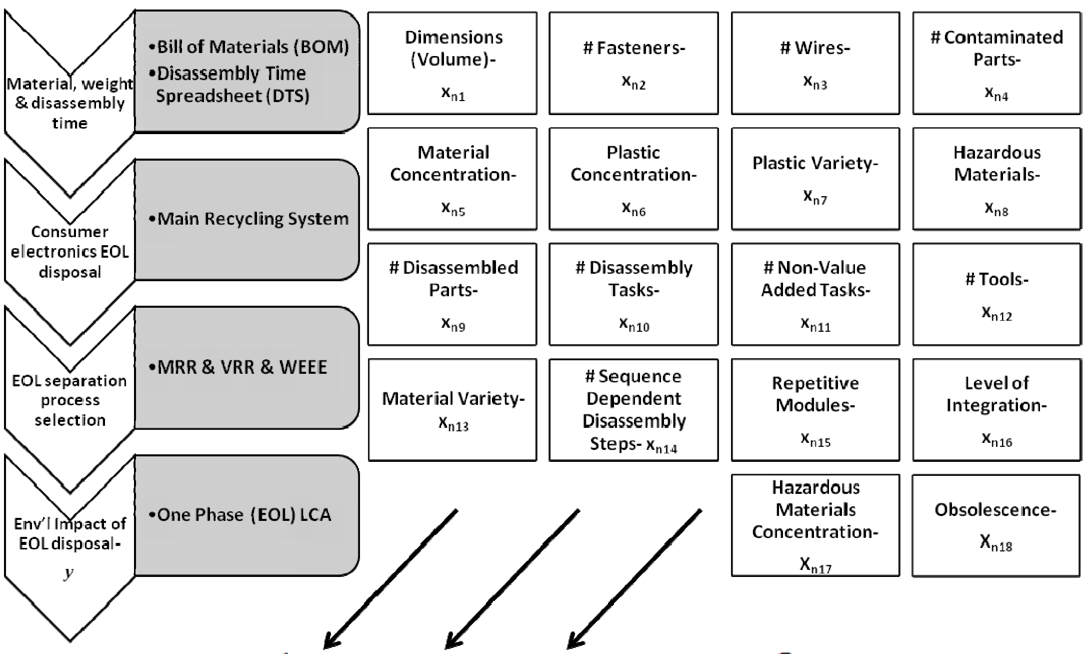
9.5 Discussion

The results of the one-phase end-of-life disposition LCA describe the environmental impact of end-of-life disposition of cellular phones. These results are used to examine potential relationships between end-of-life disposition environmental impact and design characteristics. For both the ReCipe and IMPACT 2002+ life cycle Assessment methods, the results of the LCA rely heavily on the battery and the printed circuit board, because the benefit of their recovery overshadows the benefits of the other components. Since these components are manually removed at end-of-life disposition in accordance with the WEEE regulation, other design characteristics do not have an effect on the end-of-life environmental impact of the battery and printed circuit boards. Therefore, design characteristics may not have a significant effect on the end-of-life environmental impact of the cellular phone as a whole.

Chapter 10

DETERMINING A RELATIONSHIP WITH DESIGN CHARACTERISTICS AND THE ENVIRONMENTAL IMPACT OF END-OF-LIFE DISPOSITION

To determine if there is a relationship between design characteristics and the environmental impact of the end-of-life disposition of cellular phones linear regression analysis is used (Figure 10.1).



$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \end{pmatrix} = \begin{pmatrix} 1 & x_{11} & \cdots & x_{1k} \\ 1 & x_{21} & \cdots & x_{2k} \\ 1 & \vdots & \ddots & \vdots \\ 1 & x_{n1} & \cdots & x_{nk} \end{pmatrix} \begin{pmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{pmatrix} + \begin{pmatrix} \varepsilon_0 \\ \varepsilon_1 \\ \vdots \\ \varepsilon_k \end{pmatrix}$$

$$y = X\beta + \varepsilon$$

Figure 10.1: Determining a Relationship between Design Characteristics and End-of-Life Disposition Environmental Impact with Linear Regression Analysis.

Linear regression analysis has the ability to determine significance, relative importance, correlation, and interaction effects. It is a mature, flexible tool widely used in engineering,

especially in the manufacturing industry and Six Sigma process optimization methods. Previously, linear regression analysis was partially used by Rose (2001) to build a hierarchical decision tree for determining the appropriate end-of-life disposition of electronics. In this method, linear regression analysis is used to determine the following:

(1) Is there a relationship between design characteristics and the environmental impact of end-of-life disposition?;

(2) If there is a relationship, which design characteristics are significant?;

(3) Do interactions exist between the design characteristics?; and

(4) What is the relative importance of the significant design characteristics to the environmental impact of end-of-life disposition? i.e. what combination of design characteristics and their interactions explain the end-of-life disposition environmental impact the best?

To answer these questions, the following process is proposed:

(1) Create a Base Regression Model.

Create a base regression model relating the design characteristic values or regressors and the end-of-life disposition environmental impacts or responses of 36 phones. To distinguish between smart and non-smart phone, an indicator variable, *IND1,* is created. When *IND1* equals 0, the phone is categorized as a smart phone.

(2) Test the Least Squares Assumptions of the Regression Model.

Residual plots will be used to test the goodness of fit of linear regression models and test the least squares assumptions (Figure 10.2). If the points form a straight line in the normal probability plot, then the normality assumption is valid. If the points have a random pattern on both sides of the residual in the residuals vs. fits plot, then the constant variance assumption is valid. If the points form a normal distribution without a long tail or segregated bars in the histogram of the residuals, then the model is valid. Since the order that the data was collected is unknown, the residuals versus order plot is not valid for this analysis.

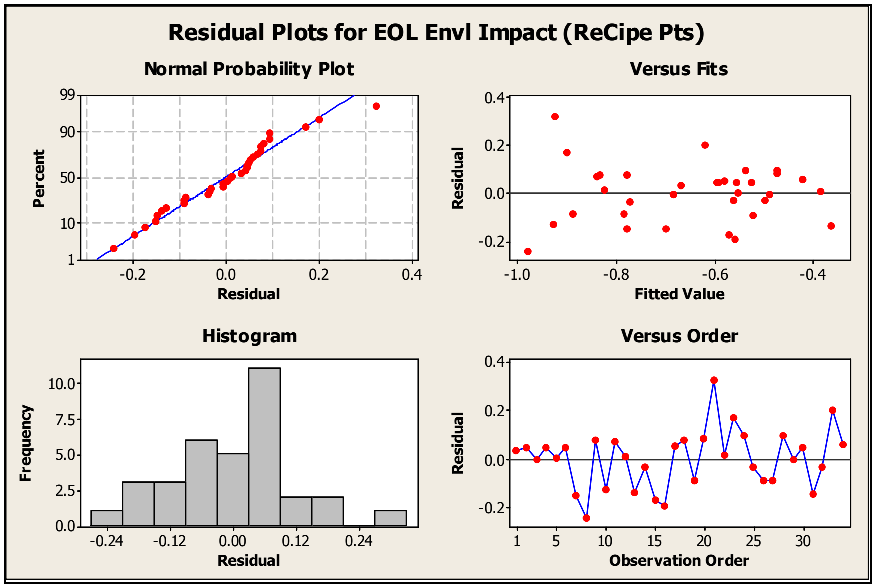


Figure 10.2: Example of residual plots.

(3) Test the Significance of the Regression Model.

To test the significance of the regression model, the F-test is used. Tests are conducted at the $\alpha = 0.05$ level of significance.

(4) Test the Significance of the Model Variables.

If the regression model is significant, the T-test is used to test the significance of the model variables. If the coefficients of the variables have a p-value less than 0.05, the variables are significant.

(5) Simplify the Model.

If the regression model is not significant, the model is simplified using the Best Subsets method.

(6) Select the Best-Simplified Model.

The Best Subsets method describes all possible combinations of simplified regression models in order of least to greatest number of variables. To compare 1, 2, 3, and 4 variable models the following analysis is conducted:

a. The least squares assumptions of the simplified models will be tested using residual plots.

b. Compare the ANOVA results, including number of variables, SSE, R^2, F-test, and T-test, and Aitkin's (1974) R^2 adequate of the simplified models.

The sum of square error (SSE) and R^2 describe the ability of the model to explain the behavior of the system. The F-test determines if the model is statistically significant. The T-test determines the significance of the regression coefficients. The R^2 adequate (Equation 10.1) determines the minimum R^2 value that the best simplified model needs to adequately represent the system.

$$R^2 adequate = 1 - (1 - R^2_{K+1})\left(1 + \frac{KF_{\alpha,K,n-K-1}}{n-K-1}\right) \quad (10.1)$$

c. The simplified model with the minimum number of variables whose R^2 is greater than the R^2 adequate for the full model will be selected as the best model.

(7) Validate the Best-Simplified Models

To validate the Best-Simplified Models the sign of the coefficients will be compared to the correlation between the design characteristics and the end-of-life disposition environmental impact, described in more detail in Chapter 12, and the variables will be checked for potential interactions with each other. From reviewing the literature, most of the design characteristics have a positive correlation with the end-of-life disposition environmental impact (Table 10.1). Interactions exist between certain design characteristics, such as product dimensions and obsolescence, because cellular phones have been reduced in size over time (Table 10.1). To hypothesize the outcome of the model, design characteristics are described, their correlation with end-of-life disposition environmental impact is predicted, and their potential interactions with other design characteristics metrics are proposed (Table 10.1).

Table 10.1: Design Characteristic and Environmental Impact of End-of-Life Disposition Hypotheses.

Design Characteristic Metric	Description/Formula	Predicted Correlation with End-of-Life Disposition Environmental Impact	Potential Interactions between Design Characteristics
Product Dimensions			
Volume of a rectangular prism.	Volume (in^3) = length (l) x width (w) x height (h) .	Positive (contributes negatively to avoided burden)	-Plastics concentration -Obsolescence -Materials concentration
Fasteners, Tools, Wires, Contaminated Parts			
Number of fasteners	The number of fasteners in the product.	Positive	-Number of tools -Number of sequence dependent disassembly steps
Number of tools	The number of tools needed for disassembly.	Positive	-Number of disassembly tasks -Number of fasteners -Parts with adhesives, labels, or paint
Number of wires	The number of wires in the product.	Positive	-Number of disassembly Tasks -Number of non-value added tasks -Repetitive components
Parts with adhesives, labels, or paint	The number of parts with adhesives, labels, or paint in the product.	Positive	-Number of tools
Material Concentration			
Material Mixing	$H = c_{j_i} log c_{j_i}$, where $c_{j_i} = \frac{m_{j_i}}{m_j}$ $\forall\, materials, i, in\ product, j$	Positive	-Plastics concentration -Variety of materials
Plastics Concentration			
Mass percentage of plastics	$\sum_1^i \frac{mp_{j_i}}{mp_j}, where\ mp_{j_i} =$ $weight\ of\ plastic, i$ $\forall\, plastics, i\ in\ product, j$	Positive	-Material concentration -Variety of materials -Product dimensions
Variety of plastics	The number of different plastic materials in the product.	Positive	-Materials concentration -Plastics concentration -Variety of materials

Design Characteristic Metric	Description/Formula	Predicted Correlation with End-of-Life Disposition Environmental Impact	Potential Interactions between Design Characteristics
Hazardous Materials			
Refer to Annex II of WEEE	Look up components in the table of components containing hazardous materials.	Positive	-Obsolescence
Percentage of hazardous materials in a product	$\sum_{1}^{i} \frac{mhp_{j_i}}{mhp_j}$, where mph_{j_i} = weight of part with hazardous material, i $\forall$ parts with hazardous material, i in product, j	Positive	-Obsolescence
Ability to Disassemble			
Number of disassembled parts	The number of parts removed for disassembly.	Positive	-Number of fasteners -Number of tools -Parts with adhesives, labels, or paint -Level of integration
Number of disassembly tasks	The number of tasks needed to dismantle the product.	Positive	-Number of fasteners -Number of tools -Number of wires -Number of disassembled parts -Number of non-value added tasks
Number of non-value added tasks	The number of tasks that do not result in a disassembled part or component.	Positive	-Number of wires -Number of disassembly tasks
Variety of materials	The number of different materials in the product.	Positive	-Materials concentration -Plastics concentration
Number of sequence dependent disassembly steps	The number of disassembly steps that must follow a precedence sequence.	Positive	-Number of fasteners
Repetitive components	Number of components that have more than one duplicate.	Positive	-Number of fasteners -Number of wires

Design Characteristic Metric	Description/Formula	Predicted Correlation with End-of-Life Disposition Environmental Impact	Potential Interactions between Design Characteristics
Obsolescence Product's failure compared to its product family's average failure.	$(disassem.yr - mfg.yr) - product\ type's\ avg.life\ (yrs)$	Negative	-Number of fasteners -Level of integration
Level of Integration Highly dependent modules that support a variety of functions.	The number of functions per module.	Positive or Negative	-Number of fasteners -Number of wires

10.1 Discussion

Linear Regression has the ability to determine if there is a relationship between design characteristics and the environmental impact of end-of-life disposition. If there is a relationship, the design characteristics and interactions that best describe the end-of-life disposition environmental impact can be determined. According to the predicted correlations, the majority of the design characteristics have a positive correlation with the environmental impact of end-of-life disposition. Volume may have a negative correlation, because if there is more material, then there is potential for more material to be recovered. Obsolescence may have a negative correlation, because products that last longer could have a lower environmental impact, because they are not disposed and new products are not created. Level of integration may have a positive or negative correlation. If there are more functions per module, recycling may be more difficult which would increase the environmental impact. On the other hand, fewer products may be created if increasing the functions per module decreases the need for multiple products. This could decrease the environmental impact. The predicted correlations and interactions are tested with the results of the linear regression model relating design characteristics to end-of-life disposition environmental impact (Chapter 14).

Chapter 11

DATA COLLECTION

To create a realistic dataset, actual cellular phones are manually disassembled. Most products are acquired at the end of their life from recyclers. Newer products (manufactured within the last five years) are also included. Newer product tear-downs were donated from OEMS or ifixit.com. Several data collection methods are used to collect data for the design characteristics metrics and the end-of-life disposition environmental impact. Data is also extracted from case studies in the literature to verify results.

11.1 Methods

To record the disassembly and product information from product teardowns into a usable form while ensuring consistency and repeatability, the following methods are used:

(1) Reverse fishbone diagram;

(2) Bill of materials;

(3) Product specifications;

(4) Disassembly time spreadsheet;

(5) FCC ID and average lifespan; or

(6) Function tree diagram.

11.1.1 Reverse Fishbone Diagram

Ishii and Lee's (1996) reverse fishbone diagram is used to collect product disassembly data for its repeatability and its effectiveness at organizing and displaying product information (Figure 11.1). The product information it displays includes components, fasteners, wires, disassembly tasks, etc. It also captures the sequence and precedence of the disassembly tasks. The structure of the reverse fishbone diagram consists of a vertical spine, which is intersected by horizontal lines. Branches that extend from the spine or horizontal lines represent the modules (subassemblies or individual components) of the product. They are labeled by name, removal symbol, and direction of removal. Removal symbols are created specifically for the disassembly of consumer electronics and

are described in more detail in section 11.3.1. There are two numbers that are indicated on the component label and symbol that describe the disassembly task of the components on the reverse fishbone diagram. The number next to the branch's label, i.e. Torx (2), indicates the components that are repeated or the quantity of the components in the product. The number on the removal symbol, such as an arrow, indicates the number of times that the task is repeated.

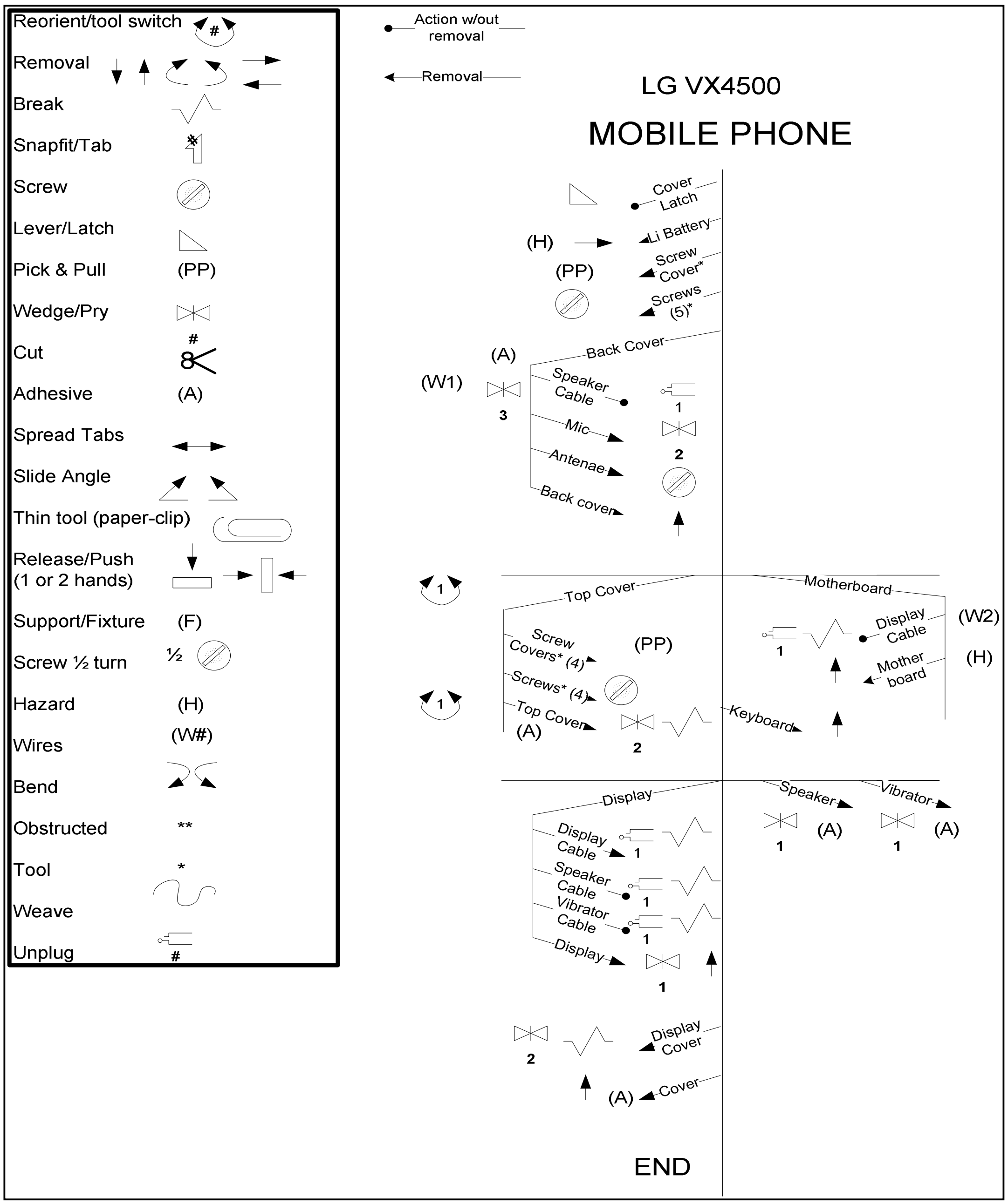


Figure 11.1: Reverse Fishbone Diagram of an LG VX4500 Cellular Phone.

The disassembly precedence is described by the vertical spine, from the top of the diagram to the bottom of the diagram. If a branch attaches directly to the spine, it is not disassembled until the previous branch (component or subassembly) is disassembled. If the branch attaches to one of the intersecting horizontal lines, then its disassembly sequence is independent of all the other branches on that same horizontal line.

The disassembly sequence is also determined by moving vertically from the top of the vertical spine to the bottom. Subassemblies may have multiple components attached to their branch. The final component removed is the last branch or extension of a subassembly with a known end-of-life disposition method. Alternatively, branches that end with dots represent disassembly actions that do not result in the removal of components. For example, a battery would be represented with a branch with an arrow, because it is disassembled and sent to recycling and recovery. On the other hand, some cables are not removed when they are initially unplugged, if they are removed at all. A branch with a dot at the end represents these cables. The reverse fishbone diagram of an LG VX4500 cellular phone has 2 sequence independent branches and 16 modules (Figure 11.1).

11.1.2 Bill of Materials

A bill of materials is used to collect product disassembly data. It is a spreadsheet that is used to record data, including part number, part name, material type, part quantity, and part weight in columns. Part numbers are assigned in the order modules are disassembled. Material type is collected using a magnet to determine if metals are ferrous or nonferrous. For plastics, material type is determined by the material code or marking etched in the part. If the plastic is not marked according to ISO 11469 or other guidelines, it is considered unlabeled plastic. Wires and antennas are presumed to contain copper. Part weight is determined using a 0.05 oz scale, converted to pounds. Part weight is used when calculating the MRR and the end-of-life disposal environmental impact.

11.1.3 Product Specifications

All OEMs create documentation that contains the product specifications for consumer electronics. Product specifications are found in the product's user guide, manual, or online website. The product dimensions and total weight are extracted from the product specifications.

11.1.4 Disassembly Time Spreadsheet

The disassembly time spreadsheet was created to calculate the disassembly time of materials or components using Dowie's (1994) tables. It is explained in more detail in section 8.1.

11.1.5 FCC ID and Average Lifespan

All consumer electronics have an associated FCC ID. To obtain the manufacturing year of the product, the FCC ID is searched on the FCC ID website (http://transition.fcc.gov/oet/ea/fccid/). Industrial Economics Inc.'s (2007) study "Management of Electronic Waste in the United States: Approach 2" is used to obtain the average life of consumer electronic product types. Cellular phones have an average life of two years. The manufacturing year and average life of products are used to determine the product obsolescence.

11.1.6 Function Tree Diagram

The function tree diagram is used to determine the number of functions in a product (Figure 11.2). It uses the Function Analysis Systematic Technique (FAST) to map the modules' functions to the product's basic function. FAST defines the basic function of the product with an active verb and a noun. For a cellular phone, the basic function is to "communicate information". Secondary functions are used to define the functions that support the product's basic function with an action verb and a noun. The branches on the function tree diagram illustrate the relationship between the basic and secondary functions (VAI, 1993). To calculate the number of functions in a product, the boxes on the function tree diagram are counted. For example, a handheld phone has 35 functions (Figure 11.2).

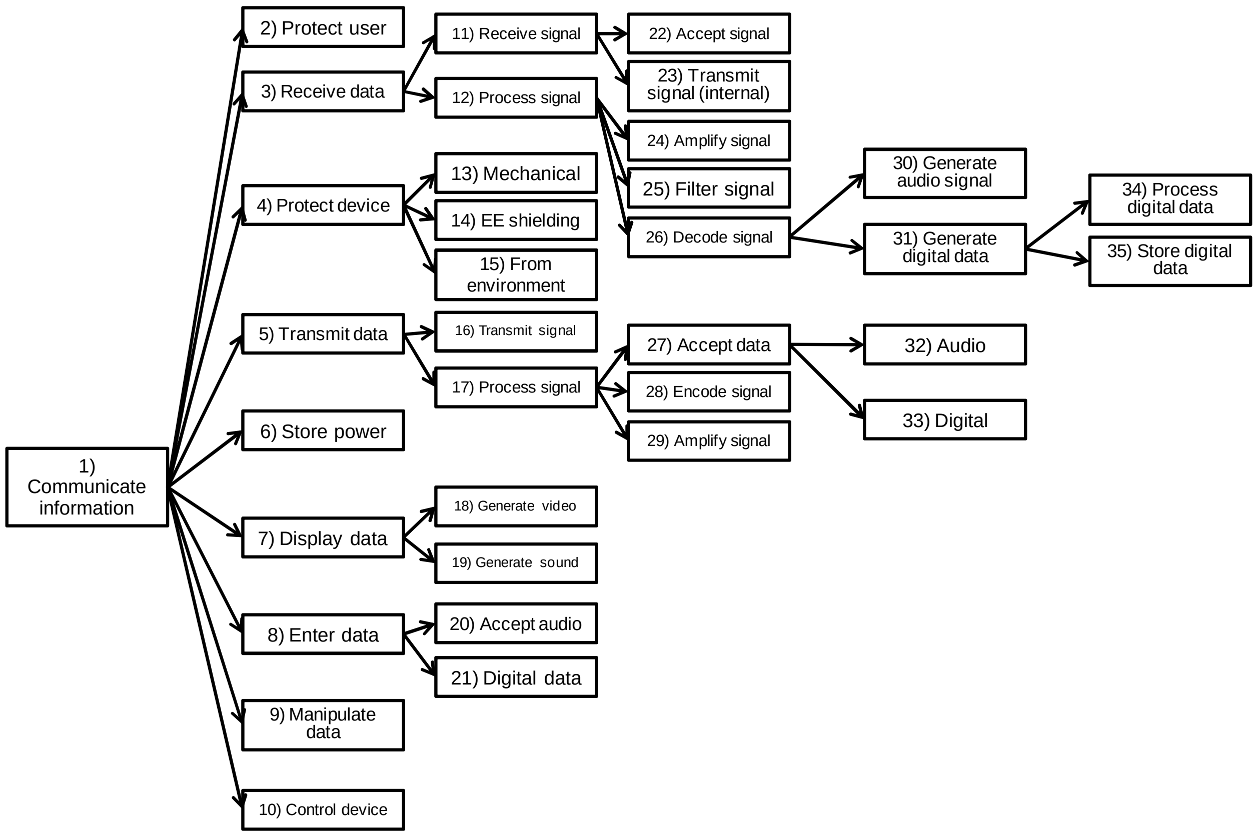


Figure 11.2: Function tree diagram of a handheld cellular phone.

11.2 Data Collection for Design Characteristic Metrics

Data collection for design characteristic metrics utilizes all of the data collection methods: the reverse fishbone diagram, bill of materials, product specifications, disassembly time spreadsheet, etc. Each design characteristic metric is described, assigned a data collection method, and calculated according to its data collection method (Table 11.1).

Table 11.1: Design Characteristic Metrics Data Collection

Potential Design Characteristic Metrics	Description/Formula	Data Collection Method	Calculation with Data Collection Method
Product Dimensions			
Volume of a rectangular prism.	Volume (in^3) = l x w x h	Product specifications from online website or manual.	Record L x W x H in inches from the product specs.
Fasteners, Tools, Wires, Contaminated Parts			
Number of fasteners	The number of fasteners in the product.	Reverse Fishbone Diagram (RFD)	Count the # of screws, snap fits, lever/latches, clips/release buttons, cut cords, cut wires, and disconnect wires from the RFD.
Number of tools	The number of tools needed for disassembly.	Disassembly Time Spreadsheet (DTS)	Count the number of different tools in Column Q of the DTS.
Number of wires	The number of wires in the product.	Reverse Fishbone Diagram (RFD)	Count the number of wires (W#) from the RFD.
Parts with adhesives, labels, or paint	The number of parts with adhesives, labels, or paint in the product.	Reverse Fishbone Diagram (RFD)	Count the number of contaminated modules (A) from the RFD.
Material Concentration			
Material Mixing	$H = c_{j_i} log c_{j_i}$, where $c_{j_i} = \frac{m_{j_i}}{m_j}$ $\forall\ materials, i, in\ product, j$	Bill of Materials	Use the weight of materials from the BOM.
Plastics Concentration			
Mass percentage of plastics	$\sum_1^i \frac{mp_{j_i}}{mp_j}, where\ mp_{j_i} = weight\ of\ plastic, i \quad \forall\ plastics, i\ in\ product, j$	Bill of Materials (BOM)	Use the weight of materials from the BOM.

Potential Design Characteristic Metrics	Description/Formula	Data Collection Method	Calculation with Data Collection Method
Variety of plastics	The number of different plastic materials in the product.	Bill of Materials (BOM)	Count the # of parts with different plastic materials in the BOM.
Hazardous Materials			
Refer to Annex II of WEEE	Look up components in the table of components containing hazardous materials.	Reverse Fishbone Diagram (RFD)	Lookup components in the hazardous materials table, label the RFD with an (H), and count the number of hazardous modules with an (H).
Percentage of hazardous materials in a product	$\sum_{1}^{i} \frac{mhp_{j_i}}{mhp_j}, where\ mph_{j_i} = weight\ of\ part\ with\ hazardous\ material, i\ \forall\ parts\ with\ hazardous\ material, i\ in\ product, j$	Reverse Fishbone Diagram (RFD) and Bill of Materials (BOM)	Lookup components on the RFD with an (H), sum up the weight of these components, and divide by the total weight of the product to get a hazardous material concentration.
Ability to Disassemble			
Number of disassembled parts	The number of parts removed for disassembly.	Reverse Fishbone Diagram (RFD)	Count the # of branches with arrows and subtract the # of branches with dots on the RFD.
Number of disassembly tasks	The number of tasks needed to dismantle the product.	Disassembly Time Spreadsheet (DTS)	$\sum_{1}^{k} \text{Column } E_{j_k} * \text{Column } N_{j_k} + \text{Column } R_{j_k}$ $\forall$ modules, k in product, j on the DTS.
Number of non-value added tasks	The number of tasks that do not result in a disassembled part or component.	Reverse Fishbone Diagram (RFD)	Count the # of branches with dots on the RFD.
Variety of materials	The number of different materials in the product.	Bill of Materials (BOM)	Count the # of parts with different materials in the BOM.

Potential Design Characteristic Metrics	Description/Formula	Data Collection Method	Calculation with Data Collection Method
Number of sequence dependent disassembly steps	The number of disassembly steps that must follow a precedence sequence.	Reverse Fishbone Diagram (RFD)	Count the # of modules on the vertical axis of the RFD. Count the entire horizontal axes as one step.
Repetitive components	Number of components that have more than one duplicate.	Reverse Fishbone Diagram (RFD)	Count the # of branches on the RFD with a number next to their label, ex. Torx(#)
Obsolescence Product's failure compared to its product family's average failure.	$(disassem.yr - mfg.yr) - product\ type's\ avg.life\ (yrs)$	FCC ID and Average Lifespan	Disassembly yr = date product was acquired, Look up mfg yr with FCC ID and look up average life of product type on ALC.
Level of Integration Highly dependent modules that support a variety of functions.	The number of functions per module.	Function Tree Diagram (FTD) and Reverse Fishbone Diagram (RFD)	Count the number of boxes on the FTD and divide by the number of branches on the RFD.

11.3 Data Collection for End-of-Life Disposition Environmental Impact

To calculate the end-of-life disposition environmental impact of cellular phones, data is collected for the following activities:

(1) Disassembly time;

(2) Material removal rate (MRR) and value removal rate (VRR); and

(3) End-of-life disposition environmental impact;

11.3.1 Disassembly Time

The disassembly time spreadsheet is created to estimate the disassembly time of cellular phones (Table 8.2). The information in the reverse fishbone diagram is used to populate the disassembly time spreadsheet. Data from the reverse fishbone diagram is entered, by component,

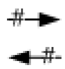
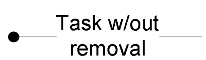
into its respective column to calculate the disassembly time for each task. To ensure consistency and repeatability the following assumptions are applied:

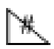
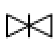
- In the disassembly time spreadsheet, Column F- Quantity = the number in parentheses next to the label on the branch of the reverse fishbone diagram, ex. Torx (#).
- If there are two different tasks that are associated with the same column of the disassembly time spreadsheet, the task with the highest time is used and it is repeated twice (in the disassembly time spreadsheet, Column R = 2).
- In the disassembly time spreadsheet, Column N- Pick up or put down (up/dwn) (# of times) - has a default of 2 and then for each additional task, 1 is added (Column N =1*(# of different tasks). Column N does not count reorientation/change, which is included in Column U.

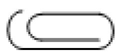
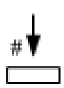
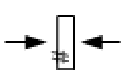
Each reverse fishbone diagram task is assigned a symbol, directions for use, and an associated disassembly time spreadsheet column (Table 11.2). The directions for use describe the situations in which the task or symbol is typically used. The disassembly time spreadsheet column describes the associated columns for the disassembly tasks and symbols. Directions for entering the task information in the column are also provided. If there are multiple options for the column, the correct response is indicated in bold and italicized text.

Table 11.2: Data Collection for Disassembly Time Spreadsheet.

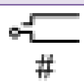
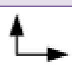
Reverse Fishbone Diagram Task and Symbol(s)	**Directions for Use**	**Disassembly Time Spreadsheet Column and Assumptions**
Reorientation/ change	*Usually occurs at the beginning of a subassembly.*	Column U- How many times did product need to be reoriented (rotate/flip/hold in hand)? = *#*
	Use when the part has to be flipped or turned. This can be simply turning the product around so its back is facing you. Use also when a tool is set down, picked up, or changed.	Apply credit to main module of subassembly, not fasteners. Count as a non-value added task.
Removal	*Every component should have some kind of removal symbol.*	Column L- Horizontal or Vertical Removal (h/v)
	Use when removal involves an opening motion. This can be towards or away from	Column L- Horizontal or Vertical Removal (*h*/v)=*h* Column R- # of Repetitions = *#*

Reverse Fishbone Diagram Task and Symbol(s)	Directions for Use	Disassembly Time Spreadsheet Column and Assumptions
	the body.	
	Use when removal is vertical, it is the last part to be removed, or the part easily falls of the component or device.	Column L- Horizontal or Vertical Removal (h/*v*)=*v* Column R- # of Repetitions = *#*
	Use only when removal must be in a downward motion (towards the floor). Use with the push symbol if you must push the part downward	Column L- Horizontal or Vertical Removal (h/*v*)=*v* Column R- # of Repetitions = *#*
	Use when removal is in the horizontal direction	Column L- Horizontal or Vertical Removal (*h*/v)=*h* Column R- # of Repetitions = *#*
	Use when a task is performed, but the module is not disassembled.	Column N- Pick up or put down (up/dwn) (# of times)=*0* Count as a non-value added task.
Break		Column T- No resistance/holding down part/*corroded* = *corroded*
	Use if the component is broken during removal. This could happen if the fastener is warped or restricted, but needs to be documented!	Column T's default value is holding down part. Column R- # of Repetitions = *#*
Snapfit		Column O- Fastener (n/a, screw, *snapfit* (lever/latch), clips, glues, cut cords, cut wire, disconnect wire) = *snapfit*
	Use if a snapfit or clip must be engaged for removal. Replace the pound sign (#) with the number of snapfits or clips that had to be engaged for removal or were obstructing the part's removal	Column R- # of Repetitions = *#*
Screw		Column O- Fastener (n/a, *screw*, *snapfit* (lever/latch), clips, glues, cut cords, cut wire, disconnect wire) = *screw*
	Use when a fastener or an antenna needs to be unscrewed. This can be done manually, manually with a tool, or with a power tool.	Different screw symbols are used to show that a new tool is needed.

Reverse Fishbone Diagram Task and Symbol(s)	Directions for Use	Disassembly Time Spreadsheet Column and Assumptions
Lever/Latch		Column O- Fastener (n/a, screw, *snapfit (lever/latch)*, clips, glues, cut cords, cut wire, disconnect wire) = *snapfit*
	Use when a lever or latch has to be pulled or released.	Column R- # of Repetitions = # Add arrows to show direction.
Pick & Pull	*Mainly for labels, stickers, and other components with adhesives or glues.*	Column O- Fastener (n/a, screw, snapfit (lever/latch), clips, *glues*, cut cords, cut wire, disconnect wire) = *glues*
(PP#)	Use when material that is bound to another material via an adhesive has to be pried for removal.	Column P- Removal Method (manual/power/tool) = tool Don't include labels or stickers.
Wedge/Pry	*Typically done with pliers.*	Column P- Removal Method (manual/power/*tool*) = *tool*
 #	Use if a tool needs to be used as lever or a large amount of force is needed to separate two components. Replace the pound sign (#) with the number of times the force needs to be applied to separate the components.	Column R- # of Repetitions = # Column T- No resistance/holding down part/*corroded* = *corroded*
Cut	*Usually used for wires or cables.*	Column O- Fastener (n/a, screw, snapfit (lever/latch), clips, glues, *cut cords, cut wire*, disconnect wire) = *cut cords or cut wire*
	Use when wires, cables, or plastic films are limiting the removal of the component.	Column R- # of Repetitions = #
Adhesive		Column O- Fastener (n/a, screw, snapfit (lever/latch), clips, *glues*, cut cords, cut wire, disconnect wire) = *glues*
(A)	Use when paints, adhesives, glues, etc. are present on the component.	Column P- Removal Method (manual/power/*tool*) = *tool* Don't include labels or stickers.
Spread Tabs		Column O- Fastener (n/a, screw, *snapfit* (lever/latch), clips, glues, cut cords, cut wire, disconnect wire) = *snapfit*

Reverse Fishbone Diagram Task and Symbol(s)	**Directions for Use**	**Disassembly Time Spreadsheet Column and Assumptions**
	Use when tabs must be pushed in opposite directions to release the part.	
Slide Angle		Column S- Motion Obstructions (easy access/*1+ directions around obstruction(1plus)*/1+ dir ard obstruction with restricted vision(1+v)/ extended reach/severely obstructed) = *1plus*
	Use when the part is obstructed by guides and must be slid at an angle.	Column S's default is easy access.
Thin Tool	*Usually to release a CD/DVD drive. A paper clip is typically used.*	Column O- Fastener (n/a, screw, snapfit (lever/latch), *clips,* glues, cut cords, cut wire, disconnect wire) = *clips*
	Use when a thin tool is required to reach the release button.	
Release/Push		Column O- Fastener (n/a, screw, snapfit (lever/latch), *clips*, glues, cut cords, cut wire, disconnect wire) = *clips*
	Use when the part has a button or other release mechanism that needs to be pushed. This can be used for any direction. Use with a removal symbol to indicate the direction.	Column M- # hands (*1* or 2) = *1* Column L- Horizontal or Vertical Removal (h/*v*)=*v*
	Use when the part has a button or other release mechanism that needs to be pushed with two hands. This can be used for any direction. Use with a removal symbol to indicate the direction.	Column M- # hands (1 or *2*) = *2* Column L- Horizontal or Vertical Removal (*h*/v)=*h*
Screw 1/2 Turn	*Probably will only use if you have a service manual that describes this procedure.*	Column O- Fastener (n/a, *screw*, snapfit (lever/latch), clips, glues, cut cords, cut wire, disconnect wire) = *screw*
	Use when only a half turn is required to unscrew the fastener.	Column P- Removal Method (manual/power/*tool*) = *tool*
Hazardous Materials	*Usually PCBs, BFRs (ABS, PC, HIPS), LCDs, etc.*	
(H)	Label all components that contain hazardous materials. Use the hazardous materials table.	

Reverse Fishbone Diagram Task and Symbol(s)	Directions for Use	Disassembly Time Spreadsheet Column and Assumptions
Wires		Column O- Fastener (n/a, screw, snapfit (lever/latch), clips, glues, *cut cords, cut wire, disconnect wire*)
(W#)	Label all cables or wires and other thin, loose components that could cause tangling. # = the order at which the wires were disassembled. Ex. W1, W2, then W3.	cut cords- with scissors and ribbon or flex cable cut wires- with scissors and cable disconnect wire- with manual ribbon, flex, or cable or with break
Bend		
	Use when the component has to be folded inward or outward for removal.	Column S- Motion Obstructions (easy access/*1+ directions around obstruction(1plus)*/1+ dir ard obstruction with restricted vision(1+v)/ extended reach/severely obstructed) = *1plus*
Obstructed	*Obstructed symbols are placed next to the label on the branch of the reverse fishbone diagram.*	Column S- Motion Obstructions (easy access/1+ directions around obstruction(1plus)/1+ dir ard obstruction with restricted vision(1+v)/ extended reach/severely obstructed)
**	Use when a component or its fastener is hard to reach, stuck, a fastener is corroded, or a large force is required for removal.	Column S- Motion Obstructions (easy access/*1+ directions around obstruction(1plus)*/1+ dir and obstruction with restricted vision(1+v)/ extended reach/severely obstructed) = *1plus*
**v	Use when a component or its fastener is obstructed and is blocked visually.	Column S- Motion Obstructions (easy access/1+ directions around obstruction(1plus)/*1+ dir and obstruction with restricted vision(1+v)*/ extended reach/severely obstructed) = *(1+v)*
**r	Use when a component or its fastener is hard to reach, stuck, a fastener is corroded, or a large force is required for removal.	Column S- Motion Obstructions (easy access/1+ directions around obstruction(1plus)/1+ dir ard obstruction with restricted vision(1+v)/ *extended reach*/severely obstructed) = *extended reach*
**s	Use when a component or its fastener is hard to reach, stuck, a fastener is corroded, or a large force is required for removal.	Column S- Motion Obstructions (easy access/1+ directions around obstruction(1plus)/1+ dir and obstruction with restricted vision(1+v)/ extended reach/severely obstructed) = *severely obstructed*
Tool		Column P- Removal Method (manual/power/*tool*) = *tool*
*	Use when a tool is used for removal. Type the asterisk (*) next to the name of the component on the RFD.	Column P's default value is manual. Column Q- Tool Name- pliers = ply, Screwdriver = torx, Philips head (PH), flathead (FH), scissors,

Reverse Fishbone Diagram Task and Symbol(s)	Directions for Use	Disassembly Time Spreadsheet Column and Assumptions
		knife = cutter, etc.
Weave	*Usually for cables or other wires.*	Column O- Fastener (n/a, screw, snapfit (lever/latch), clips, glues, cut cords, cut wire, *disconnect wire) = disconnect wire*
	Use when a cable is wrapped around a peg, etc.	Column S- Motion Obstructions (easy access/1+ directions around obstruction(1plus)/*1+ dir ard obstruction with restricted vision(1+v)*/ extended reach/severely obstructed) = *(1+v)*
Unplug	*Usually used when a cable is connected to a PCB.*	Column O- Fastener (n/a, screw, snapfit (lever/latch), clips, glues, cut cords, cut wire, *disconnect wire*) = *disconnect wire*
	Use when unplugging a cable from a port or outlet.	
One Hand	*Usually two hands are needed for removal.*	Column M- # hands (*1* or 2) = *1*
	Use when only one hand is needed for removal.	Column M's default value is 2. Column T- *no resistance*/holding down part/corroded= *no resistance*
Two dof	*Modules usually only have 1 dof.*	Column J- Degrees of freedom (1 or *2*) [linear in x-dir, y-dir, or z-dir; rotation around x, y, or z] = *2*
	Use when part can be removed with 2 or more degrees of freedom. These can be linear in x-dir, y-dir, or z-dir; rotation around x, y, or z.	Column J's default value is 1.
Heat	*Used when de-soldering or melting other adhesives, if available. Used in case study tear-downs.*	Column O- Fastener (n/a, screw, snapfit (lever/latch), clips, *glues*, cut cords, cut wire, disconnect wire) = *glues*
	Use when heat needs to be applied for removal.	Column P- Removal Method (manual/power/*tool*) = *tool*

11.3.2 Material removal rate and value removal rate

The material removal rate (MRR) and value removal rate (VRR) are used to select the end-of-life disposition separation processes. MRR is the rate at which the components or materials are

disassembled. Data collection for disassembly time, described above, uses the reverse fishbone diagram. Data collection for the weight of the component or material uses a 0.05 oz scale. The components or materials and their values are recorded into the bill of materials. VRR is the rate at which the component or material value is disassembled. Data collection for the value of the component or material uses the 2009 U.S. dollars per pound of the component or material (Table 8.3) multiplied by the material or component weight in pounds.

11.3.3 End-of-Life Disposition Environmental Impact

To calculate the end-of-life disposition environmental impact, data for the end-of-life disposition processes and the avoided production of new components or materials is needed. The data collection for end-of-life disposition processes is described in Chapter 9. To calculate the benefit of avoided production of new components or materials, the material composition and weight of the components or materials from the bill of materials are used.

11.4 Data Collection for Verification

Data for verifying the model is collected from case studies in the literature. Case studies were pulled from design for the environment (DfE), life cycle assessment (LCA), environmental management studies that included cellular phones. These studies typically only had partial data, so they could not be used for the full linear regression model.

Chapter 12

VERIFICATION AND VALIDATION

The design characteristics and the end-of-life environmental impact are verified and the linear regression analysis is validated. Verification determines if the design characteristics and end-of-life environmental impact calculations have accurate results. Verification is conducted with (1) partial case study data and (2) duplicate product data. Validation confirms that the linear regression analysis represents the relationship between product design and the environmental impact of end-of-life disposition properly. The one phase end-of-life disposition LCA is validated with the ecoinvent manual, Disposal of Electric and Electronic Equipment (e-Waste). Then, the linear regression model is validated by comparing the signs of the regression coefficients with the predicted correlation between design characteristics and end-of-life disposition environmental impact.

12.1 Verification with Partial Case Study Data

From case studies in the literature, some data is available for verification of design characteristics. With the available material compositions of cellular phones from case studies, it is possible to calculate the design characteristic, material mixing, H and the design characteristic, plastics concentration c_i (Table 12.1). The case studies are compared to the 34 cellular phones used in the linear regression analysis. The average material mixing of a cellular phone from the case studies is 1.73 and the average plastics concentration of the case studies is 0.38. For the 34 cellular phones, the average material mixing is 2.46 and the average plastics concentration is 0.28. Since the results are on the same order of magnitude, the cellular phone data and calculations are consistent with the literature.

Table 12.1: Verification of Material Mixing (H) and Plastics Concentraition (c_i) with Cellular phone Case Studies

Source	Product Name	Material Mixing (H)	Plastics Concentration (c_i)
Bhuie	Generic Cellular Phone	0.56	0.04
Chancerel 2009	19 Mobile Phones	2.31	0.33
EPA (app-2)	Mobile Phone	2.48	0.46
EEBCTool_v2	Mobile Phone	1.48	0.49
Hagelüken 2006	Cellular Phone	1.80	0.57
Mean		1.73	0.38
Standard Deviation		0.77	0.21
Mean of Case Study (34 phones)		2.46	0.28
Std. Dev. of Case Study (34 phones)		0.27	0.11

12.2 Verification with Duplicate Products

Data is available for duplicate products to be used for verification. Duplicate products are used to verify that results are consistent and precise. The following cellular phones have duplicates, which were differentiated by the last three numbers in their serial numbers:

- LG VX4400 Cellular Phone; and
- LG VX4500 Cellular Phone;

There were two LG VX4400 models in the dataset. The models did not have identical values for their end-of-life disposition environmental impact and design characteristics. This is justified because their components had different weights and they did not have the same number of components. All values that were not dependent on weight or part number were identical, however. This verifies that the variability was in the data itself and not in the data collection method. The three LGVX4500 cellular phone models had identical weights and part counts. Their end-of-life disposition environmental impact and design characteristic values were identical for all three phones.

12.3 Validation of the Life Cycle Assessment

The one phase end-of-life disposition LCA is validated against the ecoinvent manual, Disposal of Electric and Electronic Equpment (e-Waste). The table describes the fate of electronic components for manual and mechanical dismantling processes for the end-of-life disposition LCA and the ecoinvent model. The ecoinvent model and the one phase end-of-life model are almost

identical in their modeling of manual and mechanical dismantling processes for materials and components (Table 12.2 and Table 12.3).

Table 12.2: Validation of One Phase End-of-Life Disposition LCA with Comparison to the ecoinvent Electronics Disposal Manual.

	Ecoinvent Disposal of Electrical and Electronic Equipment (e-Waste)		One Phase End-of-Life Disposition LCA	
Components/ Parts	Amount	Further/Treatment	Amount	Further/Treatment
[i] Housing/Support				
-metal parts, outside (steel, Al, Cu, etc.)	100%	Scrap, for metal production	100%	Scrap, for metal production
-metal parts, inside (steel, Al, Cu, etc.)	100%	Scrap, for metal production	100%	Scrap, for metal production
-plastic parts, outside	100%	plastics, to incineration	Thermoplasts w/o BFRs	Scrap, for plastic production (extruding & repelletizing)
-plastic parts, inside	100%	plastics, to incineration	Thermosets & Thermoplasts w/ BFRs	plastics, to incineration, (Thermoplasts result in 5% WtE recovery)
[ii] Slide-in Modules (e.g. HDD, DVD/CD-ROM)	100%	*in "Shredder material"*	n/a	n/a
[iii] Printed Wiring Boards				
-high-quality, mounted	100%	PWB, to further treatment	100%	PWB, to further treatment
-low quality, mounted	50%	PWB, to further treatment	100%	PWB, to further treatment
	50%	*in "Shredder material"*	*WEEE mandates that all cellular phone PWBs must be manually dismantled*	
[iv] Cables				
-cable (power w/o plugs)	100%	Cable, for further treatment	n/a	n/a
- plugs (power cable)	100%	PWB, to further treatment	n/a	n/a
[v] Hazardous Components				
- Batteries	100%	Batteries, for further treatment	100%	Batteries, for further treatment
- Capacitors (big capacitors)	100%	Capacitors, to special disposal	n/a	n/a
(small capacitors)		*(part of "Printed Wiring Boards"*		*(part of "Printed Wiring Boards"*

	Ecoinvent Disposal of Electrical and Electronic Equipment (e-Waste)		One Phase End-of-Life Disposition LCA	
[vi] Special Components/Modules				
- toner (approx. as PS)	100%	Incineration (in MSW)	n/a	n/a
- LCD module, dismantled	100%	LCD module, to incineration	100%	LCD module, to incineration
- LCD, backlight (CCFL)	100%	backlight lamp, to further treatment	n/a	n/a
- CRT tube, without gun	100%	CRT glass treatment	n/a	n/a
- CRT, electron gun	100%	*in "Shredder material"*	n/a	n/a
- CRT, deflection yoke	100%	*in "Shredder material"*	n/a	n/a

Table 12.3: Validation of One Phase End-of-Life Disposition LCA with Comparison to ecoinvent Transfer Coeffiecients in the Mechanical Treatment of WEEE.

	Ecoinvent Disposal of Electrical and Electronic Equipment (e-Waste)		One Phase End-of-Life Disposition LCA	
Components/ Parts	Amount	Further/Treatment	Amount	Further/Treatment
[i] Housing/Support				
-metal parts, outside (steel, Al, Cu, etc.)	50%	Scrap, for metal production	100%	-> to shredder process
	50%	-> to shredder process		Scrap, for metal production
-metal parts, inside	100%	-> to shredder process	100%	-> to shredder process
				Scrap, for metal production
-plastic parts, outside	50%	plastics, to incineration	Thermosets	-> to shredder process
	50%	-> to shredder process		plastics, to incineration
-plastic parts, inside	100%	-> to shredder process	Thermoplasts	-> to shredder process
				plastics, to incineration, w/ 5% WtE recovery
[ii] Slide-in Modules (e.g. HDD, DVD/CD-ROM)	100%	-> to shredder process	n/a	n/a
[iii] Printed Wiring Boards				
-high-quality, mounted	50%	PWB, to further treatment	*WEEE mandates that all cellular phone PWBs must be manually dismantled.*	
	50%	-> to shredder process		
-low quality, mounted	100%	-> to shredder process		
[iv] Cables				
-cable (power w/o plugs)	100%	Cable, for further treatment	n/a	n/a

	Ecoinvent Disposal of Electrical and Electronic Equipment (e-Waste)		One Phase End-of-Life Disposition LCA	
- plugs (power cable)	100%	PWB, to further treatment	n/a	n/a
- cables (others, with plugs)	100%	-> to shredder process	100%	-> to shredder process
[v] Hazardous Components				
- Batteries	100%	Batteries, for further treatment	WEEE mandates that all cellular phone batteries must be manually dismantled.	
- Capacitors (big capacitors)	100%	Capacitors, to special disposal	n/a	n/a
(small capacitors)	100%	-> to shredder process		*(part of "Printed Wiring Boards")*
[vi] Special Components/Modules				
- toner (approx. as PS)	100%	Incineration (in MSW)	n/a	n/a
- LCD module, dismantled	100%	LCD module, to incineration	100%	LCD module, to incineration
- LCD, backlight (CCFL)	100%	backlight lamp, to further treatment	n/a	n/a
- CRT tube, without gun	100%	CRT glass treatment	n/a	n/a
- CRT, electron gun	100%	-> to shredder process	n/a	n/a
- CRT, deflection yoke	100%	-> to shredder process	n/a	n/a

12.4 Validation of the Regression Model

The linear regression model is validated by comparing the signs of the regression coefficients with the predicted correlation between design characteristics and end-of-life disposition environmental impact (Table 10.1). The signs of the coefficients of the best models for the base case and the sensitivity analysis are compared to the hypothesized correlation between the design characteristics and end-of-life disposition environmental impact. If the sign matches the correlation, then the model is representing the system as anticipated. If not, further investigation is required.

12.5 Discussion

The design characteristics and end-of-life disposition environmental impact are verified with partial data from case studies and duplicate products. Partial data was unfortunately only available to calculate the material concentration and the plastics concentration of the cellular phones (Table 12.1). The mean material concentration of the case study's cellular phones was

twice that of the partial data. On the other hand, it was similar to the larger, more recent datasets obtained from Chancerel & Rotter (2009) and the EPA (2007). The mean plastics concentration of the case study's cellular phones was lower than the partial data, but they were on the same order of magnitude. This verifies that the methods for obtaining material concentration and plastics concentration are reasonable.

The one phase end-of-life disposition LCA is validated with the ecoinvent manual, The Disposal of Electric and Electronic Equipment (e-Waste). The one phase end-of-life disposition LCA is similar to the ecoinvent model with a few exceptions. The plastics end-of-life treatments are dictated by if the type of plastic, thermoset or thermoplast. An option for plastics recovery is also included for thermoplasts not containing BFRs that are manually dismantled. Printed wiring or circuit boards and batteries in cellular phones are mandated by WEEE to be manually dismantled, therefore they are never sent to a shredding process. Since the exceptions either add a layer of detail to the model or they are specific to cellular phones, the one phase end-of-life disposition LCA model is reasonable.

The linear regression analysis is validated with the signs of the regression coefficients and the predicted correlation between design characteristics and end-of-life disposition environmental impact. This validation coincides with analysis of the linear regression results and it is presented in Chapter 14.

Chapter 13

SENSITIVITY ANALYSIS

Many assumptions are made to describe the end-of-life disposition environmental impact. To understand the uncertainty and variation associated with these assumptions, a sensitivity analysis is performed on the following assumptions:

(1) The impact of material and component values on the selection of end-of-life disposition separation processes;

(2) The impact of recycling process cost (labor, etc.) on the selection of end-of-life disposition separation processes;

(3) The impact of the MRR threshold (MRR > 5 lbs/min) on the selection of end-of-life disposition separation processes;

(4) The impact of recovery process loss on the environmental impact of end-of-life disposition;

(5) The impact of the percentage of avoided product on the environmental impact of end-of-life disposition; and

(6) The impact of the environmental perspective of the ReCipe impact assessment method on the environmental impact of end-of-life disposition.

For each assumption, the environmental impact is calculated by changing one or more parameters for all 34 cellular phones. If the environmental impact, from the new parameters, is different than the Base Model's environmental impact for the 34 phones, then a linear regression model is created for the new parameter. All of the sensitivity linear regression models will follow the same method as the Base Model as outlined in Chapter 10.

Chapter 14

RESULTS

The proposed method (Chapter 4-13) was used to analyze twenty-four regular cellular phones and ten smart phones. Data was collected from each mobile phone and translated into the 19 design characteristic metrics and an end-of-life disposition environmental impact for each phone. Linear Regression was used to determine if a relationship exists between the design characteristic metrics and the end-of-life disposition environmental impact. Then it was used to determine which of the design characteristics, if any, are significant. Finally, a sensitivity analysis was conducted to test the robustness of the assumptions of the end-of-life disposition selection process for materials and components and the one-phase end-of-life disposition life cycle assessment.

14.1 Regression Base Model

Thirty-four cellular phones, including ten smart phones, were analyzed using the proposed method (Appendix A). The results were used to create a base linear regression model relating the design characteristics with the end-of-life disposition environmental impact (Appendix A). The base linear regression model includes 18 design characteristics and an indicator variable for the type of cellular phone, regular or smart (Table 14.1). When the variable, *IND1* is equal to one, the phone is a regular cellular phone. When the variable, *IND1* is equal to zero, the cellular phone is a smart phone. From the residuals plots, the Base Model meets the least squares assumptions (Figure 14.1).

Table 14.1: Design Characteristics and Corresponding Varibles used in Linear Regression Model

Design Characteristic	Variable Name
Type of Cellular Phone (regular or smart)	*IND1*
Volume of a Rectangular Prism	*Volume*
Number of fasteners	*Fasteners*
Number of wires	*Wires*
Parts with adhesives, labels, or paint	*ContParts*
Material Mixing	*Matl-Mixing-H*
Mass percentage of plastics	*PlaConcen*
Variety of plastics	*PlaMixing*
Number of components/materials containing hazardous materials	*HazMat*
Percentage of hazardous materials in a product	*HazConc*
Number of disassembled parts	*DisassParts*
Number of disassembly tasks	*DisassTasks*
Number of non-value added tasks	*NVATasks*
Number of tools used	*Tools*
Variety of materials	*MatlVar*
Number of sequence dependent disassembly steps	*Seq.dep.*
Repetitive components	*Repmods*
Level of integration	*LOI*
Obsolescence	*Obsolescence (yrs)*

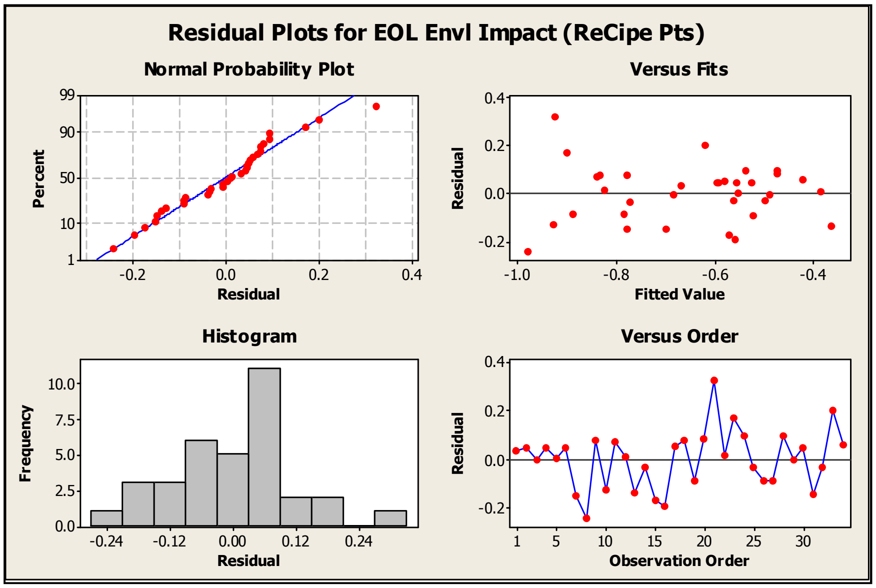


Figure 14.1: Base Model.

The Base Model does not describe a statistically significant relationship between the design characteristics and the environmental impact of end-of-life disposition, with a p-value of 0.214 and an R^2 of 67.4%. To improve the Base Model, the method of Best Subsets was used to reduce the number of variables or design characteristics in the model. The R^2 adequate (Equation 10.1) was calculated to see the minimum R^2 value that the best simplified model needs to adequately represent the system. The R^2 adequate for the Base Model is 38.9%. The model is adequately represented with a minimum of one variable, *Volume* or the volume design characteristic, with an R^2 value of 41.3%. From the residual plots, the one variable model satisfies the least squares assumptions (Figure 14.2). The number of variables, sum of square error or residual sum of squares (SSE), R^2, F-test, T-test, and R^2 adequate are summarized in Table 14.2. The SSE describes the variation, which is attributed to the error of the model. The SSE and associated value of R^2 describe the ability of the model to explain the behavior of the system. The F-test determines if the model is statistically significant. The T-test determines the significance of the regression coefficients.

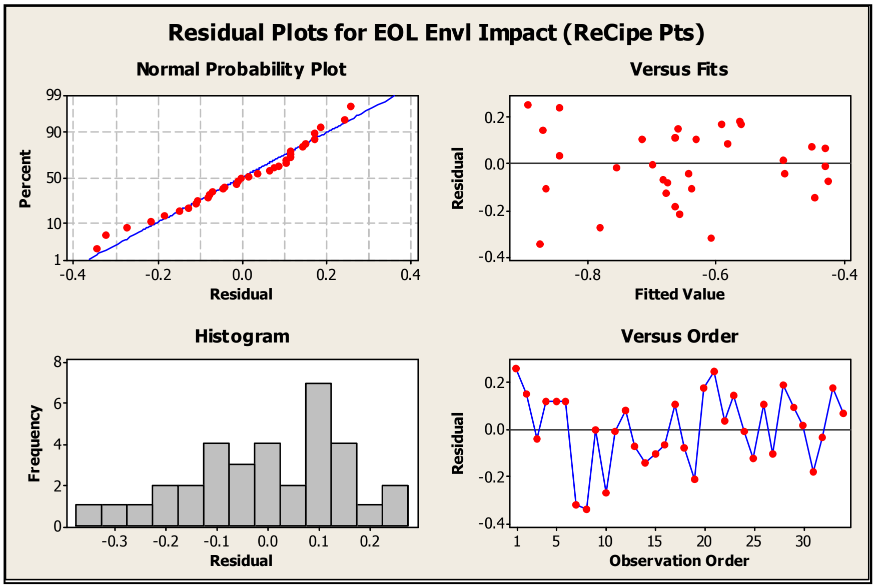


Figure 14.2: Base Model Best Subset with One Variable- *Volume.*

Table 14.2: ANOVA Summary Table for Base Model Best Subset Models.

	Model	Vars (K)	SSE	R2	F	dof	T- test: p-value > 0.05	Adequate subset?	SSR (BVOL|Btools, or BPLACON and Bwiresor Brepmods ,B0)
1	EOL Envl Impact (ReCipe Pts) = - 0.104 - 0.0856 *Volume*	1	0.839 27	41%	22.41	32	none	yes	
2	EOL Envl Impact (ReCipe Pts) = - 0.246 - 0.0808 *Volume* + 0.0433 *Tools*	2	0.803	44%	12.05	31	*Tools*	yes	0.499
3	EOL Envl Impact (ReCipe Pts) = - 0.386 - 0.0721 *Volume* + 0.0288 *Wires* + 0.461 *PlaConcen*	3	0.737	48%	9.37	30	*Wires, PlaConcen*	yes	0.350
4	EOL Envl Impact (ReCipe Pts) = - 0.546 - 0.0633 *Volume* + 0.0364 *Wires* + 0.436 *PlaConcen* + 0.0370 *Repmods*	4	0.713	51%	7.58	29	*PlaConcen , Repmods*	yes	0.238

14.1.1 Model Selection

From the best subsets results models with 2, 3, or 4 variables were tested for their ability to describe a significant relationship between design characteristics and the environmental impact of

end-of-life disposition. From the residual plots, the 2, 3, or 4 variable models satisfy the least squares assumptions (Figure 14.3, Figure 14.4, and Figure 14.5). The number of variables, SSE, R^2, F-test, and T-test are summarized in Table 14.2.

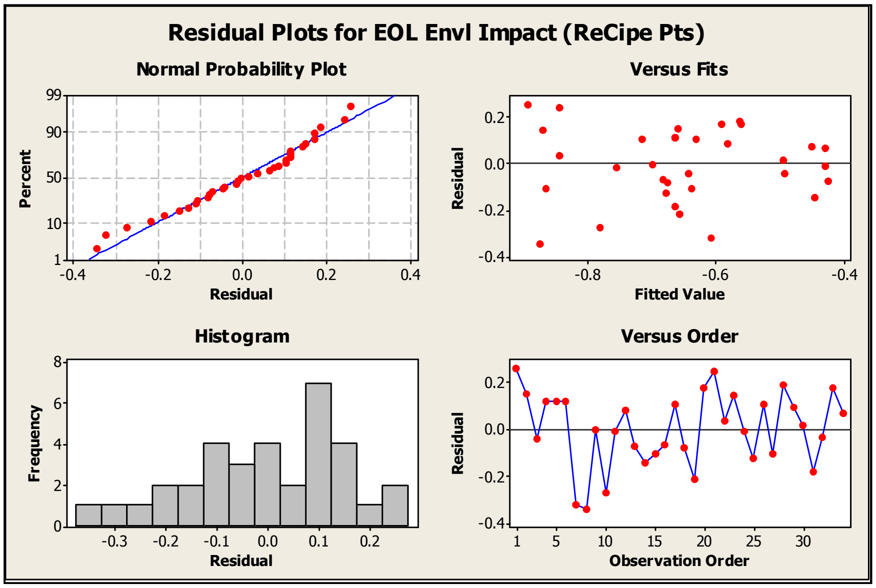


Figure 14.3: Base Model Best Subset with Two Variables- *Volume & Tools*.

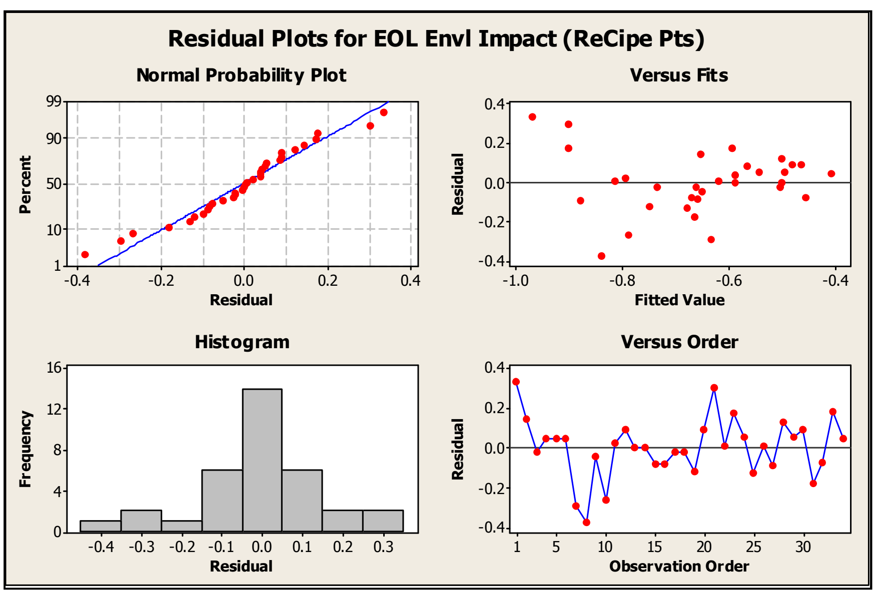


Figure 14.4: Base Model Best Subset with Three Variables- *Volume, Tools, and PlaConcen*.

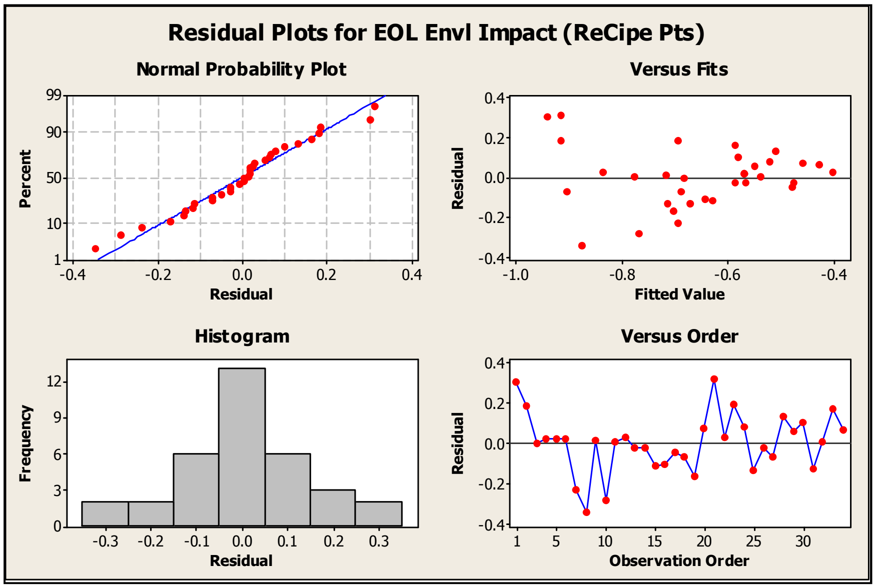


Figure 14.5: Base Model Best Subset with Four Variables- *Volume, Tools, PlaConcen, and Repmods.*

The Base Model Best Subset with one variable, *Volume* has an adequate R^2 value of 41%. This R^2 is not considerably increased by the 2, 3, and 4 variable models. The design characteristic that is significant in all models is *Volume*. The design characteristic, *Wires* is significant in the 4 variable model, but not it the three variable model. *Wires* will be tested for interaction effects and multicolinearity in subsequent sections. *Tools, PlaConcen*, and *Repmods* all have a p-value of greater than 0.05, so they are not significant.

14.1.1.1 Validation

The best subsets of the Base Model were validated by comparing the predicted correlation and the sign of the variables' coefficients (Table 14.3). The coefficients validated that the linear regression model is behaving as intended. The negative sign on *volume's* coefficient is acceptable, because as the volume increases, the environmental impact of creating the materials in the cellular phone's components increases. The one-phase end-of-life disposition LCA gives an avoided burden credit to recovering materials, which decreases the environmental impact of creating the materials as the volume of the cellular phone increases (Figure 14.6). This trend is highly correlated for both regular and smart phones. For smart phones, the environmental impact decreases more rapidly with volume. The batteries and PCBs in smart phones are larger due to increased functionality, so more high impact materials are available for recovery during recycling, lowering the environmental impact.

Table 14.3: Base Model Best Subsets Validation.

Design Characteristic Metric	Description/Formula	Correlation with End-of-Life Disposition Environmental Impact	Coefficient's Sign
Product Dimensions			
Volume of a Rectangular Prism	Volume (in^3)= l x w x h	Positive (could be negative due to avoided burden)	-
Fasteners, Tools, Wires, Contaminated Parts			
Number of wires	The number of wires in the product.	Positive	+
Plastics Concentration			
Mass percentage of plastics	$\sum_1^i \frac{mp_{j_i}}{mp_j}, where\ mp_{j_i} = weight\ of\ plastic, i\ \forall\ plastics, i\ in\ product, j$	Positive	+
Ability to Disassemble			
Number of tools used	The number of different tools used for disassembly.	Positive	+
Modularity			
Repetitive Components	The number of components that have one or more duplicates.	Positive	+

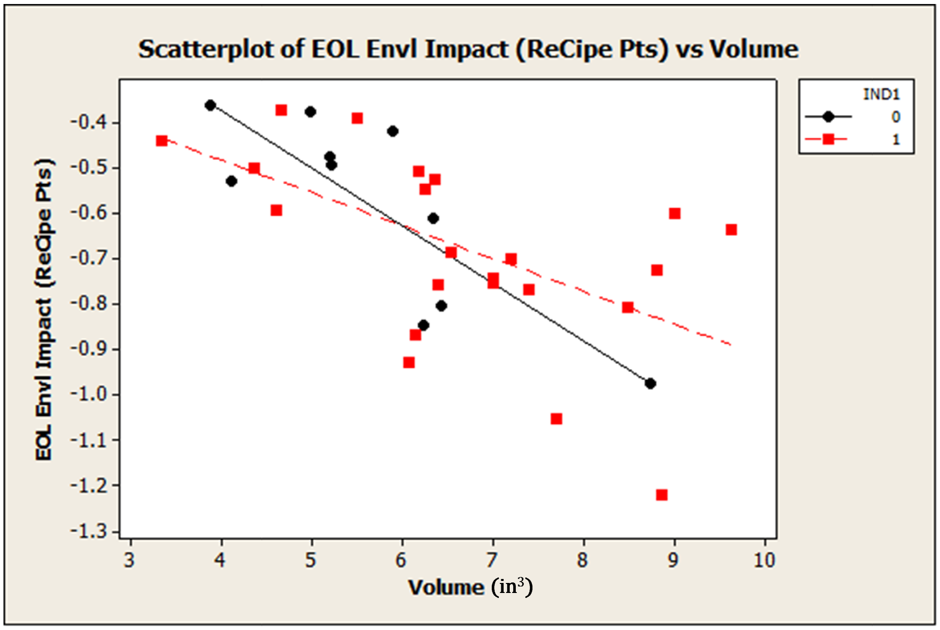


Figure 14.6: The relationship between end-of-life environmental impact and *Volume.* Ind1= 1 when the phone is categorized as regular and Ind1 = 0 when the phone is categorized as smart.

To validate that cellular phones with a greater volume result in a greater amount of avoided high impact material at end of life, the relationships between *weight* and *volume* (Figure 14.7) and *weight* and environmental impact (Figure 14.8) were investigated. For *weight* and *volume,* regular phones have a positive correlation, with an R^2 of 52.8% and smart phones have a weaker relationship with an R^2 of 11%. The positive correlation between *weight* and *volume suggests* that cellular phones with more volume contain more materials. For *weight* and environmental impact, regular phones have a negative correlation with an R^2 of 20.9% and smart phones have a weaker relationship with an R^2 of 3.3%. The relationship between *volume* and environmental impact also had a negative correlation, but it is stronger with an R^2 of 41%.Hence, the volume of the cellular phone is more significant than its weight. The relationships also suggest that as the cellular phones increase in functionality, as with the smart phones, weight becomes even less important.

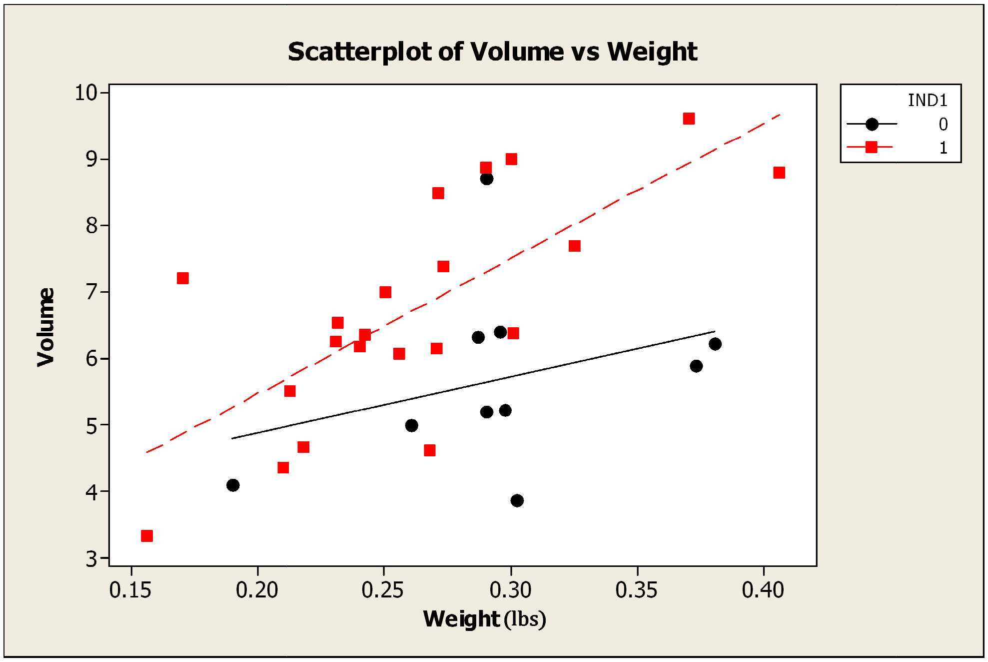


Figure 14.7: The relationship between *Volume* and *Weight*. Ind1= 1 when the phone is categorized as regular and Ind1 = 0 when the phone is categorized as smart.

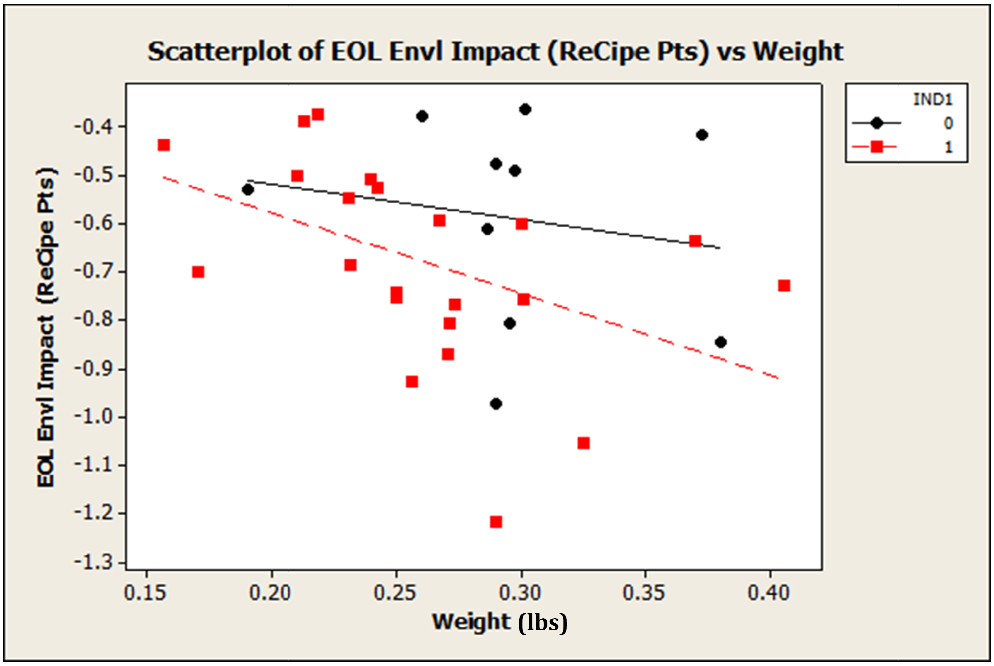


Figure 14.8: The relationship between end-of-life environmental impact and *Weight*. Ind1= 1 when the phone is categorized as regular and Ind1 = 0 when the phone is categorized as smart.

14.1.1.2 Interactions

For both the 3 and 4 variable models, interactions effects were tested with the variable *Wires* to validate its significance and the variance inflation factor (VIF) test was used to test for multicolinearity. If the VIF is greater than 10, then the variable has strong multicolinearity and is evaluated further. Interaction effects were also tested for the Base Model Best Subset with Three Variables, because a possible interaction between volume and plastics concentration was expected. In addition, they were tested for the Base Model Best Subset with Four Variables, because a possible interaction between wires and repetitive components was expected. While the residual plots satisfied the least squares assumptions (Figure 14.9 and Figure 14.10) and the ANOVA results concluded that interaction models were significant, the interaction variable introduced multicolinearity with a VIF greater than 10 for all variables, except *Repmods* (Table 14.4). *Volume* was also not significant according to the T-test for both interaction models.

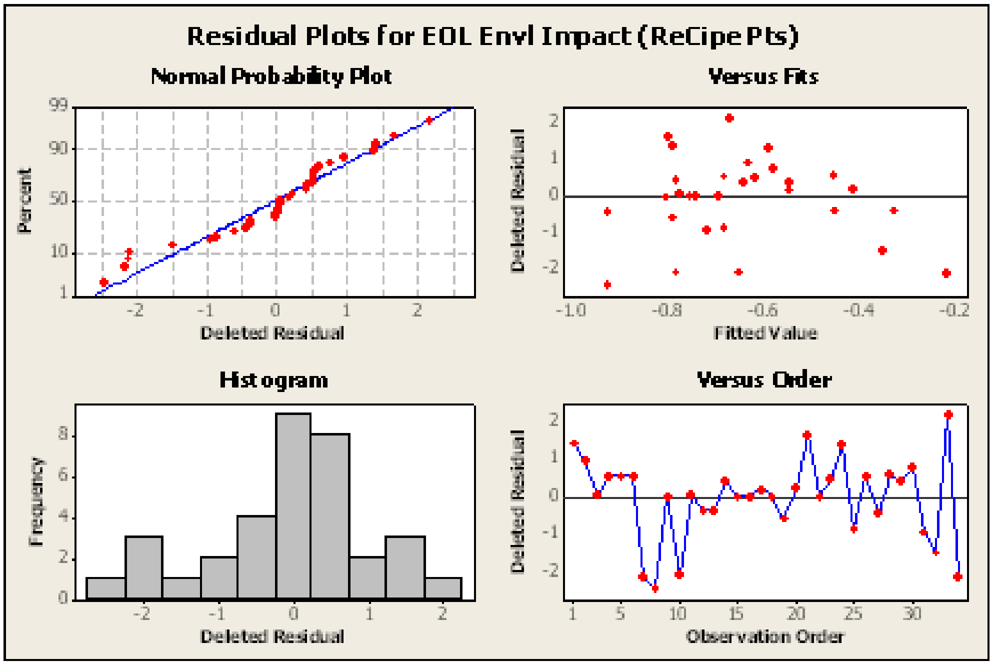


Figure 14.9: Base Model Best Subset with Three Variables and Volume*Placoncen and Volume*Wires Interaction Variables.

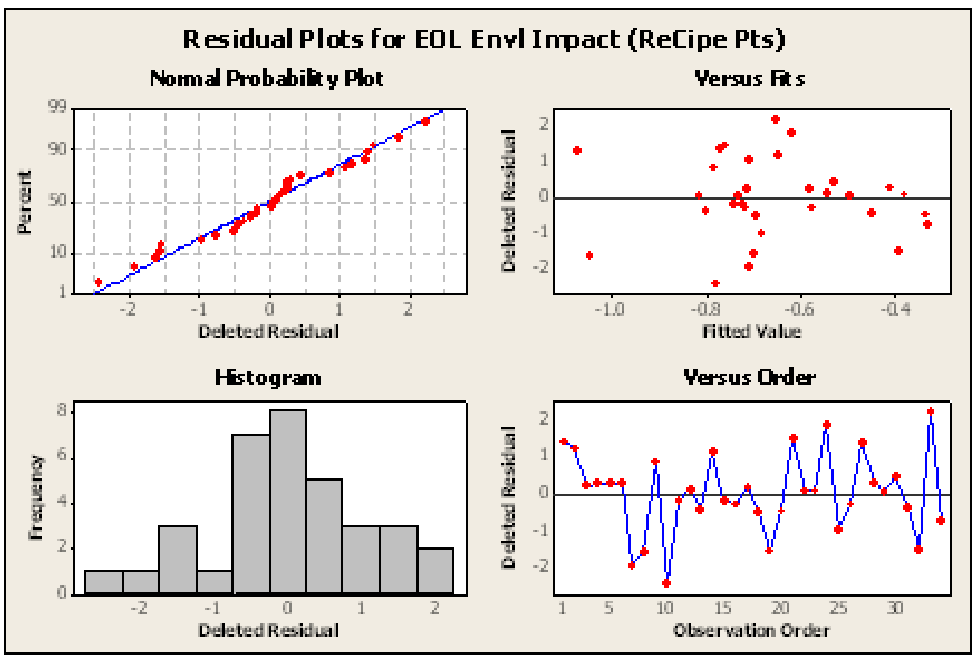


Figure 14.10: Base Model Best Subset with Three Variables and Volume*Placoncen, Wires*Repmod, and Volume*Wires Interaction Variables.

Table 14.4: Base Model Best Subset Three and Four Variable Models with Interaction Variables

Interaction Variables	Model	Vars (K)	SSE	R^2	F	dof	T- test: p-value > 0.05	adequate subset?	5< VIF< 10
*Volume*Plastics concentration* and *Volume*Wires*	EOL Envl Impact (ReCipe Pts) = - 1.29979 + 0.0683441 *Volume* + 0.211249 *Wires* + 2.87206 *PlaConcen* - 0.031527 *Volume*Wires* - 0.364208 *Volume*PlaConcen*	5	0.547	62%	9.01	28	*Volume, Volume*PlaConcen*	yes	*Volume, Wires, PlaConcen, Volume*Wires, Volume*PlaConcen*
*Volume*Plastics concentration, Volume*Wires,* and *Wires*Repetitive modules*	EOL Envl Impact (ReCipe Pts) = - 1.10128 + 0.0734168 *Volume* + 0.189065 *Wires* + 2.48209 *PlaConcen* - 0.0425005 *Repmods* - 0.0457328 *Volume*Wires* - 0.367248 *Volume*PlaConcen* + 0.0459323 *Wires*Repmods*	7	0.422	70%	8.84	26	*Volume, PlaConcen, Repmods, Volume*PlaConcen*	yes	*Volume, Wires, PlaConcen, Volume*Wires, Volume*PlaConcen, Wires*Repmods*

14.1.2 Base Model, Excluding *Wires*

The variable, *Wires*, is removed from the Base Model, because its interaction with *Volume* introduces multicolinearity into the model. From the residual plots, the Base Model, excluding *Wires* satisfies the least squares assumptions (Figure 14.11).

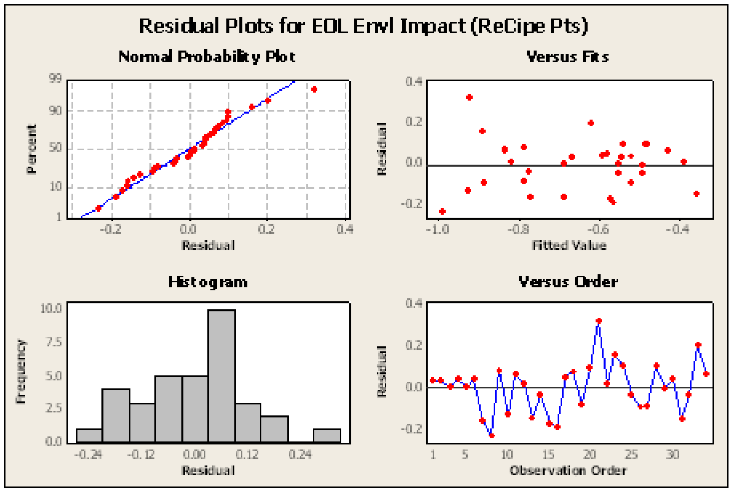


Figure 14.11: Base Model, Excluding *Wires.*

The Base Model, excluding *Wires* does not describe a statistically significant relationship between the design characteristics and the environmental impact of end-of-life disposition, with a p-value of 0.147 and an R^2 of 67.3%. Each of the design characteristics does not have a p-value less than 0.05, so they are not significant.

Best Subsets was used to improve the Base Model, excluding *Wires*. The R^2 adequate for the Base Model, excluding *Wires* is 36.6%. The model is adequately represented with a minimum of one variable, *volume*, with an R^2 value of 41.1% (Table 14.4). From the residual plots, the one variable model satisfies the least squares assumptions (Figure 14.12).

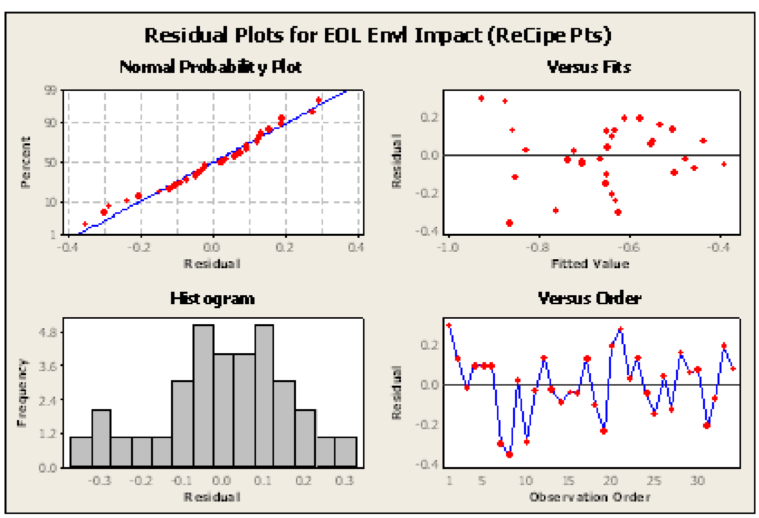


Figure 14.12: Base Model, Excluding *Wires* Best Subset with One Variable- *Volume.*

Table 14.5: ANOVA Summary Table for Base Model, Excluding *Wires* Best Models.

	Model	Vars (K)	SSE	R2	F	dof	T- test: p-value > 0.05	Adequate subset?	SS_R (B_{VOL}|B_{tools}, or $B_{NVAtasks}$)
1	EOL Envl Impact (ReCipe Pts) = - 0.104 - 0.0856 Volume	1	0.839	41%	22.41	32	none	yes	N/A
2	EOL Envl Impact (ReCipe Pts) = - 0.246 - 0.0808 Volume + 0.0433 Tools	2	0.803	44%	12.05	31	Tools	yes	0.499
3	EOL Envl Impact (ReCipe Pts) = - 0.296 - 0.0779 Volume + 0.0088 NVAtasks + 0.0441 Tools	3	0.783	45%	8.21	30	NVAtasks, Tools	yes	0.449
4	EOL Envl Impact (ReCipe Pts) = - 0.460 - 0.171 IND1 - 0.0813 Volume + 0.444 HazConc + 0.0702 Tools	4	0.737	48%	6.78	29	IND1, HazConc, Tools	yes	N/A

14.1.2.1 Model Selection

From the best subsets results models with 2, 3, or 4 variables were evaluated. From the residual plots, the 2, 3, and 4 variable models satisfy the least squares assumptions (Figure 14.13, Figure 14.14, and Figure 14.15). The number of variables, SSE, R^2, F-test, and T-test summarize the ANOVA tables of these models (Table 14.5).

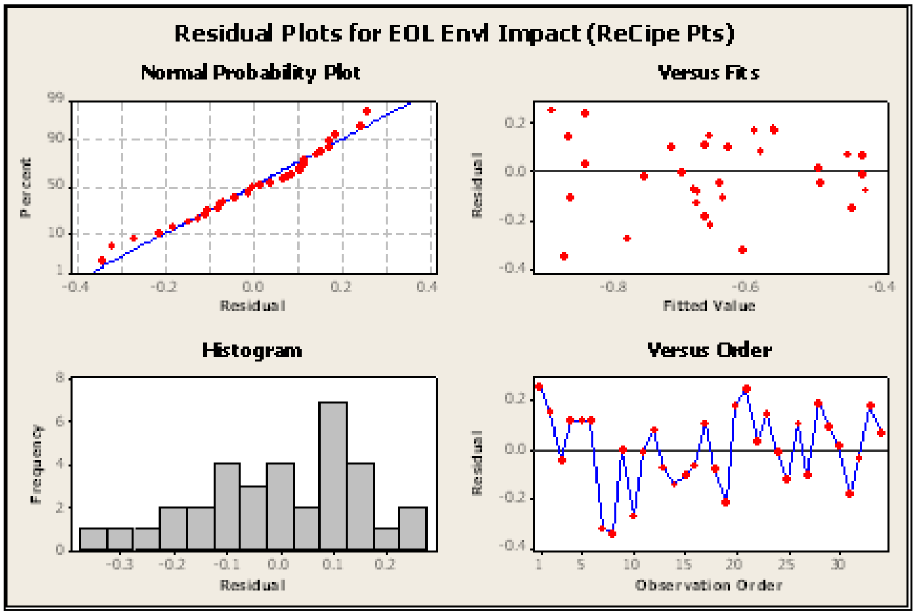


Figure 14.13: Base Model, excluding *Wires* Best Subset with Two Variables- *Volume & Tools*.

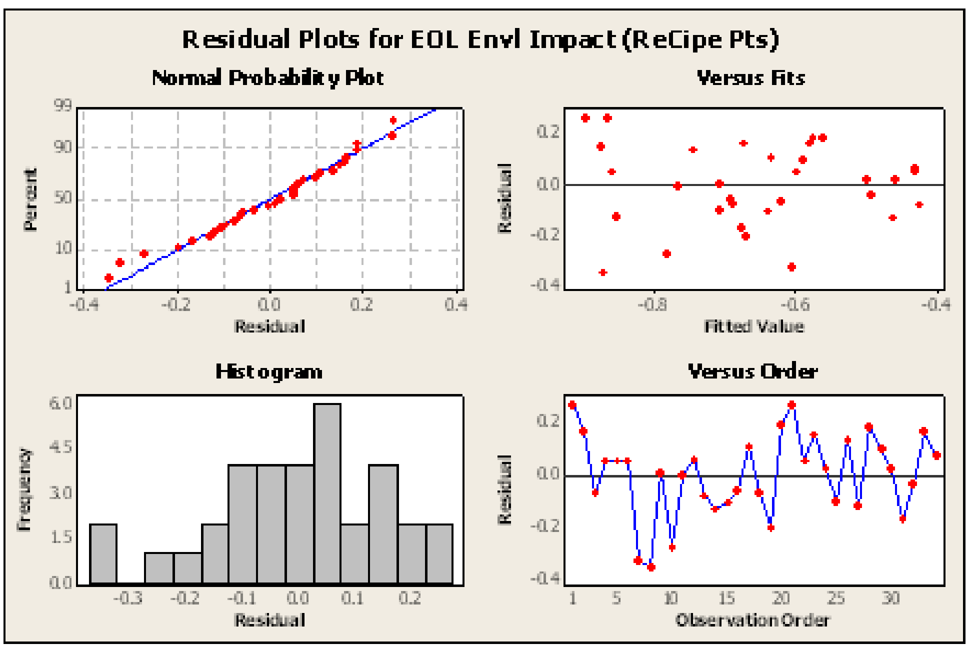


Figure 14.14: Base Model, excluding *Wires* Best Subset with Three Variables- *Volume, NVAtasks, and Tools*.

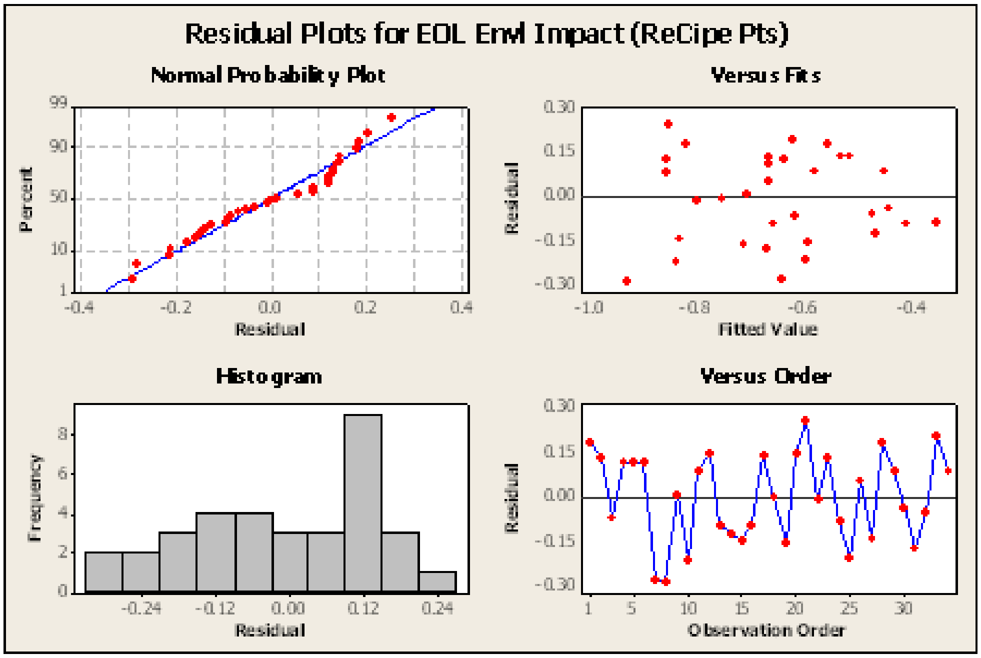


Figure 14.15: Base Model, Excluding *Wires* Best Subset with Four Variables- *IND1, Volume, Hazconc, and Tools.*

The Base Model, excluding *Wires* Best Subset with one variable, *Volume* has an adequate R^2 value of 39%. This R^2 is not considerably increased by the 2, 3, and 4 variable models. The design characteristic that is significant in all models is *Volume*. The design characteristics, *Tools, NVAtasks*, and *IND1* all have a p-value of greater than 0.05, so they are not significant.

14.1.2.1.1 Validation

The best subsets of the Base Model, excluding *Wires* were validated by comparing the predicted correlation and the sign of the variables' coefficients (Table 14.6). Similar to the Base Model, the coefficients validated that the linear regression model is behaving as intended.

Table 14.6: Base Model, Excluding *Wires* Best Subsets Validation.

Design Characteristic Metric	Description/Formula	Correlation with End-of-Life Disposition Environmental Impact	Coefficient's Sign
Product Dimensions			
Volume of a Rectangular Prism	Volume (in^3)= lxwxh	Positive (could be negative due to avoided burden)	**-**
Hazardous Materials			
Percentage of hazardous materials in a product	$\sum_{1}^{i} \frac{mhp_{j_i}}{mhp_j}$, where mph_{j_i} = weight of part with hazardous material, i ∀ parts with hazardous material, i in product, j	Positive	**+**
Ability to Disassemble			
Number of tools used	The number of different tools used for disassembly.	Positive	**+**
Number of non-value added tasks	The number of tasks that do not result in a disassembled part or component.	Positive	**+**

14.1.3 Discussion

The Base Model, excluding *Wires* Best Subset with One Variable best describes the relationship between design characteristics and the environmental impact of end-of-life disposition, because it has an adequate R^2 value and R^2 is not considerably increased by the 2, 3, and 4 variable models. Similar to the Base Model, the design characteristic that is significant in all models is *Volume*. *Wires* will continue to be excluded from the Base Model and all of the sensitivity analysis.

14.2 Sensitivity Analysis

A sensitivity analysis was conducted to understand the uncertainty and variation associated with the end-of-life disposition environmental impact. The assumptions that were tested, as outlined in Chapter 13, are material or component value, recycling process cost (labor, etc.), material removal rate (MRR) threshold (MRR > 5 lbs/min), recovery process loss, avoided product recovery rate, and the environmental perspective of the ReCipe impact assessment method.

14.2.1 Material or Component Value

In the selection of end-of-life disposition scenarios, the recycling process cost and value removal rate (VRR) determine if a cellular phone's components will be manually or mechanically dismantled. In the Base Model, the value removal rate (VRR) is equal to the material or component value divided by the disassembly time. If the VRR is greater than the recycling process cost ($/min), then the component will be manually dismantled. Otherwise, the component is sent to a mechanical dismantling process, such as shredding. To test the sensitivity of the VRR, the material or component cost for each type of material or component was increased by 50% or decreased by 50%. For example, steel has a value of approximately $0.10/lb. Increasing steel's value 50%, would yield $0.15/lb and decreasing steel's value 50% would yield $0.05/lb.

14.2.1.1 Increasing Material and Component Value 50%

Increasing the material and component values 50% had little effect on the environmental impact of end-of-life disposition. In the Base Model, the value removal rate (VRR) is equal to the material or component value divided by the disassembly time. If the VRR is greater than the recycling process cost ($/min), then the component will be manually dismantled. Occasionally, the LCD display or heavy plastic components without BFRs became more valuable to manually dismantle, because their VRR's became greater than the U.S. labor rate ($7.25/hr). The LCD display had little effect on the environmental impact, because it is always incinerated. The plastic components without BFRs were in small quantities and had little effect compared to the battery and the printed circuit board. Manually dismantling these products did not change the end-of-life disposition environmental impact of the cellular phones, so a linear regression model was not created for this case.

14.2.1.2 Decreasing Material and Component Value 50%

Decreasing the material and component values 50% had little effect on the environmental impact of end-of-life disposition. Occasionally, the LCD display, glass components, heavy ferrous metal components or heavy plastic components without BFRs became less valuable to manually dismantle, because their VRR's were less than the U.S. labor rate ($7.25/hr). Mechanically dismantling these components instead of manually dismantling them did not change the end-of-life disposition environmental impact of the cellular phones, so a linear regression model was not created for this case.

14.2.2 Recycling Process Cost or Value Removal Rate (VRR) Threshold

In the selection of end-of-life disposition scenarios, the recycling process cost and value removal rate (VRR) determine if a cellular phone's components will be manually or mechanically dismantled. In the Base Model, the recycling process cost is equal to the United States labor rate of $7.25/hr. If the VRR is greater than the U.S. labor rate, then the component will be manually dismantled. Otherwise, the component is sent to a mechanical dismantling process, such as shredding. To test the sensitivity of the recycling process cost, the VRR was compared to the Brazil labor rate, which is equivalent to $1.36/hr and a recycling process cost of $50/hr.

14.2.2.1 VRR > Brazil ($1.36/hr)

Changing the recycling process cost to the Brazil labor rate of $1.36/hr had little effect on the environmental impact of end-of-life disposition. Typically, the LCD display, components containing copper, like the antenna, components containing rubber, like the keypad, heavy ferrous metal components, or heavy plastic components without BFRs became more valuable to manually dismantle, because their VRR's were greater than the Brazil labor rate. The LCD display had little effect on the environmental impact, because it is always incinerated. The copper, rubber, ferrous, or plastic components without BFRs were in small quantities and had little effect on the end-of-life disposition environmental impact compared to the battery and the printed circuit board.

The Brazil Labor Rate Sensitivity Model has an R^2 adequate similar to the Base Model at 37%. Using Best Subsets resulted in a one variable, *Volume* model with an adequate R^2 of 41%. Best Subsets also resulted in the same two, three, and four variable models as the Base Model. The only significant variable in these models was *Volume,* which is the same as the Base Model.

14.2.2.2 VRR > $50/hr

Changing the recycling process cost to the recycling process cost of $50/hr had little effect on the environmental impact of end-of-life disposition. Typically, the LCD display, glass components, or heavy metal components became less valuable to manually dismantle, because their VRR's were less than $50/hr. Mechanically dismantling these products did not change the end-of-life disposition environmental impact of the cellular phones, so a linear regression model was not created for this case.

14.2.3 Material Removal Rate (MRR) Threshold

In the selection of end-of-life disposition scenarios, the material removal rate (MRR) and MRR threshold determine if a cellular phone's component will be manually or mechanically

dismantled. As recommended by Coulter, et al (1996), the MRR threshold is equal to 5 lbs/min. If the MRR is greater than 5 lbs/min, then the component will be manually dismantled. Otherwise, the component is sent to a mechanical dismantling process, such as shredding. To test the sensitivity of the MRR threshold, the MRR was compared to an MRR threshold of 1 lb/min.

Changing the MRR threshold to 1 lb/min had little effect on the environmental impact of end-of-life disposition. Occasionally, heavy metal components, or heavy plastic components not containing BFRs became more valuable to manually dismantle, because their MRR's were greater than 5 lbs/min. Manually dismantling these products did not change the end-of-life disposition environmental impact of the cellular phones, so a linear regression model was not created for this case.

14.2.4 Recovery Process Loss

The one phase end-of-life disposition LCA assumes that the reuse and recycling processes cannot recover 10% of materials, so they are sent to the landfill. To test the sensitivity of the process loss assumption, the environmental impact was calculated with a process loss of 0% and a process loss of 25%.

14.2.4.1 0% Process Loss

The 0% Process Loss Model had the same R^2 adequate as the Base Model at 37%. Using Best Subsets resulted in a one variable, *Volume* model with an adequate R^2 of 41%. Best Subsets also resulted in the same two, three, and four variable models as the Base Model. The only significant variable in these models was *Volume,* which is the same as the Base Model.

14.2.4.2 25% Process Loss

The 25% Process Loss Model had the same R^2 adequate as the Base Model at 37%. Using Best Subsets resulted in a one variable, *Volume* model with an adequate R^2 of 41%. Best Subsets also resulted in the same two, three, and four variable models as the Base Model. The only significant variable in these models was *Volume,* which is the same as the Base Model.

14.2.5 Avoided Product Recovery Rate

The avoided product recovery rate determines the amount of material that is recovered in the end-of-life disposition processes. Only materials with a closed-loop process that feeds the recovered material back into electronics components will have a percentage of material recovered. These materials include batteries, printed circuit boards, plastics without BFRs, and metals. The

Base Model aggressively assumes an avoided product of 55% as a starting point. To test the sensitivity of this parameter, avoided products of 0%, 20%, and 80% were compared.

14.2.5.1 0% Avoided Product

An avoided product of 0% changes the method for calculating the end-of-life disposition environmental impact from an avoided burden approach to the second life of a cut-off approach (Equation 3.14). This affects the results of the linear regression model. From the Base Model, the R^2 decreases 20% from 67% to 47% and the R^2 adequate decreases 11% from 37% to 26%. From the residual plots, the 0% avoided product sensitivity model (0% AP Model) satisfies the least squares assumptions (Figure 14.16). Dissimilar to the Base Model, the 0% AP Model cannot be adequately represented with a single variable, *Volume,* (Table 14.7).

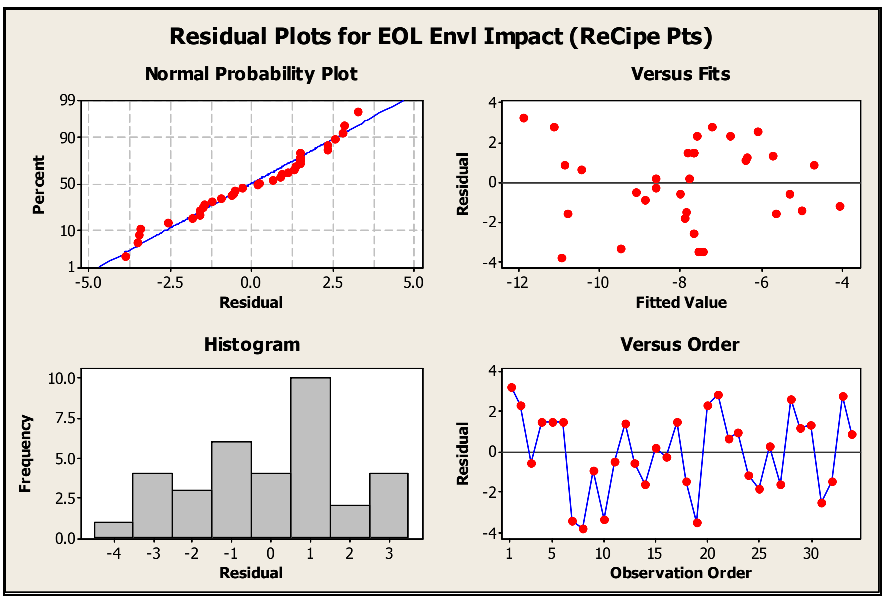


Figure 14.16: 0% AP Model Sensitivity Model Best Subsets with One Variable- *Volume.*

Table 14.7: The Base Model, excluding *Wires* vs. 0% AP Sensitivity Model with One Variable- *Volume*

	Model- Regression Equation	Vars (K)	SSE	R^2	F	dof	T- test: p-value > 0.05?	R2 adequate
Base Model, excluding *Wires*	EOL Envl Impact (ReCipe Pts) = -0.104 - 0.0856 *Volume*	1	0.839	41%	22.41	32	none	36.6%
0% AP Model	EOL Envl Impact (ReCipe Pts) = 0.00703 + 0.000584 Volume	1	1.16E-04	19%	7.51	32	none	25.5%

Best Subsets was also used on the 0% AP Model to compare it to the Base Model. For the two, three, and four variable models, new variables are introduced: *MaterialMixing-H, LOI, and DisassTasks* (Table 14.8). From the residual plots, the 0% AP two, three, and four variable models satisfy the least squares assumptions (Figure 14.17, Figure 14.18, and Figure 14.19). The number of variables, SSE, R^2, F-test, and T-test summarize the ANOVA tables of these models versus the Base Model, excluding *Wires* (BMEW) (Table 14.8).

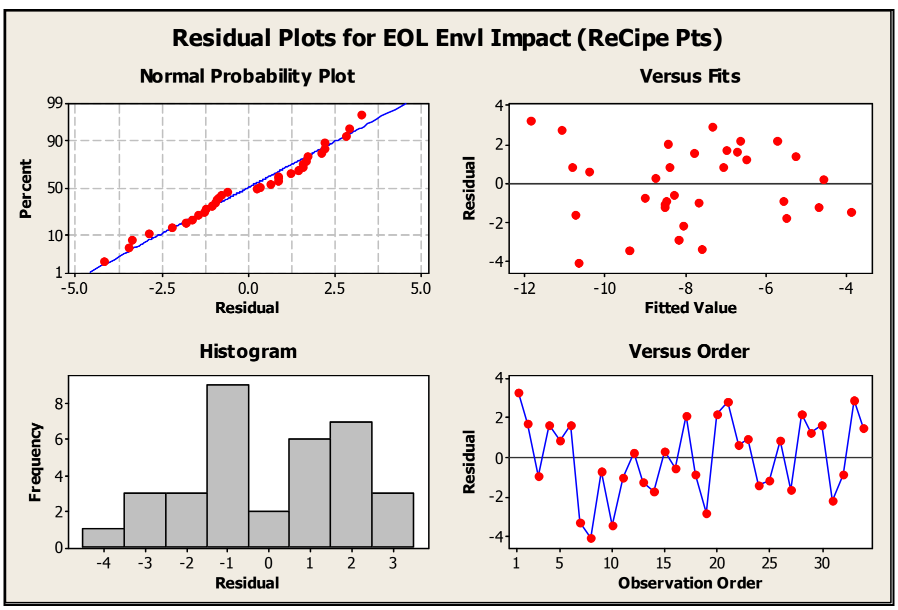


Figure 14.17: 0% AP Model Best Subsets with Two Variables- *Volume* and *MaterialMixing-H.*

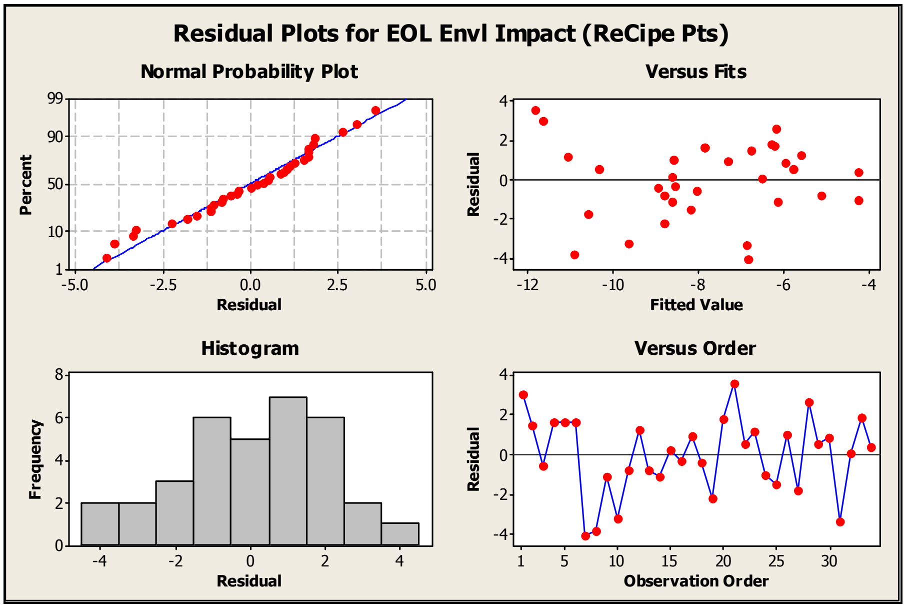


Figure 14.18: 0% AP Model Best Subsets with Three Variables- *Volume*, *MaterialMixing-H* and *LOI*.

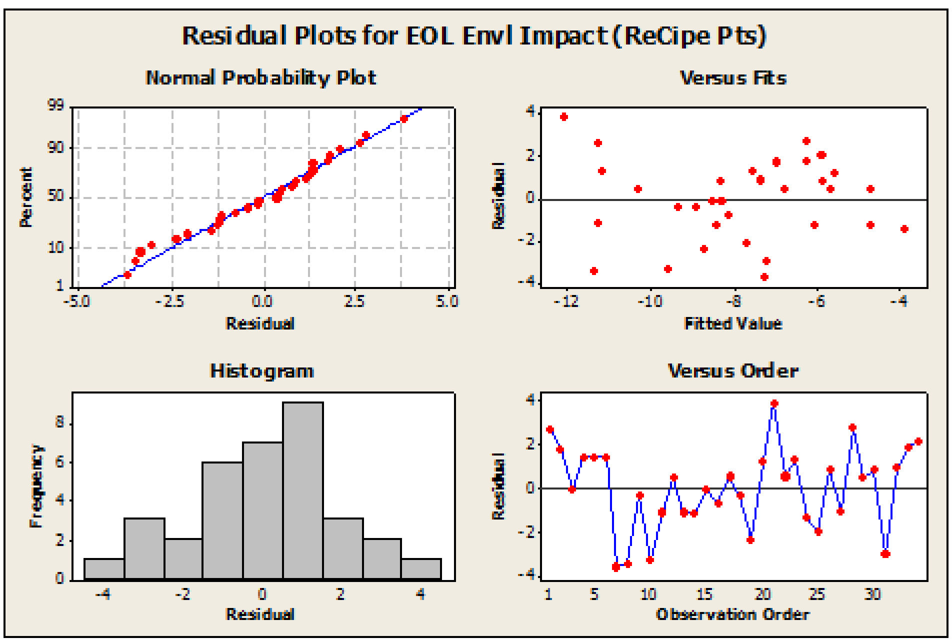


Figure 14.19: 0% AP Model Best Subsets with Four Variables- *IND1*, *Volume*, *MaterialMixing-H,* and *DisassTasks*.

Table 14.8: Base Model, excluding *Wires* vs. 0% AP Sensitivity Two, Three, and Four Variable Models.

	Model	Vars (K)	SSE	R2	F	dof	T- test: p-value > 0.05	Adequate subset?	SS_R (B_{VOL}|B_{tools}, or $B_{NVAtasks}$)
BMEW	EOL Envl Impact (ReCipe Pts) = - 0.246 - 0.0808 Volume + 0.0433 Tools	2	0.803	44%	12.05	31	*Tools*	yes	0.499
0% AP	EOL Envl Impact (ReCipe Pts) = 0.00074 + 0.000580 Volume + 0.00257 MatlMixing-H	2	1.01E-04	30%	6.65	31	*none*	yes	130.085
BMEW	EOL Envl Impact (ReCipe Pts) = - 0.296 - 0.0779 Volume + 0.0088 NVAtasks + 0.0441 Tools	3	0.783	45%	8.21	30	*NVAtasks, Tools*	yes	0.449
0% AP	EOL Envl Impact (ReCipe Pts) = 0.00380 + 0.000535 Volume + 0.00220 MatlMixing-H - 0.000797 LOI	3	8.96E-05	38%	6.07	30	*MatlMixing-H, LOI*	yes	119.459
BMEW	EOL Envl Impact (ReCipe Pts) = - 0.460 - 0.171 IND1 - 0.0813 Volume + 0.444 HazConc + 0.0702 Tools	4	0.737	48%	6.78	29	*IND1, HazConc, Tools*	yes	N/A
0% AP	EOL Envl Impact (ReCipe Pts) = - 0.00113 - 0.00106 IND1 + 0.000865 Volume + 0.00178 MatlMixing-H + 0.000039 DisassTasks	4	8.72E-05	39%	4.71	29	*IND1 MatlMixing-H*	yes	125.857

14.2.5.2 20% Avoided Product

The 20% Avoided Product Sensitivity Model has a R^2 adequate similar to the Base Model at 37%. Using Best Subsets resulted in a one variable, *Volume* model with an adequate R^2 of 40%. Best Subsets also resulted in the same two, three, and four variable models as the Base Model. The only significant variable in these models was *Volume,* which is the same as the Base Model.

14.2.5.3 80% Avoided Product

The 80% Avoided Product Sensitivity Model has a R^2 adequate similar to the Base Model at 37%. Using Best Subsets resulted in a one variable, *Volume* model with an adequate R^2 of 41%. Best Subsets also resulted in the same two, three, and four variable models as the Base Model. The only significant variable in these models was *Volume,* which is the same as the Base Model.

14.2.6 Environmental Perspective in ReCipe Impact Assessment

The ReCipe endpoint method has three versions of normalization and weighting set combinations: egalitarian (E/A), hierarchist (H/A), or individualist (I/A). The egalitarian perspective applies the precautionary principle and all possible relationships with environmental impact are included for a long-term period. The hierarchist perspective includes those relationships widely accepted by the LCA community to describe environmental impact. The individualist perspective includes only proven cause-effect relationships to describe environmental impact in a short-term period. For this method, the baseline impact assessment uses the hierarchist perspective. The egalitarian perspective should have a higher magnitude of end-of-life disposition environmental impact than the baseline and the individualist perspective should have a lower magnitude of end-of-life disposition environmental impact. To test the sensitivity of the environmental perspective, all three methods were compared.

14.2.6.1 Egalitarian Perspective (E/A)

Taking an egalitarian perspective in the ReCipe method drastically increases the magnitude of the end-of-life disposition environmental impact. This affects the results of the linear regression model. From the Base Model, the R^2 increases 9% from 67% to 76% and the R^2 adequate increases 5% from 37% to 42%. From the residual plots, the E/A Sensitivity Model satisfies the least squares assumptions (Figure 14.20). Using Best Subsets, the E/A Model is adequately represented with a minimum of one variable, *Volume*, with an R^2 of 48.4% (Table 14.9).

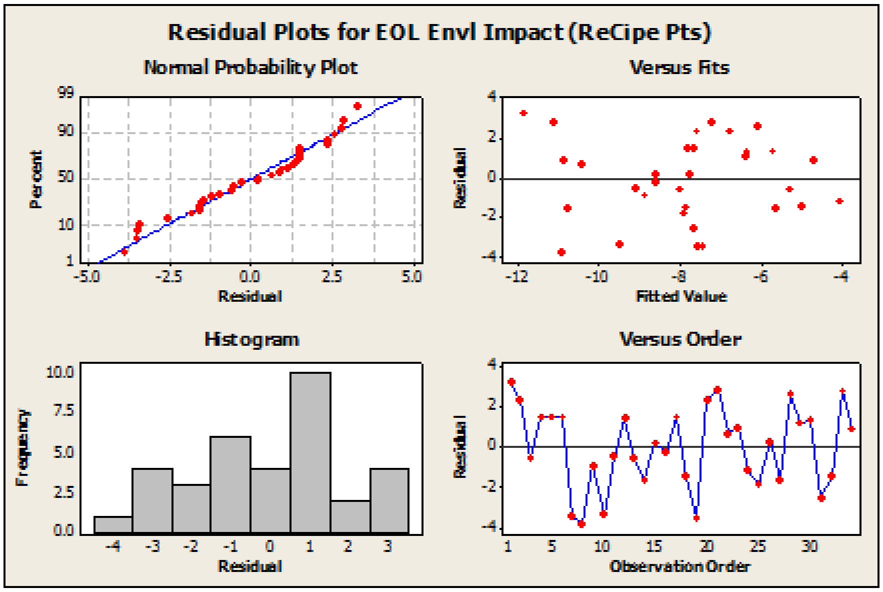


Figure 14.20: E/A Sensitivity Model Best Subsets with One Variable- Volume.

Table 14.9: Base Model, excluding *Wires* vs. E/A Sensitivity Model with One Variable- *Volume*

	Model- Regression Equation	Vars (K)	SSE	R^2	F	dof	T- test: p-value > 0.05?	R2 adequate
Base Model, excluding *Wires*	EOL Envl Impact (ReCipe Pts) = - 0.104 - 0.0856 *Volume*	1	0.839	41%	22.41	32	none	36.6%
E/A Model	EOL Envl Impact (ReCipe Pts) = 0.12 - 1.25 Volume	1	133.72	48%	29.97	32	none	41.7%

Best Subsets was also used on the E/A Model to compare it to the Base Model. For the two. three and four variable models, new variables are introduced, *hazmat, disassparts, LOI, and repmods* (Table 14.10). From the residual plots, the E/A sensitivity two, three, and four variable models satisfy the least squares assumptions (Figure 14.21, Figure 14.22, and Figure 14.23). The number of variables, SSE, R^2, F-test, and T-test summarize the ANOVA tables of these models versus the Base Model, excluding *Wires* (BMEW) (Table 14.10).

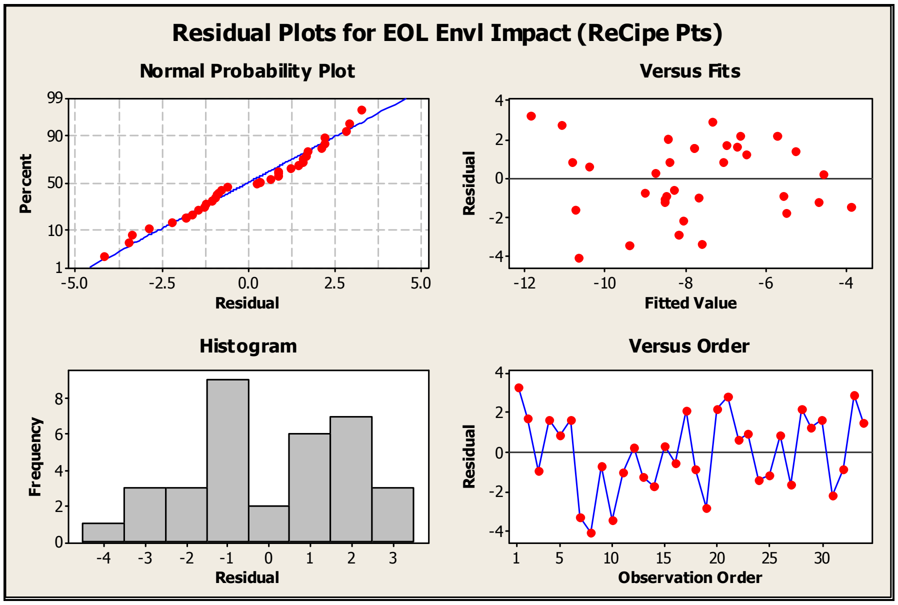


Figure 14.21: E/A Model Best Subsets with Two Variables- *Volume* and *HazMat*

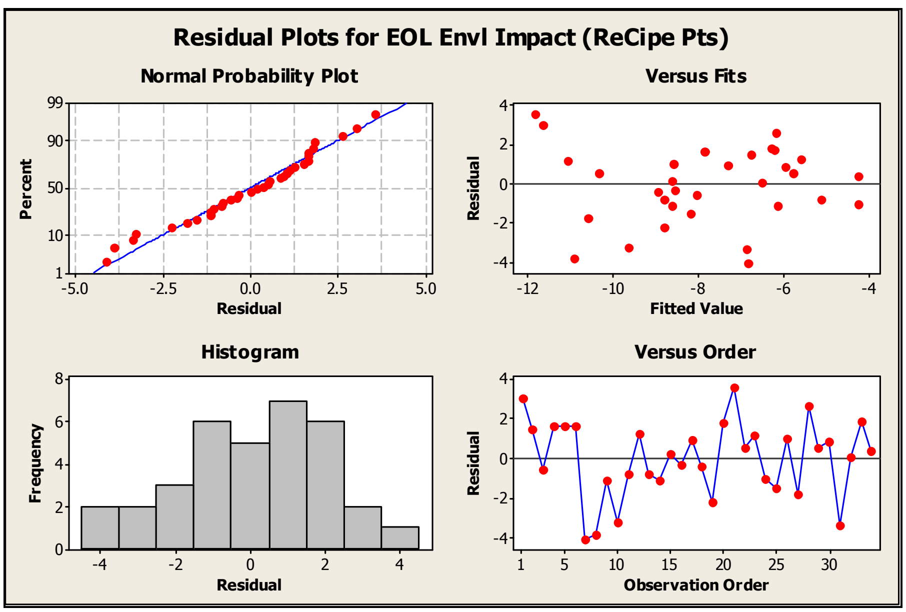


Figure 14.22: E/A Model Best Subsets with Three Variables- *Volume*, *DisassParts* and *LOI*.

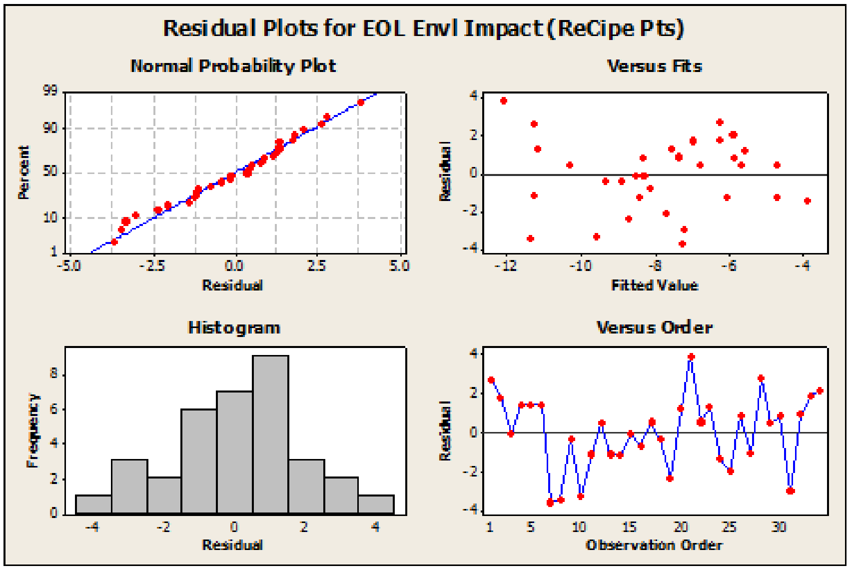


Figure 14.23: E/A Model Best Subsets with Four Variables- *IND1*, *Volume*, *Hazconc,* and *Tools*.

Table 14.10: Base Model, excluding *Wires* vs. E/A Sensitivity Two, Three, and Four Variable Models.

	Model	Vars (K)	SSE	R2	F	dof	T- test: p-value > 0.05	Adequate subset?	SS_R (B_{VOL}|B_{tools}, or $B_{NVAtasks}$)
BMEW	EOL Envl Impact (ReCipe Pts) = - 0.246 - 0.0808 Volume + 0.0433 Tools	2	0.803	44%	12.05	31	*Tools*	yes	0.499
E/A	EOL Envl Impact (ReCipe Pts) = - 0.77 - 1.28 Volume + 0.244 HazMat	2	127.48	51%	15.98	31	*HazMat*	41.7%	130.085
BMEW	EOL Envl Impact (ReCipe Pts) = - 0.296 - 0.0779 Volume + 0.0088 NVAtasks + 0.0441 Tools	3	0.783	45%	8.21	30	*NVAtasks, Tools*	yes	0.449
E/A	EOL Envl Impact (ReCipe Pts) = 6.11 - 1.47 Volume - 0.0780 DisassParts - 1.13 LOI	3	122.65	53%	11.11	30	*DissassParts, LOI*	41.7%	119.459
BMEW	EOL Envl Impact (ReCipe Pts) = - 0.460 - 0.171 IND1 - 0.0813 Volume + 0.444 HazConc + 0.0702 Tools	4	0.737	48%	6.78	29	*IND1, HazConc, Tools*	yes	N/A

	Model	Vars (K)	SSE	R2	F	dof	T- test: p-value > 0.05	Adequate subset?	SS_R (B_{VOL}|B_{tools}, or $B_{NVAtasks}$)
E/A	EOL Envl Impact (ReCipe Pts) = 7.22 - 1.52 Volume - 0.139 DisassParts + 0.604 repmods - 1.45 LOI	4	114.465	56%	11.56	29	*DissassParts, Repmods, LOI*	41.7%	125.857

14.2.6.2 Individualist Perspective (I/A)

Taking an individualist perspective in the ReCipe method reduces the magnitude of the end-of-life disposition environmental impact. This affects the results of the linear regression model. From the Base Model, the R^2 decreases 10% from 67% to 57% and the R^2 adequate decreases 6% from 37% to 31%. From the residual plots, the I/A Sensitivity Model satisfies the least squares assumptions (Figure 14.24). Unlike the Base Model, the I/A Model is not adequately represented with a single variable, *Volume* (Table 14.11). This is due to the decrease in damage characterization factors included in the ReCipe LCIA that give importance to the printed circuit boards, thus giving other characteristics, such as plastic concentration, more room to be important or significant.

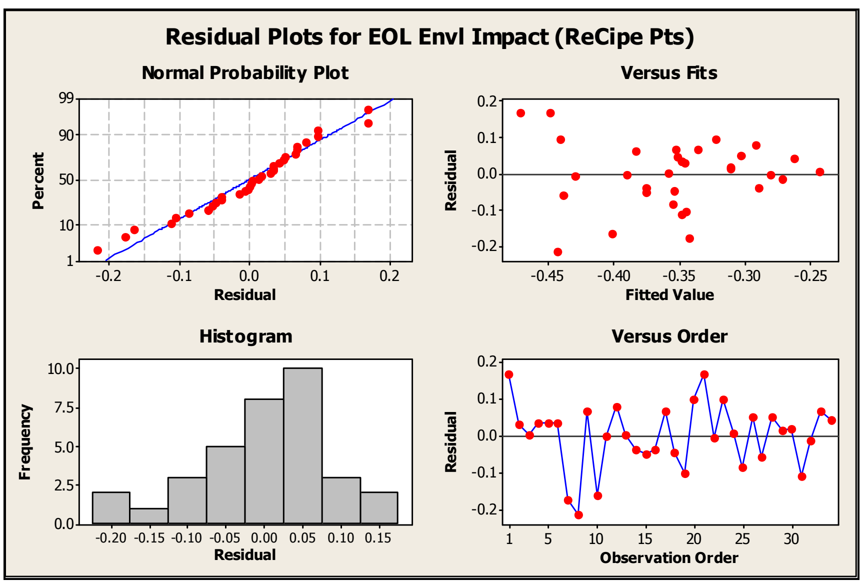


Figure 14.24: I/A Sensitivity Model Best Subsets with One Variable- Volume.

Table 14.11: Base Model, excluding *Wires* vs. I/A Sensitivity Model with One Variable- *Volume*

	Model- Regression Equation	Vars (K)	SSE	R2	F	dof	T- test: p-value > 0.05?	R2 adequate
Base Model, excluding Wires	EOL Envl Impact (ReCipe Pts) = - 0.104 - 0.0856 Volume	1	0.839	41%	22.41	32	none	36.6%
I/A Model	EOL Envl Impact (ReCipe Pts) = - 0.122 - 0.0362 Volume	1	0.257	29%	13.12	32	none	41.7%

Best Subsets was also used on the I/A Model to compare it to the Base Model. For the two, three, and four variable models, a new variable is introduced, *placoncen* (Table 14.12). From the residual plots, the I/A two, three, and four variable models satisfy the least squares assumptions (Figure 14.25, Figure 14.26, and Figure 14.27). The number of variables, SSE, R^2, F-test, and T-test summarize the ANOVA tables of these models versus the Base Model, excluding *Wires* (BMEW) (Table 14.12).

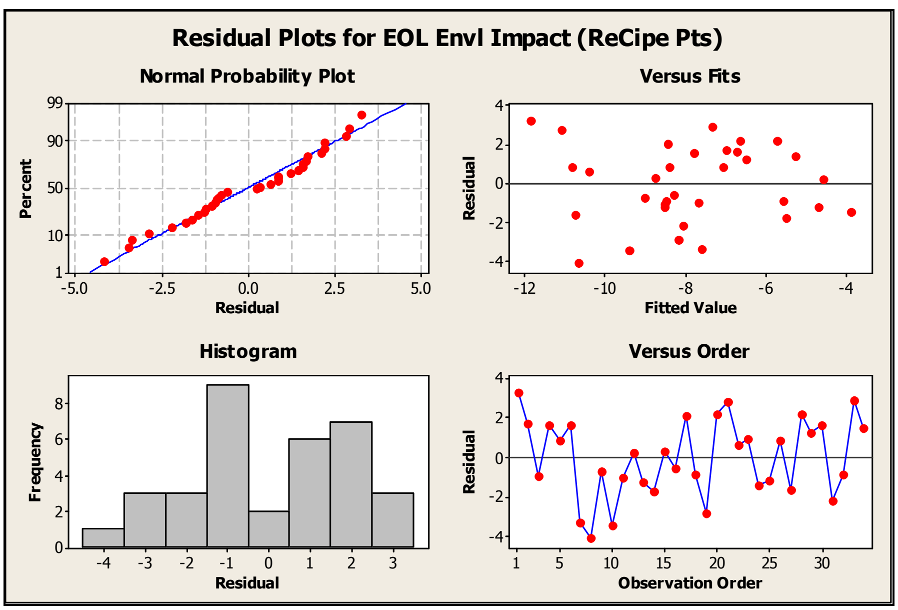


Figure 14.25: I/A Model Best Subsets with Two Variables- *Volume* and *PlaConcen.*

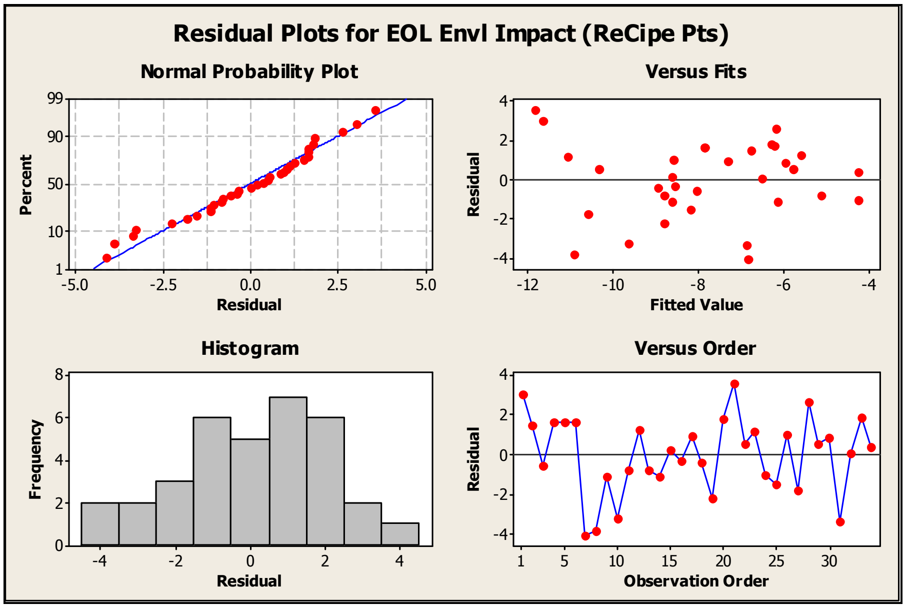


Figure 14.26: I/A Model Best Subsets with Three Variables- *Volume*, *Placoncen* and *Repmods*.

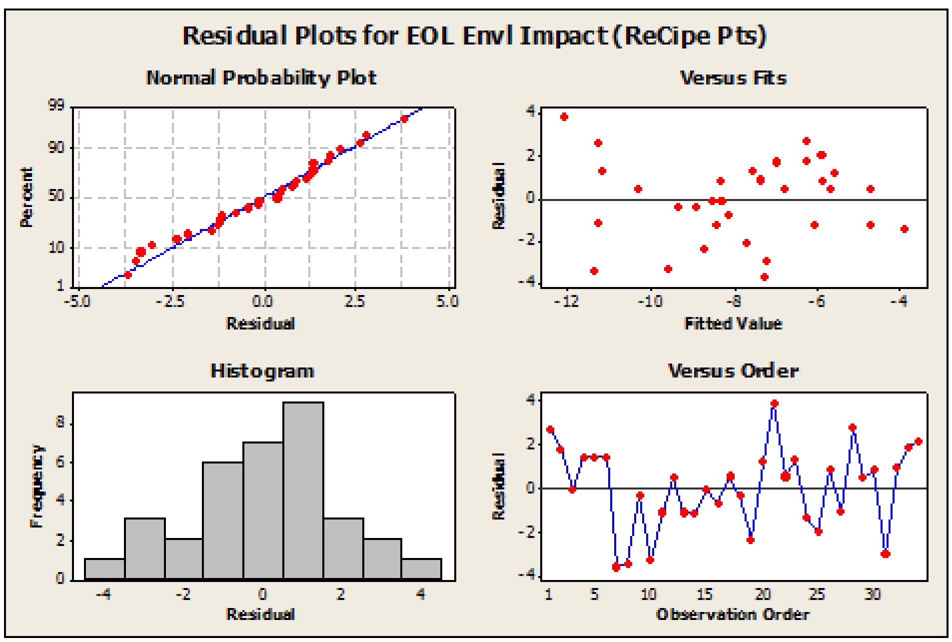


Figure 14.27: I/A Model Best Subsets with Four Variables- *IND1*, *Volume*, *Hazconc,* and *Tools*.

Table 14.12: Base Model, excluding *Wires* vs. I/A Sensitivity Two, Three, and Four Variable Models.

	Model	Vars (K)	SSE	R2	F	dof	T- test: p-value > 0.05	Adequate subset?	SS_R (B_{VOL}|B_{tools}, or $B_{NVAtasks}$)
BMEW	EOL Envl Impact (ReCipe Pts) = - 0.246 - 0.0808 Volume + 0.0433 Tools	2	0.803	44%	12.05	31	*Tools*	yes	0.499
I/A	EOL Envl Impact (ReCipe Pts) = - 0.165 - 0.0363 Volume + 0.153 PlaConcen	2	0.247	32%	7.25	31	*PlaConcen*	yes	0.106
BMEW	EOL Envl Impact (ReCipe Pts) = - 0.296 - 0.0779 Volume + 0.0088 NVAtasks + 0.0441 Tools	3	0.783	45%	8.21	30	*NVAtasks, Tools*	yes	0.449
I/A	EOL Envl Impact (ReCipe Pts) = - 0.192 - 0.0349 Volume + 0.130 PlaConcen+ 0.0099 repmods	3	0.244	33%	4.87	30	*PlaConcen, repmods*	yes	0.093
BMEW	EOL Envl Impact (ReCipe Pts) = - 0.460 - 0.171 IND1 - 0.0813 Volume + 0.444 HazConc + 0.0702 Tools	4	0.737	48%	6.78	29	*IND1, HazConc, Tools*	yes	N/A
I/A	EOL Envl Impact (ReCipe Pts) = - 0.309 - 0.0857 IND1 - 0.0351 Volume + 0.248 HazConc + 0.0354 Tools	4	0.228	37%	4.25	29	*IND1, Hazconc,Tools*	yes	0.081

14.3 Discussion

Linear Regression was used to determine if a relationship exists between the 19 design characteristics and the end-of-life disposition environmental impact. It was also used to determine which of the design characteristics, if any, are significant. A sensitivity analysis was conducted to test the robustness of the model assumptions. If the end-of-life disposition environmental impact was influenced by adjusting the parameters of the model assumptions, new linear regression models were created (Table 14.13). Then the results of each linear regression sensitivity model

were compared to the results of the Base Model. The *Model Name* describes the model assumption that was tested and the parameter that was changed, excluding the Base Model. For example, the second sensitivity model tests the assumption, recycling process cost and the parameter Brazil labor rate ($1.36/hr) as the value removal rate (VRR) threshold. The *Base Model Parameter* represents the value of the parameter in the Base Model that the sensitivity analysis is testing. For example, the third model, 0% Recovery Process Loss Model, tests the model assumption, recovery process loss and the parameter, 0%. In the Base Model, this parameter is 10%, as in the second column. The *Best Model* describes the simplified models in each respective sensitivity analysis that were selected as best models, because their R^2 was greater than the R^2 adequate of their corresponding full model. The column, *Vars (K)* states the number of variables in the best model. *SSE* describes the sum of squared error in the best model. *R^2* states the R^2 value of the best model. *F* states the F value of the best model. *R^2 Adequate* states the R^2 adequate of the best model.

Table 14.13: Summary of Sensitivity Results.

Model Name	Base Model Parameter	Best Model	Vars (K)	SSE	R^2	F	R^2 Adequate
Base Model, excluding *Wires*	N/A	EOL Envl Impact (ReCipe Pts) = -0.104 - 0.0856 Volume	1	0.839	41%	22.41	36.6%
Recycling Process Cost- Brazil labor rate ($1.36/hr) Model	VRR > U.S ($7.25/hr)	EOL Envl Impact (ReCipe Pts) = -0.105 - 0.0857 Volume	1	0.842	41%	22.41	36.8%
0% Recovery Process Loss Model	10%	EOL Envl Impact (ReCipe Pts) = -0.114 - 0.0943 Volume	1	1.014	41%	22.49	36.6%
25% Recovery Process Loss Model	10%	EOL Envl Impact (ReCipe Pts) = -0.0863 - 0.0705 Volume	1	0.572	41%	22.28	36.6%
0% Avoided Product Recovery Rate Model	55%	EOL Envl Impact (ReCipe Pts) = 0.00074 *+ 0.000580 Volume* + 0.00257 MatlMixing-H	2	1.01E-04	30%	6.65	25.5%
20% Avoided Product Recovery Rate Model	55%	EOL Envl Impact (ReCipe Pts) = -0.0346 - 0.0302 Volume	1	0.110	40%	21.31	36.6%
80% Avoided Product Recovery Rate Model	55%	EOL Envl Impact (ReCipe Pts) = -0.155 - 0.123 Volume	1	1.738	41%	22.40	36.8%
Egalitarian Perspective (E/A)	Hierarchist Perspective	EOL Envl Impact (ReCipe Pts) = 0.12 - 1.25 Volume	1	133.72	48%	29.97	41.7%

Model Name	Base Model Parameter	Best Model	Vars (K)	SSE	R^2	F	R^2 Adequate
Model	(H/A)						
Individualist Perspective (I/A) Model	Hierachist Perspective (H/A)	EOL Envl Impact (ReCipe Pts) = -0.165 - 0.0363 Volume + 0.153 PlaConcen	2	0.247	32%	7.25	31.0%

The majority of the sensitivity models are similar to the Base Model. There is barely a difference between the Recycling Process Cost, Brazil Labor Rate Model and the Base Model. They have similar coefficients, the same F and slightly higher SSE, R^2, and R^2 adequate. The 0% Process Loss Model has the same R^2 and R^2 adequate as the Base Model with slightly lower coefficients and higher SSE and F. The 25% Process Loss Model has the same R^2 and R^2 adequate as the Base Model with slightly higher coefficients and lower SSE and F. The 20% Avoided Product Recovery Rate Model has the same R^2 adequate as the Base Model with higher coefficients and lower R^2, SSE, and F. The 80% Avoided Product Recovery Rate Model has the same R^2 as the Base Model with a slightly lower F and coefficients and higher SSE, and R^2 adequate. All of the aforementioned models are adequately described with one variable, *Volume,* where *Volume* is significant.

The 0% Avoided Product Recovery Rate, Egalitarian Perspective (E/A), and Individualist Perspective (I/A) sensitivity models are not similar to the Base Model. The 0% Avoided Product Recovery Rate Model is described by a two variable model with *MaterialMixing- H* as the second variable which is not significant. Without the avoided burden, the end-of-life is described as the second life of the cut-off method (Equation 3.14). This means that the end-of-life disposition environmental impact depends solely on the environmental impact of the dismantling processes. This explains why the intercept and the coefficient of the variable, *Volume*, are now positive. Even though the *MaterialMixing- H* design characteristic is not significant, the diversity of materials in a product can increase the number of dismantling processes, which can lead to a higher environmental impact (Figure 14.28).

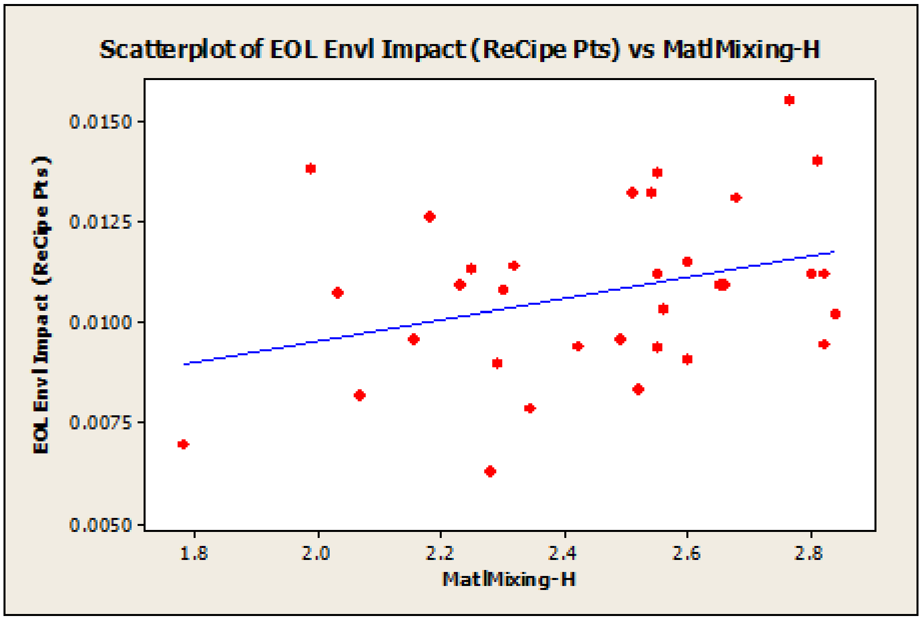


Figure 14.28: Relationship between EOL Environmental Impact and *MatlMixing-H.*

The Egalitarian Perspective (E/A) Sensitivity Model is described by one variable, *Volume*, where *Volume* is significant. The SSE, R^2, F, and R^2 adequate are greater than the Base Model and the coefficients are lower. The SSE is 134, which is more than a 100 times greater than that of the Base Model. This can be attributed to the increased variability in the ReCipe LCIA with the Egalitarian Perspective due to the inclusion of more damage characterization factors. The Egalitarian Perspective also includes more environmental impacts associated with hazardous materials, such as printed circuit boards (Figure 14.29). The Individualist Perspective (I/A) Sensitivity Model is described by a two variable model with *Placoncen* as the second variable which is not significant. Even though *Placoncen* is not significant, its presence can be attributed to the decrease in damage characterization factors included in the ReCipe LCIA (Figure 14.29).

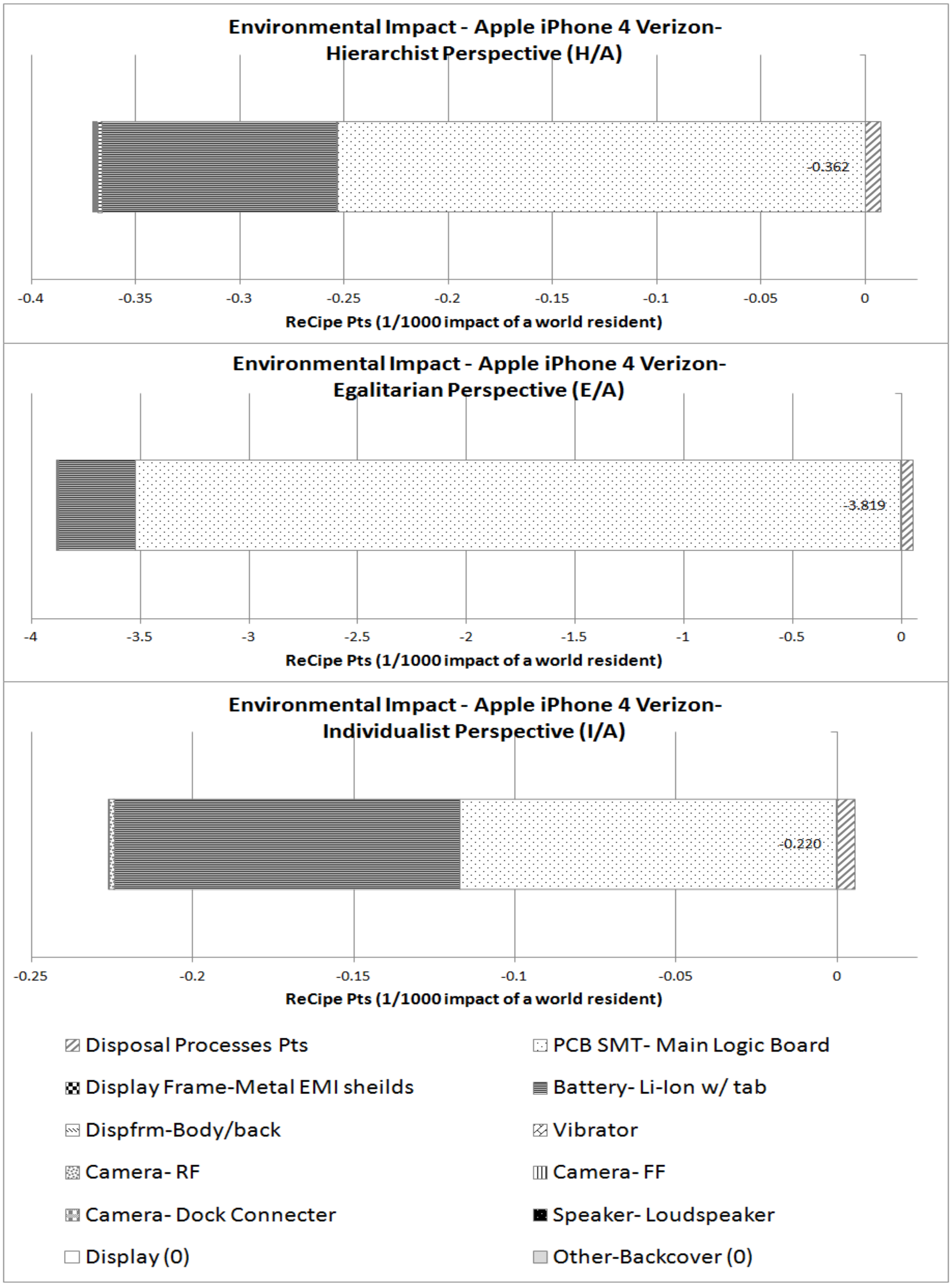


Figure 14.29: The one-phase end-of-life disposition environmental impact of the Apple iPhone 4 Verizon with the Hierarchist Perspective vs. the Egalitarian Perspective vs. the Individualist Perspective.

The robustness of the Base Model is evaluated by testing the model assumptions in the sensitivity analysis. The Material or Component Value, the Recycling Process cost or Value Removal Rate Threshold, and the Material Removal Rate Threshold sensitivity analyses determine the ability of the Base Model to adequately represent the end-of-life process selection of materials and components. The Recovery Process Loss, Avoided Product Recovery Rate, and the Environmental Perspective in ReCipe LCIA sensitivity analyses determine the ability of the base mode to adequately represent the environmental impact of end-of-life disposition. From the sensitivity analysis, the conclusion is drawn that the end-of-life process selection of materials and components is robust. On the other hand, the Base Model representation of the environmental impact of end-of-life disposition is robust only if the Avoided Product Recovery Rate is not equal to zero and the Environmental Perspective in the ReCipe LCIA is Hierarchist.

Chapter 15

CONCLUSIONS

The main objective of this thesis is to determine if design characteristics have a significant relationship with the environmental impact of end-of-life disposition. To determine this, the following actions are performed:

(1) Design characteristics related to end-of-life disposition are extracted from DfE, LCA, environmental management studies, etc (Chapter 5);

(2) End-of-life disposition characteristics are assessed for their ability to quantitatively describe consumer electronics and selected as design characteristic metrics (Chapter 6);

(3) Thirty-four cellular phones, including ten smart phones, are described by the nineteen design characteristic metrics (Chapter 6);

(4) The end-of-life disposition methods are selected for the cellular phones' materials and components using the MRR, VRR, and WEEE regulations (Chapter 8);

(5) The end-of-life disposition environmental impact of the 34 cellular phones are calculated using a one-phase end-of-life disposition life cycle assessment (LCA) using the avoided burden approach (Chapter 9);

(6) Linear regression analysis (LRA) is used to relate the design characteristics and the end-of-life disposition environmental impact to determine the most significant design characteristics (Chapter 10);

(7) Finally, sensitivity analysis is used to determine the robustness of the end-of-life disposition selection for materials and components and the one-phase LCA (Chapter 13).

The methodology (Chapters 4-13) was used to determine if design characteristics of cellular phones had a significant contribution to the end-of-life disposition environmental impact of cellular phones (Section 14.1). It was also used to determine which design characteristics were significant (Section 14.1). Finally, the model was tested under various conditions to determine the scope in which it provides accurate, meaningful information (Section 14.2). In this section, the results are

reviewed to evaluate the ability of the methodology to meet the thesis objective. Then the results are used to determine if there is a relationship between cellular phone designs and their environmental impacts. Finally, the potential for the methodology to be extended to other consumer electronics and design activities is explored.

The results of the research method demonstrate that it is possible to establish a relationship between cellular phone design characteristics and their end-of-life disposition environmental impact. The linear regression analysis (LRA) concluded that *Volume* is the only significant design characteristic for cellular phones end-of-life disposition environmental impact. A cellular phone's end-of-life disposition environmental impact is dominated by components that are regulated by the WEEE protocol (batteries and printed circuit boards (PCBs)), so their environmental impact is driven by the size and weight of these components and not the other design characteristics. Manipulating the studied design characteristics does not have as much of an effect on the end-of-life environmental impact as adhering to the WEEE protocol. This trend is consistent with the results of the one-phase end-of-life disposition life cycle assessments that evaluated the 24 regular cellular phones and the 10 smart phones.

Design for the Environment (DfE) methods can use the results of the LRA by incorporating the WEEE protocol and ensuring the ease of removal of the components driven by the WEEE protocol, so their valuable materials can be recovered. Since the results of the end-of-life disposition LCA are consistent and do not differ by cellular phone type or design (Chapter 9), a generic method for determining the environmental benefits of recovering materials and components regulated by WEEE can be created. A method for estimating the environmental benefit of recycling cellular phones could also be created from the Base Model's best model (Equation 15.1). For example, the Apple iPhone 4 Verizon has a volume of 3.88 in^3. Using Equation 15.1, the estimated environmental impact is -0.44 ReCipe Pts. The calculated environmental impact is -0.36 ReCipe points, so there is an error of approximately 17%. For all of the cellular phone models used in this study, the error ranges from -49% to 32% (Figure 14.6). Due to the variability in the model, the designer could use the model to make rough estimates based on significant changes to the size of the cellular phone at best.

$$\text{EOL Envl Impact (ReCipe Pts)} = -0.104 - 0.0856 * Volume \qquad (15.1)$$

The results of the study are specific to cellular phones and may not apply to other consumer electronics, but the method as a whole is transferrable to other consumer electronics and other design activities. Other consumer electronic devices such as desktops and laptops can be defined by the design characteristics used herein and the corresponding end-of-life disposition environmental impact can be determined using the thesis method outlined in Chapters 4-13. To determine the end-of-life disposition of the materials and components for the laptops and desktops, (1) the list of hazardous materials manually dismantled according to the WEEE protocol and (2) the value of the materials and components, defined in Chapter 8, need to be adjusted. For consumer electronics with consumables, such as printers, the design characteristics, defined in Chapter 5 and Chapter 6, need to be adjusted to include consumption parameters, such as pages printed. Then (1) the list of hazardous materials manually dismantled according to the WEEE protocol and (2) the value of the materials and components, defined in Chapter 8, need to be adjusted to determine the end-of-life disposition of the consumables. Finally the scope of the one-phase end-of-life disposition life cycle assessment, defined in Chapter 9, specifically the functional unit, needs to be adjusted to account for the consumables waste.

For other design activities, it is possible to determine a set of design criteria to be compared to a potential environmental impact. This can be accomplished by extending the end-of-life disposition model or by creating new models. To extend the end-of-life disposition model, the following actions must be taken:

(1) Model the end-of-life disposition environmental impact using a different allocation method such as cut-off or 50/50; or
(2) Calculate the environmental impact using a different life cycle impact assessment method, such as the IPCC Global Warming Potential method, which is a midpoint method.

In the future, for example, the model can be extended to determine the significance of e-reader user behavior on the environmental impact of the e-reader. A set of design criteria could be defined for the user behavior of an e-reader. Then the environmental impact of the e-reader could be calculated. Finally, linear regression analysis could be used to determine the characteristics of e-reader user behavior that significantly contributes to the environmental impact of e-readers.

This thesis proves the ability of the method to establish a relationship between the design characteristics of cellular phones and their corresponding end-of-life disposition environmental impact. It demonstrates *Volume* as a significant design characteristic in the end-of-life disposition

of cellular phones, which justifies the environmental benefit of recovering components regulated by the WEEE protocol. Finally, it provides a scientific approach to choosing the criteria for the reduction of the environmental impact of consumer electronic products and has the potential to expand into broader waste electrical and electronic equipment (WEEE) design activities.

Appendix

A. Base Model Data

Response through Predictor 9

		y1	Indicator	x1	x2	x3	x4	x5	x6	x7	x8	x9
Obs	**Product Name**	EOL Env'l Impact **(ReCipe Pts)**	IND1 **(Reg. Cell Phone)**	Volume **(LxWxH)**	# of Fasteners **(# of screws/ bolts/ snaps)**	Number of Wires/Cables/Ribbons	# of contaminated parts **(# parts with adhesives, labels, or paint)**	Material Concentration **(Material Mixing, H)**	Plastics Concentration **(Mass %i)**	Plastics Variety **(# diff plastics)**	Hazardous Mat'ls **(# parts w/ hazmats)**	Hazardous Mat'l Concentration **(Mass %)**
1	**Nokia NHA-3NA**	-0.64	**1.00**	9.63	15.00	0.00	3.00	1.99	0.24	4.00	5.00	0.86
2	**LG VX5300**	-0.51	**1.00**	6.17	16.00	0.00	6.00	2.32	0.39	4.00	7.00	0.80
3	**LG VX4650-819**	-0.69	**1.00**	6.53	18.00	2.00	6.00	2.23	0.30	2.00	6.00	0.75
4	**LG VX4500-741**	-0.55	**1.00**	6.24	18.00	3.00	6.00	2.66	0.35	4.00	5.00	0.75
5	**LG VX4500-980**	-0.55	**1.00**	6.24	18.00	3.00	6.00	2.65	0.35	4.00	5.00	0.75
6	**LG VX4500-508**	-0.55	**1.00**	6.24	18.00	3.00	6.00	2.65	0.35	4.00	5.00	0.75
7	**Samsung SPH-N300**	-0.93	**1.00**	6.08	10.00	2.00	4.00	2.30	0.29	3.00	2.00	0.61
8	**Samsung SCH-3500**	-1.22	**1.00**	8.86	10.00	2.00	4.00	2.15	0.28	3.00	2.00	0.63
9	**Audiovox**	-0.70	**1.00**	7.20	9.00	1.00	3.00	2.52	0.49	4.00	6.00	0.67
10	**Nextel i530**	-1.05	**1.00**	7.70	11.00	1.00	2.00	2.68	0.27	4.00	4.00	0.63
11	**Motorolla V60s**	-0.77	**1.00**	7.39	11.00	1.00	4.00	2.82	0.21	2.00	5.00	0.53
12	**Motorolla V3m Razr**	-0.37	**1.00**	4.67	19.00	1.00	4.00	2.55	0.50	3.00	7.00	0.48
13	**Motorolla BZ60 Razr**	-0.50	**1.00**	4.36	14.00	1.00	4.00	2.51	0.37	2.00	9.00	0.66
14	**LG CU720**	-0.59	**1.00**	4.61	32.00	0.00	7.00	2.60	0.28	3.00	6.00	0.58
15	**LG VX4400-272**	-0.74	**1.00**	7.00	15.00	3.00	4.00	2.55	0.32	3.00	5.00	0.73
16	**LG VX4400-778**	-0.75	**1.00**	7.00	15.00	3.00	3.00	2.49	0.29	3.00	5.00	0.74
17	**LG VX8300**	-0.53	**1.00**	6.36	14.00	4.00	4.00	2.81	0.49	3.00	5.00	0.61
18	**Samsung SPH-M540**	-0.76	**1.00**	6.39	30.00	1.00	7.00	2.80	0.18	3.00	7.00	0.57
19	**Samsung SCH-R560**	-0.87	**1.00**	6.14	27.00	1.00	5.00	2.60	0.11	2.00	5.00	0.62
20	**Samsung SCH-A870**	-0.39	**1.00**	5.51	14.00	4.00	5.00	2.29	0.41	3.00	6.00	0.75
21	**Nokia NPW-1NB 3360**	-0.60	**1.00**	9.00	8.00	0.00	3.00	2.55	0.29	3.00	4.00	0.67
22	**Kyocera 2325**	-0.81	**1.00**	8.47	5.00	0.00	5.00	2.18	0.40	3.00	7.00	0.85
23	**Nokia NHA-3SA**	-0.73	**1.00**	8.80	9.00	0.00	3.00	2.03	0.26	3.00	4.00	0.78
24	**UTStarcom**	-0.44	**1.00**	3.34	14.00	0.00	3.00	1.78	0.29	3.00	4.00	0.92
25	**Blackberry 8820**	-0.81	**0.00**	6.42	6.00	1.00	8.00	2.82	0.31	4.00	4.00	0.55
26	**Blackberry 9630**	-0.61	**0.00**	6.34	12.00	4.00	4.00	2.84	0.24	2.00	4.00	0.54
27	**Palm Treo 500v**	-0.97	**0.00**	8.73	10.00	3.00	4.00	2.54	0.11	2.00	2.00	0.44
28	**Samsung Galaxy S 4G**	-0.38	**0.00**	4.99	10.00	5.00	1.00	2.42	0.22	1.00	3.00	0.38
29	**Motorola Atrix 4G**	-0.49	**0.00**	5.22	13.00	5.00	2.00	2.56	0.17	1.00	2.00	0.37
30	**Samsung Nexus S 4G**	-0.48	**0.00**	5.20	13.00	4.00	2.00	2.28	0.18	1.00	3.00	0.36
31	**HTC Evo 4G**	-0.85	**0.00**	6.24	13.00	3.00	1.00	2.25	0.18	1.00	2.00	0.35
32	**Sony Ericsson Xperia X10 Mini E10i**	-0.53	**0.00**	4.11	14.00	2.00	1.00	2.07	0.37	1.00	2.00	0.40
33	**Motorola Droid 2**	-0.42	**0.00**	5.89	16.00	6.00	3.00	2.76	0.10	1.00	4.00	0.24
34	**Apple iPhone 4 Verizon**	-0.36	**0.00**	3.88	30.00	9.00	4.00	2.34	0.01	1.00	2.00	0.25

Predictors 10-18

		x10	x11	x12	x13	x14	x15	x16	x17	x18
Obs	**Product Name**	Number of disassembled parts **(#of parts)**	Ability to Disassemble **(# of disassembly tasks)**	Ability to Disassemble **(# of non-value added tasks)**	Ability to Disassemble **(# of tools)**	Material Variety **(# parts w/ diff mats.)**	Ability to Disassemble **(# of seq. depend. disass. steps)**	# of repetitive modules **(# of duplicated modules)**	Level of Integration **(# functions/modules)**	Obsolescence- **(yrs to failure - product families avg. life (yrs))**
1	**Nokia NHA-3NA**	25.00	61.00	2.00	3.00	9.00	23.00	3.00	1.52	9.00
2	**LG VX5300**	29.00	69.00	2.00	2.00	11.00	22.00	2.00	1.39	1.00
3	**LG VX4650-819**	29.00	93.00	6.00	3.00	8.00	11.00	2.00	2.06	3.00
4	**LG VX4500-741**	24.00	70.00	11.00	2.00	11.00	13.00	3.00	2.60	4.00
5	**LG VX4500-980**	24.00	70.00	11.00	2.00	11.00	13.00	3.00	2.60	4.00
6	**LG VX4500-508**	24.00	70.00	11.00	2.00	11.00	13.00	3.00	2.60	4.00
7	**Samsung SPH-N300**	18.00	54.00	4.00	3.00	10.00	15.00	1.00	2.33	6.00
8	**Samsung SCH-3500**	13.00	36.00	3.00	2.00	9.00	13.00	1.00	2.69	8.00
9	**Audiovox**	22.00	66.00	2.00	3.00	12.00	10.00	1.00	2.19	5.00
10	**Nextel i530**	31.00	87.00	3.00	2.00	9.00	13.00	3.00	1.80	5.00
11	**Motorolla V60s**	25.00	92.00	2.00	2.00	10.00	17.00	3.00	1.89	4.00
12	**Motorolla V3m Razr**	42.00	129.00	6.00	4.00	7.00	23.00	5.00	1.39	4.00
13	**Motorolla BZ60 Razr**	40.00	132.00	4.00	4.00	8.00	21.00	4.00	1.50	2.00
14	**LG CU720**	42.00	92.00	2.00	4.00	7.00	15.00	4.00	1.95	2.00
15	**LG VX4400-272**	24.00	69.00	3.00	4.00	8.00	9.00	3.00	2.31	7.00
16	**LG VX4400-778**	23.00	63.00	2.00	3.00	9.00	9.00	3.00	2.31	7.00
17	**LG VX8300**	24.00	85.00	3.00	3.00	8.00	11.00	3.00	1.95	3.00
18	**Samsung SPH-M540**	39.00	73.00	2.00	2.00	8.00	15.00	4.00	2.35	2.00
19	**Samsung SCH-R560**	37.00	81.00	2.00	2.00	8.00	14.00	4.00	2.67	0.00
20	**Samsung SCH-A870**	21.00	68.00	2.00	3.00	7.00	13.00	3.00	2.29	3.00
21	**Nokia NPW-1NB 3360**	19.00	53.00	0.00	3.00	9.00	10.00	2.00	2.92	8.00
22	**Kyocera 2325**	18.00	55.00	1.00	2.00	8.00	9.00	2.00	2.31	7.00
23	**Nokia NHA-3SA**	19.00	58.00	2.00	2.00	7.00	11.00	2.00	2.50	12.00
24	**UTStarcom**	21.00	90.00	1.00	2.00	6.00	8.00	3.00	3.36	2.00
25	**Blackberry 8820**	18.00	49.00	0.00	2.00	8.00	14.00	3.00	3.08	2.00
26	**Blackberry 9630**	21.00	53.00	0.00	1.00	7.00	13.00	3.00	3.33	0.00
27	**Palm Treo 500v**	21.00	64.00	4.00	2.00	8.00	16.00	1.00	2.00	1.00
28	**Samsung Galaxy S 4G**	19.00	48.00	4.00	2.00	7.00	8.00	2.00	3.08	-2.00
29	**Motorola Atrix 4G**	18.00	44.00	3.00	2.00	9.00	8.00	2.00	2.50	-2.00
30	**Samsung Nexus S 4G**	18.00	41.00	3.00	4.00	5.00	6.00	2.00	2.67	-1.00
31	**HTC Evo 4G**	17.00	43.00	2.00	2.00	7.00	5.00	1.00	2.22	-1.00
32	**Sony Ericsson Xperia X10 Mini E10i**	12.00	38.00	4.00	2.00	6.00	6.00	1.00	5.00	-1.00
33	**Motorola Droid 2**	23.00	60.00	5.00	3.00	8.00	10.00	2.00	1.74	-1.00
34	**Apple iPhone 4 Verizon**	48.00	92.00	4.00	3.00	8.00	34.00	1.00	0.78	-2.00

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