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Evaluating the End-of-Life Phase of Consumer Electronics:Methods and Tools to Improve Product Design and Material Recovery

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Evaluating the End-of-Life Phase of Consumer Electronics: Methods and Tools to Improve Product Design and Material Recovery

by

Jennifer Ann Mangold

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requirements for the degree of
Doctor of Philosophy

in

Engineering - Mechanical Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor David Dornfeld, Chair
Professor Paul Wright
Professor Sara Beckman

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Abstract

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Jennifer Ann Mangold

Doctor of Philosophy in Engineering - Mechanical Engineering

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Professor David Dornfeld, Chair

Rapid sales growth and technology advancements are generating a growing stream of consumer electronics products that are being placed on the market. Once these products are no longer useful to their current owners they become e-waste as they enter the end-of-life phase. For many years, the end-of-life phase has been ignored or overlooked due to its perceived low impact across the product life cycle. However, the growing concerns of the environmental burden of e-waste and the increased legislation that focuses on this life cycle phase, it is garnering more attention. To sustainably manage end-of-life electronic products, solutions should be developed that focus on the decisions made in the beginning and end of the product life cycle. To address this need, this research developed methods and tools to inform end-of-life strategies for consumer electronic products during the design and end-of-life phases of the product life cycle.

First, an assessment framework was developed to evaluate and characterize 14 material recovery facilities within the U.S. that process e-waste. The framework consists of five key categories that were used to conduct the assessment including, facility overview, operating model and process flows, product flows, collection methods, and facility resource use. The results of the assessment were used to conduct a material flow analysis to develop a representative set of end-of-life pathways (e.g., reuse, refurbish, recycle) in order to better understand the flow of e-waste within the end-of-life management industry in the U.S. A quantitative assessment of e-waste flows was conducted and insights into the mechanisms and pathways were identified. From the analysis, the majority of products collected at almost all facilities were mobile phones. This could be attributed to their short lifespans compared to other products. Based on the results of the material flow analysis of the products collected at each facility, the majority (over 80%) followed the recycling end-of-life pathway. Laptop computers was identified as the primary product category that follows the reuse and refurbish pathways. While the majority of consumer electronic products are sold to the consumer sector, the results showed that over 60% of products collected were from the business sector.

The second part of this work focused on product level solutions. Evaluating the recyclability of products is the most common method used by stakeholders in producer responsibility to determine the environmental performance of products in the end-of-life phase. A consumer electronic product recyclability model was developed to calculate the recyclable mass of the product and economic value of the recovered materials. The model is comprised of smaller component models and a database of the recycling efficiency and scrap value of materials used in electronic products. With the complexity of components and supplier based purchasing it is difficult for OEMs to provide detailed material information at the product and component levels. In order to reduce the amount of data required to use the tool, the component models were developed for standard components found in consumer electronic products. A case study of a laptop was used to verify the model. From this, the recyclability of the laptop was determined to be 37% and the value of the recycled materials was $4.90.

This dissertation has developed methods that can be used to evaluate end-of-life electronic products at product and facility levels. There is a need for accurate assessments of process technologies at material recovery facilities to collect primary data to better inform and quantify product recyclability. With this data advanced modeling and process simulations tools could be developed that are utilized both by product designers and end-of-life practitioners.

To my family.

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Acknowledgments

I first would like to thank all of those that came before me that have led the way and made this journey possible.

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I would like to thank God for making all of this possible.

Chapter 1

Introduction

1.1 The Intersection of Sustainability and Technology

Major technological advancements in computing and the rapid progression of hardware over the last half century have been significant; from vacuum tubes (1950s), transistors (1950s-60s), integrated circuits (1960s-70s), to silicon computer chips (1970s-today). In addition to the development of technology, the size of computing or information and communication technology (ICT) equipment has decreased significantly as processing power has increased, as evidenced by Moore's Law. In 1965, Moore predicted the following trend: the number of components (later adapted to transistors) per chip "roughly" doubles every two years [1]. Figure 1.1 shows the validation of Moore's law over the past four decades.

There has been recent debate about whether we are nearing the end of Moore's Law, or at least that growth is slowing, due to rising fabrication costs as well as physical limits of materials. Nevertheless, the ubiquitous nature of computing devices in our society and daily lives continues to increase. The advancements in processing technology and reduced cost have enabled these devices to be more accessible to an increasing number of users. The widespread adoption of technology, has allowed us to gain more access to education, healthcare, and commerce while increasing the ability for communication and connection within our society. These technical advances provide many opportunities and societal benefits but also pose major challenges. Coinciding with these advancements in technology has been society's increased use of resources and concern for sustainability. Advancements in technology have allowed us to develop more sustainable solutions, such as improving energy efficiency, the development of alternative fuels, and safer, less toxic materials; but, they also pose challenges such as data privacy concerns, increased consumption of resources, and rising amounts of waste electronic products. The rapid development of ICT equipment and the pervasive influence on our society has added to the complex and evolving challenge of sustainable development.

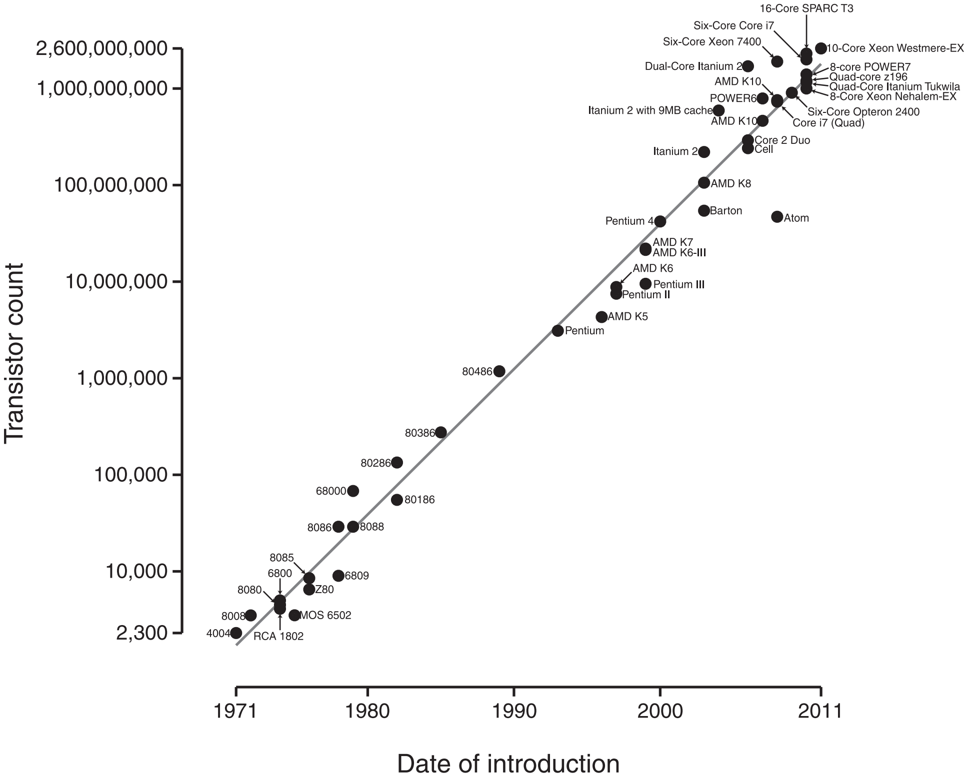


Figure 1.1: Evidence of Moore's Law - Transistor counts from 1971-2011 [1]

In 1987, the Brundtland Commission defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]. A basic sustainability framework that has been adopted and widely used shows the three pillars of sustainability; economic development, social development, and environmental protection (see Figure 1.2).

1.1.1 Sustainable Development

Since 1987, attention to sustainable development has increased rapidly, due to consumer pressure, market competition, increased legislation, and most importantly the effects of neglecting sustainability. The world is now believed to have crossed three of the planetary boundaries including, climate change, biodiversity loss, and interference with nitrogen cycle. These planetary boundaries represent tipping points beyond which environmental change may become irreversible [3]. The growing concern of this sustainable negligence and its impact on our planet is evident by the increasing legislation and global initiatives that have been developed to address sustainability (See Figure 1.3). These early initiatives were primarily focused on energy use and emissions during manufacturing and the use phase of a

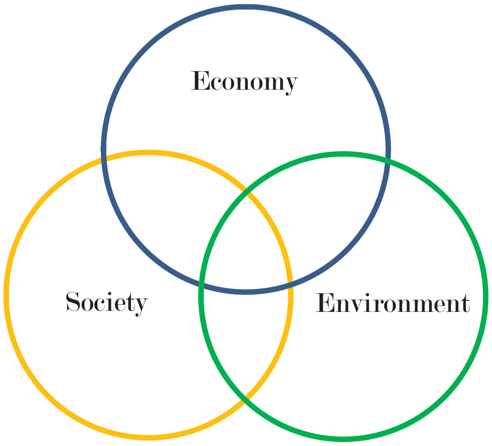


Figure 1.2: The three pillars of sustainability: society, economy, and environment

product. However, there has been a recent shift towards product stewardship that focuses on the safety and recovery of the materials and substances used in products. For example, the Restriction of Hazardous Substances (RoHS) Directive was adopted by the European Union (EU) to restrict the use of certain hazardous materials in electronic and electrical equipment [4]. The Waste Electrical and Electronic Equipment Directive (WEEE) Directive sets collection, recycling and recovery targets for electronic and electrical equipment; as part of the legislative initiative to solve the problem of hazardous electronic waste [5].

Resource depletion and scarcity have attracted recent visibility as global consumption of resources continues to increase. It has been said that the use of technology to build a more sustainable society depends to a large extent on sufficient access to technology metals, a trend that has been accelerated by their demand [6]. Technology metals refers to metals, such as precious metals and rare earth elements that are used in technology and electronic

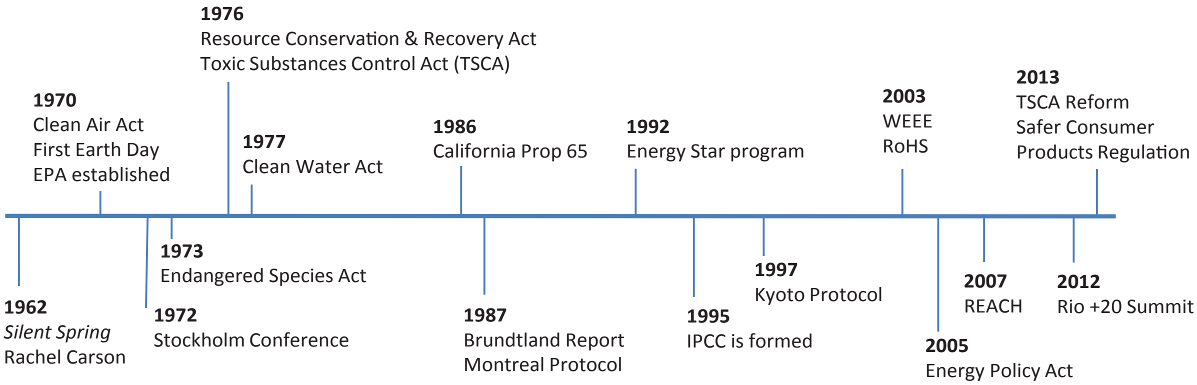


Figure 1.3: Sustainability timeline of key legislation and initiatives over the past 40 years

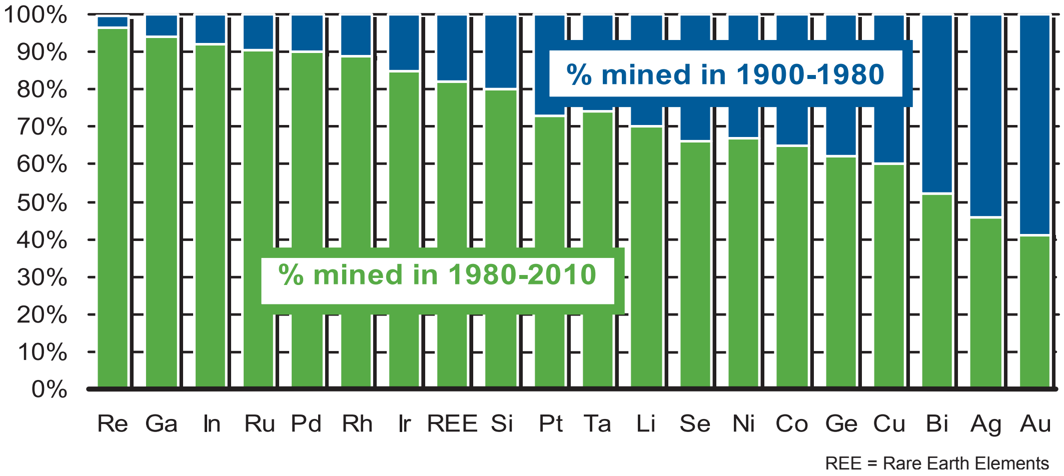


Figure 1.4: Mining production of technology metals: Comparing the percentage of metals mined in 1900-1980 and 1980-2010 [7]

equipment. Figure 1.4 shows that 80% or more of cumulative mine production of several technology metals has recently occurred in the last 30 years.

In addition, as global demand for resources continues to increase the quality of ore grades continues to decrease (see Figure 1.5). Ore grade refers to the concentration of metal or mineral in the ore that is being mined. Currently about three times as much material needs to be removed for the same ore extraction as a century ago [8]. The mining of lower grade ore contributes to increased environmental impacts with increased energy use, emissions, land extraction, water use, and pollution.

While providing the materials necessary to develop and advance technology is necessary, the extraction, use, and disposal can cause environmental degradation and loss of non-renewable resources [9]. Even considering resource efficiency improvements and dematerialization, there is still concern about the increasing consumption of resources. Despite these improvements, global trends in resource consumption indicate that the natural resource base is in severe danger of overexploitation. In economics, the Jevons paradox is the proposition that technological progress that increases the efficiency with which a resource is used tends to increase (rather than decrease) the rate of consumption of that resource [10]. If this is true, the results will be compounded with increasing global development and the rise of developing economies, as the potential consumer base will grow exponentially.

The development of a society involves a progressive transformation of economy and society while meeting the satisfaction of human needs and aspirations [2]. Beyond basic needs such as food, clothing, and shelter; one way our society develops is through technological advancements as described earlier. ICT equipment has had major impacts on all three dimensions (social, environmental, and economic) of sustainability over the past several decades. It has improved access to financial markets and ecommerce, allowed for the creation of new

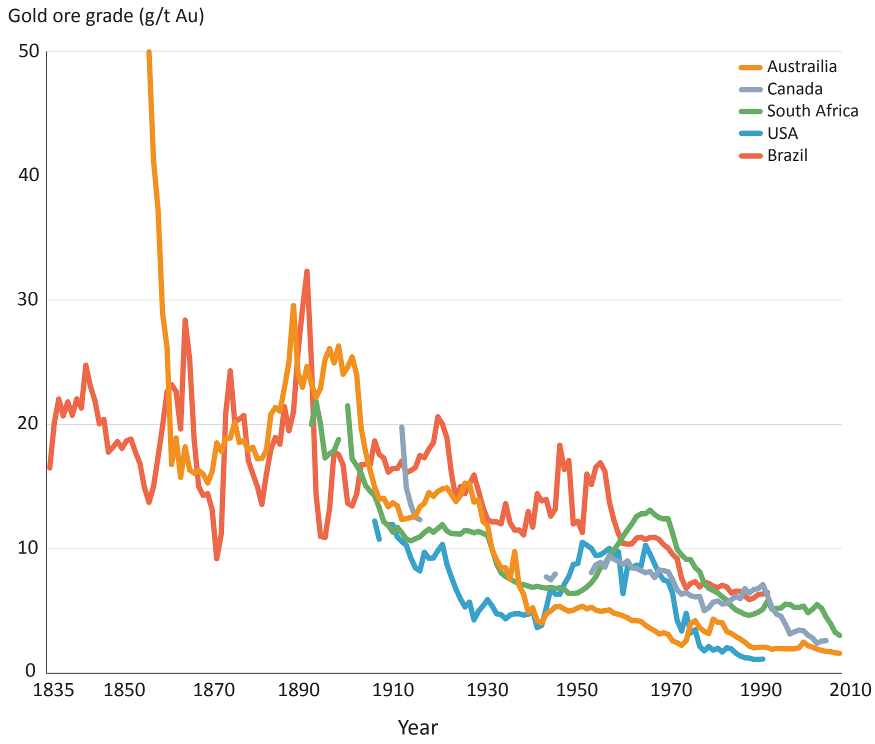


Figure 1.5: Historical degradation of gold ore grade by country from 1835 to 2010 [8]

models for conducting business and delivering services, and has contributed to the globalization of our economy. ICT products have also helped societies overcome economic opportunity obstacles, such as geographic isolation or lack of competition in the marketplace [11]. ICT equipment has had substantial impacts on social development; improved access and availability of information, enabled the development of mobile healthcare and increased opportunities for long distance communication. The impact of ICTs on the third dimension of sustainability, the environment, is often limited to the negative aspects; consumption of resources, rapid growth of electronic waste, and potential human health hazards and toxicity impacts associated with use of toxic chemicals. However, ICT has also benefited our environment through dematerialization and displacement of physical goods and introduction of smart systems to improve efficiency; some suggest that the reduced impacts due to technology will outweigh the negative impacts caused by technology [12]. However, the evidence of this still remains unknown and the challenge that is presented is to find technology solutions that advance society while minimizing potential negative impacts that impede sustainable development.

Figure 1.6: The life cycle phases of a product

1.2 The Life Cycle Approach

Life cycle thinking has been widely suggested as essential in addressing sustainable development [13]. The life cycle approach or life cycle engineering (LCE) addresses sustainability at the product level and incorporates a systematic approach to design the life cycle of a product while addressing the environmental, economic, and social impacts over the entire life cycle of that product. The product life cycle has been represented many different ways throughout literature and industry, Figure 1.6 depicts the basic life cycle phases that are commonly represented.

Raw material extraction involves extracting ores and raw materials from the earth. Material processing includes secondary processing of the materials extracted or any other processing of materials that is needed for the manufacturing stage of the life cycle. The manufacturing stage processes these materials into parts. Assembly is often included in the manufacturing life cycle phase and is utilized when the parts need to be assembled into components and components assembled together to form a product. Product use is the phase of the life cycle when the product is in use by the consumer. The end-of-life (EoL) phase is the next phase and occurs when the product is no longer of use to its owner and is discarded.

ICT products pose several unique challenges when addressing their life cycle phases. For many products the manufacturing stage of the life cycle is the most energy and resource intensive; refurbishing or reusing the product can reduce the environmental impacts over the life cycle of the product by reusing existing materials rather than extracting new materials to manufacture a replacement product. However, for products that use a significant amount of energy in the use phase, like electronics, it is important to understand the tradeoff between increased energy efficiency of new products and refurbishing older ones. Small changes in the use phase energy efficiency of a new product can outweigh the savings gained from remanufacturing an older product. If the use phase energy is significant, and the technology improvements reduce the energy used by newer products, it may be better to replace products earlier [14]. The benefits of refurbishment and reuse can be negated when the product is not as energy efficient as a newer model [9, 15]. There are also challenges in refurbishing due to the condition and variety of the products returned, which requires the entire remanufacturing system be flexible and adaptable. The EoL phase is also very important during the life cycle of these products, perhaps even more so than for other products. Concerns of toxicity and human health impacts rarely focus on the use phase of these products and are most relevant in the EoL phase when products are being dismantled and processed in order to reclaim valuable materials.

One of the goals of LCE is to optimize all of the life cycle phases together instead of separately, because the decisions made in one phase can have implications in another and vice versa. There have been several concepts that developed from the life cycle approach including closed-loop product life cycles, design for the environment, and industrial ecology [16–18]. Frosch and Gallopoulus proposed a new closed loop model for industrial activity that replaces the traditional linear system that extracts large amounts of raw materials that then pass through society and are finally discarded as waste. While they noted that a truly closed-loop industrial ecosystem would be difficult if not impossible to achieve, it represents a goal for industry and society to move towards. This idea of a closed loop model reinforces the importance of optimizing each life cycle phase using a systems perspective. Design for Environment (DfE) is the systematic consideration of design performance with respect to environmental, health and safety objectives during the entire product and process life cycle [19]. The transition from “design for needs” to a “design for the environment” model was first introduced in the 1970s, where design concepts made early in the design phase began to address the negative environmental impacts of a product life cycle. Industrial ecology studies the material and energy flows through industrial systems and is a systems-based discipline that considers the interactions between the industrial and natural systems [18]. All of these concepts consider the importance of the interactions and impacts throughout all phases of a product’s life cycle. These concepts lay the foundation for sustainable management and development within our society.

1.3 The End-of-Life Phase of Consumer Electronics

Rapid sales growth and technological advancements are generating a growing stream of consumer electronic products. Consumer electronics refers to electronic equipment intended for everyday use, such as mobile phones, laptop computers, or televisions. Over the last decade consumer electronic sales have risen significantly in the U.S, Europe, and Asia. Consumer electronic sales in the U.S. have been rapidly rising over the last three decades as depicted in Figure 1.7, based on the results of a study conducted by the United States Environmental Protection Agency (USEPA) in order to forecast the quantity of consumer electronic products placed on the market by product type.

According to the Consumer Electronics Association (CEA), the typical American household contains 24 electronic products [20]. From 1992 to 2007 portable personal computer sales increased from 1.9 million units to 30 million units sold [21]. In the European Union, the total units of electronic devices placed on the market in 2009 were more than 3.8 billion, including 265 million computers, almost 245 million in home consumer electronics, and 197 million consumer appliances [22]. In China, approximately 20 million refrigerators and more than 48 million televisions were sold in 2001, and almost 40 million personal computers were sold in 2009 [23]. Once these products are no longer useful to their current owners they become electronic waste and as sales increase so does the amount of electronic waste.

E-waste is a generic term encompassing various forms of electric and electronic equipment

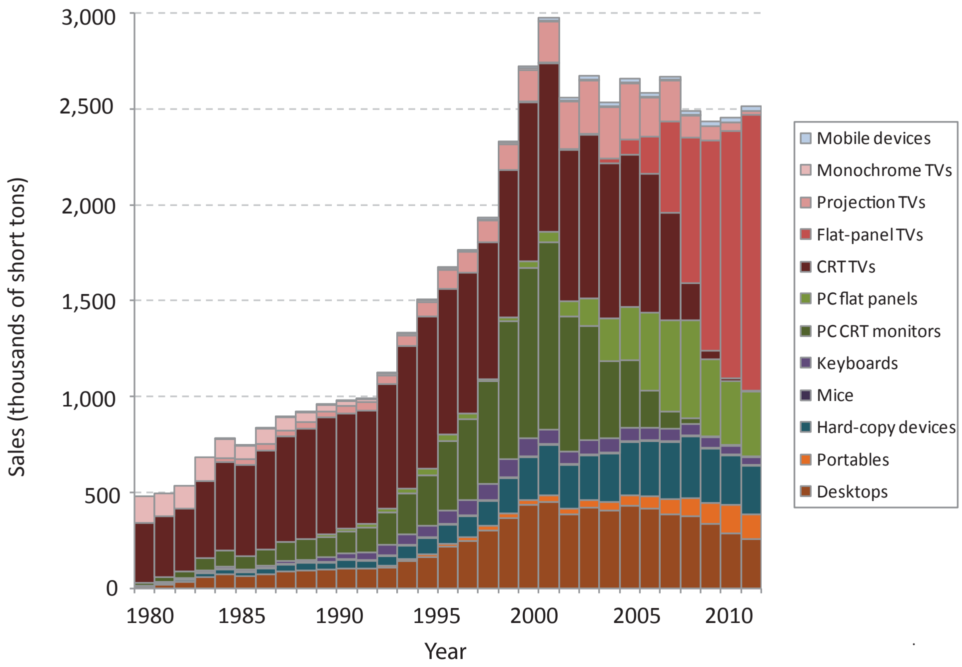


Figure 1.7: Estimated consumer electronic sales in the U.S. from 1980 to 2010 [24]

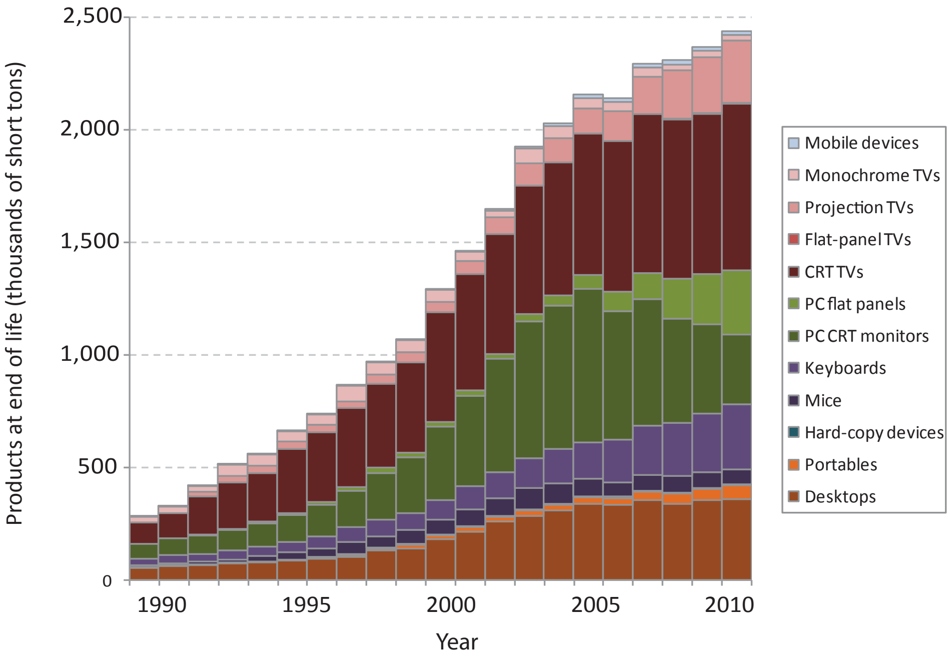


Figure 1.8: Estimated products ready for end-of-life in the U.S. from 1990 to 2010 [24]

that have ceased to be of any value to their owners for a variety of reasons [25]. According to a 2005 United Nations (UN) report, up to 50 million metric tons of e-waste is generated globally per year. In 2009, the USEPA estimated that consumer electronics (televisions, phones, computers, and assorted peripherals) make up almost 2% of the municipal solid waste stream [26]. Figure 1.8 shows the results of a study conducted by the USEPA in order to forecast the amount of product ready for the end-of-life phase.

The growth of e-waste is of global concern. In Japan, an estimated 200 million units and 1.7 million tonnes of end-of-life electronic equipment is generated annually [27]. In China around 1.1 million tons of e-waste are generated every year. Europe is generating around 12 million tonnes per year [8]. It is reasonable to assume that the quantity of e-waste will continue to grow as global development occurs.

1.3.1 Importance and Challenges in the End-of-Life Phase

For many years the EoL phase of a product's life cycle has been ignored or overlooked due to its perceived low impact across the product life cycle. The amount of expenditures and resources that are directed to the EoL phase of products by companies is much lower in comparison to what is devoted to product development, marketing, and sales [28]. However, as mentioned previously, the growing concerns of the environmental burden of e-waste and the increased legislation that focuses on this life cycle phase is attracting attention [25, 29].

As attention to e-waste increases, so does the concern about its effect on the environment and human health. There are several motivations that drive the concern of electronic waste. From a social perspective there is concern of e-waste exports and the informal processing of e-waste. Burning e-waste to recover valuable metals is common and at this low temperature there is a release of toxic emissions. From a business perspective resource efficiency is a motivating factor; urban mining has the potential to be more efficient than traditional mining practices. From a policy perspective e-waste regulation is becoming more common globally and in the U.S.

Electronic products are complex products that contain both hazardous and valuable materials. The potential value that could be reclaimed from these products is not minimal. Comparisons between primary and urban mining have been made throughout the literature. For example, in primary gold mining the efficiency is 5 grams per ton of ore compared to 200 grams per ton of computer motherboards, or 300 grams per ton in mobile phones [30]. Another comparison was made suggesting that a metric ton of EoL computers contains more gold than that recovered from 17 tons of gold ore [31]. The challenge is how to collect and process the EoL equipment sustainably and efficiently. There are material losses through each step of the EoL supply chain and it is important to understand and improve efficiency at each step. A startling example of the importance of this potential material loss that occurs during recycling, is that the gold loss can be as much as 75% if motherboards are not removed prior to shredding of the products. Electronic products also contain many hazardous substances, both to human health and the environment. Many of the substances including antimony (Sb), arsenic (As), beryllium (Be), cadmium (Cd), and nickel (Ni) can persist and bioaccumulate in the environment [32, 33]. Many studies have shown that dioxin and furan emissions can be released when informally burning e-waste for material recovery, posing serious hazards to humans and the environment [34, 35]. Potential health and environmental hazards due to e-waste will be discussed in detail later in Chapter 2.

Coinciding with the growing amount of e-waste is increased consumption and use of resources as mentioned previously. One important strategy that has been identified to combat the strain of consumption is waste reduction through intensified reuse, remanufacture, and recycling [16, 36, 37]. Kriebe notes that technology for recycling e-waste is well developed and will become even more importance in the future [38]. He suggests that one of the main challenges for future recycling is the enhancement of yield and quality of material recovered from used equipment. Earlier this year the European Parliament made the following statement, "Better processing of e-waste would not only reduce the amount of potentially toxic waste send to landfills or illegally exported overseas, but lead to greater recovery of valuable raw materials." Before we can improve e-waste processing we need to have a better understanding of the system and its potential impacts. In order to do this a new systems perspective and management approach needs to be developed.

One challenge in the EoL phase is the creation of an information feedback loop between EoL management facilities and product designers. Ideally providing information about the decisions made during EoL processing, disassembly, and separation would inform designers in order to improve product design. Increasing transparency and communication throughout the downstream supply chain is the first step to understand the EoL phase and how to improve overall efficiency. The information exchange and communication between manufacturers and recyclers is one of the least developed in the supply chain. For example, the crucial decisions for product recyclability in the EoL phase are made in the product design phase; however communication between these two stages is not well developed. Developing systematic and efficient methods to improve the information feedback loop between designers, manufacturers, and EoL product management is pertinent.

There are many concepts with general guidelines on how to improve the environmental performance of products such as Design for Environment and Sustainability (DfES), Design for Disassembly (DfD) and Design for Recycling (DfR) [17] However, there is no tool that provides a set of detailed design strategies for engineers with practical advice focusing on recycling and closing the materials loop for consumer electronics [39]. The existing guidelines in DfR can be described as an unstructured collection of many specific rules. Kriwet et al. stated that the aim of researching the topic of DfR therefore should be to provide the designer with a set of guidelines that are simple, easy to apply and easy to evaluate [40]. Traditional metrics that are based on mass focused recycling are not appropriate for this waste stream [7]. New quality metrics need to be developed that focus less on mass and cost and more on critical metals and performance of EoL processing parameters. Documentation along the supply chain that includes mass balance flows, recovery efficiencies, and product design attributes is the first step in improving the sustainability of this system.

1.4 Research Overview

The goal of this research is to develop methodologies to inform end-of-life strategies for consumer electronic products that can be used by stakeholders throughout the supply chain including manufacturers, EoL management companies, and policy makers. A representative set of EoL pathways was developed in order to better understand the flow of e-waste through the EoL phase. A quantitative assessment of e-waste flows was conducted and insights into the mechanisms and pathways were identified. The second part of this research developed a standard methodology to determine recyclability of a consumer electronic product that considers mass, value, and design based criteria.

This dissertation is organized as follows: Chapter 2 provides an overview of consumer electronic products, the EoL management processes, and methods that have been used to understand and mitigate the impacts associated with processing EoL electronic equipment. Chapter 3 describes the development of the EoL pathways model based on current industry practices in order to identify the most common EoL pathway followed by each product category and the process flow and decisions made during each step of processing equipment at material recovery facilities. Chapter 4 reviews the current state of recyclability metrics for products used in literature and industry. Findings from this review are used to inform the development of a standard methodology and tool to calculate product recyclability of consumer electronic products. Chapter 5 summarizes the contributions of the work presented in this dissertation and provides discussion points and needs for future work.

Chapter 2

Background

This dissertation focuses on consumer electronic products; which includes electronic equipment that is intended for everyday use, most often for entertainment, communication, or work activities. Examples are desktop and laptop computers, displays and monitors, mobile phones, and televisions. While this work is applicable other product categories, such as small appliances, they are not the focus of this research. Electronic products are an important product category to study due to the amount and variety of materials and substances they contain, both valuable and hazardous. Compared to other product categories, electronic products use many more substances in both variety and quantity (see Table 2.1).

Table 2.1: Number of different elements used in each product category [41]

Product	Elements used
Automobiles	15-20
Electronics	55-60
Gas turbine blades	12-14
Medical equipment	50-60

As technology has developed over the past decades the demand for both a greater variety of materials and for more specialty materials has increased as discussed in Chapter 1. For example, over the past two decades the number of elements used in computer chips increased from 11 to approximately 60 [42]. Electronic products are composed of more than 1000 different substances, mainly ferrous and non-ferrous metals, plastics, glass, ceramics, and rubber (see Figure 2.1).

The non-ferrous metals used are mainly copper, aluminum, and precious metals, which primarily consist of gold, silver, platinum, and palladium. Steel and aluminum are often used for their structural properties. Copper is used in wiring and circuitry for its conductivity. Plastics also play an important role in electronic products. Manufacturers incorporate plastics for their material properties which include: durability, low weight, corrosion resistance, and insulation. These properties in addition to the low cost of plastics make it an ideal material to be used in many products.

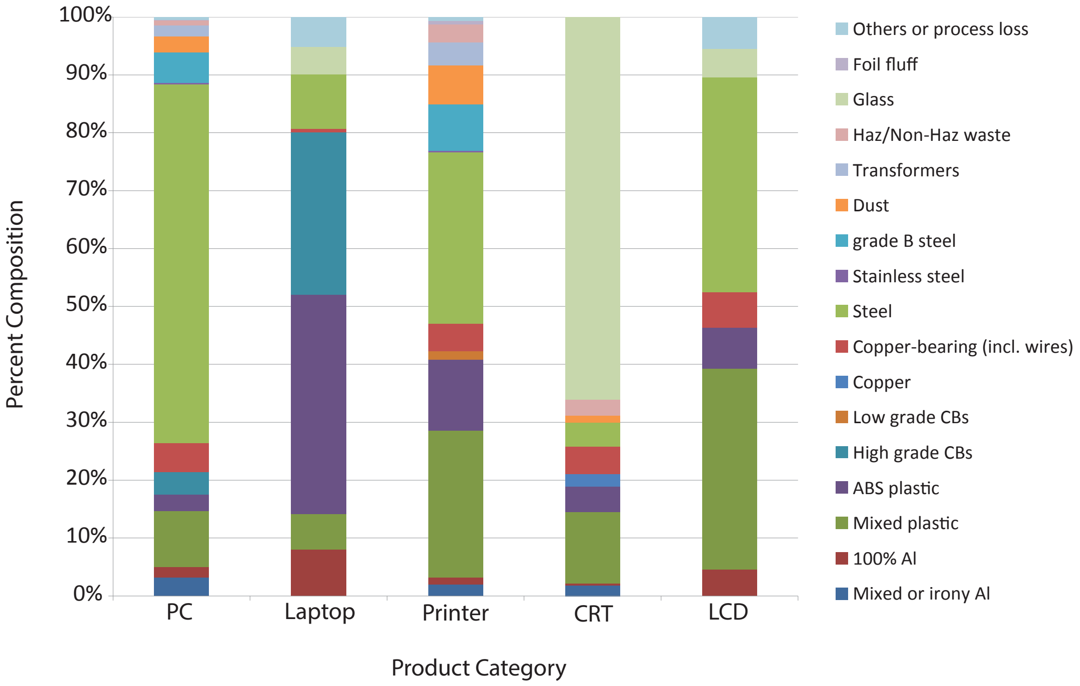


Figure 2.1: Material composition of various consumer electronic product categories [43]

Figure 2.2: Image of laptop assembly and its components [44]

The most common plastics used in electronic products are listed here: polycarbonate (PC), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyamide (PA), polymethyl methacrylate (PMMA), polyacetal (POM), polyethylene terephthalate epoxy (PET), high-impact polystyrene (HIPS), polyphenylene ether (PPE), polyurethane (PU), and acrylonitrile butadiene styrene (ABS).

Electronic products are an assembly of many different components, parts, and subassemblies (see Figure 2.2). Most often these parts and assemblies are manufactured by second and third tier suppliers and then are shipped to OEMs for final assembly of the product. Many product categories have similar components in common. Hard disc drives, displays, printed circuit boards, power supply units, batteries, and optical drives are the most common components in consumer electronic products. These will be described in further detail in Chapter 4.

2.1 End-of-Life Management Overview

The EoL management stage begins when the product has reached the end of its useful life to the user. Several studies have collected data on the EoL management stage of electronics in the U.S. The USEPA has collected this type of data over several years and according to a study in 2007, 29.9 million desktop computers and 12 million portable computers were estimated to be ready for EoL management, as shown in Chapter 1. Although reuse, refurbishment, and recycling these products are the ideal EoL management strategies, e-waste is most frequently sent to landfills or placed in storage by consumers. When products are collected, the USEPA found that of the 2.25 million tons of televisions, mobile phones, and computer products ready for EoL management in 2007, 18% (414,000 tons) was collected for recycling and 82% (1.84 million tons) was disposed of primarily in landfills [21]. Most obsolete electronic devices are currently being stored and never enter the collection stream. Of the products sold between 1980 and 2007, approximately 235 million units had accumulated in storage as of 2007, including 65.7 million desktop computers, 42.4 million computer monitors, and 2.1 million laptops [21]. Another study by Gattuso produced similar findings for obsolete computers, about 75% are stored in peoples homes, approximately 14% percent are recycled or reused, and 11% end up in landfills [45].

Once an electronic product becomes e-waste, the user has several options as mentioned above:

- Storage or disposal of the product
- Informal reuse through donation or selling the product
- Formal collection of the product for EoL management processing

Collectors are organizations that physically take back EoL equipment and can include state or local governments, retailers, OEMs, or companies that specialize in product takeback and collection of e-waste. The primary methods of collection are permanent drop-off facilities,

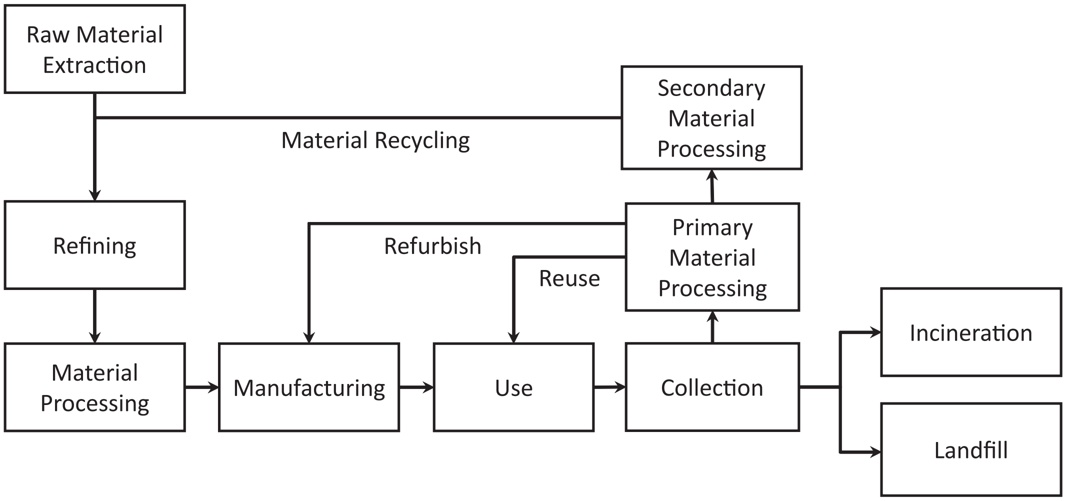


Figure 2.3: General flow diagram of product end-of-life management

special collection drives, direct from consumer, including door-to-door pick up or via a mail service. Permanent drop off facilities can be operated by a variety of stakeholders. Government facilities often include e-waste drop off with other hazardous waste drop-off sites, retailers may provide e-waste bins to collect specific types of products, and EoL collection and management facilities will allow consumers to drop off e-waste equipment directly. Specialty collection drives or events are often organized by government or academic institutions, retailers, or EoL collection or management companies. Due to the potential value of e-waste there is a new crop of brick and mortar stores that are specializing in product takeback.

Figure 2.3 presents a general flow diagram with the pathways that a product may follow during the end-of-life phase. When the product enters formal collection several processing options are available: refurbishment or reuse at the component and/or product level, recycling, landfill disposal, or incineration with or without energy recovery. A combination of these options is often used when processing the product at EoL. For the purpose of this dissertation these processing options are referred to as pathways and they will be described in further detail in Section 2.2.

The basic e-waste recovery process starts with collection and assessment of the the products collected to determine how they should be processed in the subsequent EoL processes and which pathway they will follow. Once the products are collected they are transported to a material recovery facility for primary processing. These facilities perform a wide range and combination of e-waste processes which will be detailed later in this chapter. Once the product reaches the processing facility the technician determines which products can be reused or refurbished and what parts or components have value to resell, refurbish, or recycle. If the product has retained some use value, it is sent to a refurbisher, reseller, or remanufacturer. Refurbishers and resellers prepare the entire product for resale, while remanufacturers remove and resell components. Preparing the equipment can include cleaning, upgrading of components or software, replacing parts, or any other repair that is needed in order to provide a functional product to the next user. If the product has no further resale value, it is recycled for material recovery. Recyclers disassemble EoL equipment in order to reclaim commodity materials such as plastic, copper, and aluminum, as well as components including power supplies, printed circuit boards, and wires. Components containing hazardous materials are disposed of according to relevant regulations as outlined later in this chapter. The remaining components that contain valuable materials are separated into their respective commodity streams. These material and component commodity streams are then sent further downstream to secondary processing facilities. The metals are processed by smelters and the plastics are sent to refineries or incineration facilities.

2.2 End-of-Life Pathways and Potential Impacts

This section provides further discussion on the pathways that e-waste products follow in the EoL phase, in addition to the potential impacts of each pathway. Proper recovery of a product at the EoL stage can decrease the negative environmental and human health impacts of the product life cycle, which ultimately contributes to resource conservation, hazardous substances control, and decreased landfilling of electronic waste. The definitions of each pathway are listed below:

Recycle - A process where e-waste is disassembled for material recovery of resources and reusable materials.

Reuse - A process to directly use components or products again.

Refurbish - A process to upgrade or repair components or products to make available for resale.

Landfill - To dispose of e-waste products, components, or materials in landfills.

Incineration - The process of burning e-waste products, components, or materials, with or without energy recovery.

2.2.1 Formal Recycling

This section discusses recycling practices associated with formal recycling; recycling facilities that are often regulated by local, regional, or national legislation. In its 2006 Industry Report, the International Association of Electronics Recyclers (IAER) estimated that the U.S. electronics recycling industry processed 1.4 million tons of electronic equipment in 2005, based on survey results from recyclers, OEMs, and non-profit organizations [46]. In formal or controlled e-waste recycling, usually two types of facilities are necessary. E-waste is first disassembled or dismantled and mechanically processed in one facility, often referred to as the pre-processing or primary processing facility. Primary processing facilities are referred to as material recovery facilities or recyclers throughout this dissertation. The e-waste is then prepared for further recovery in a second facility, called an end or secondary processor. Secondary processing facilities include smelters and refineries.

Material recovery facilities often provide a variety of services including sorting and separation, functional testing, dimantling, and processing of recovered equipment. Manual disassembly is typically used to remove plastic housings and larger metal components, as well as components containing hazardous materials. Small-scale recyclers commonly use manual disassembly instead of automated disassembly (e.g., shredders) typically due to lack of capital funds to purchase equipment. These organizations often serve in the "dismantler" role as mentioned above. Often these smaller facilities have to send the dismantled equipment to a larger primary processing facility to be shredded and separated into commodity streams.

At larger facilities, all material remaining after disassembly is shredded and sorted using a combination of different separation techniques (e.g., magnetic and density separation, manual sorting) [47]. Separation techniques are used to obtain clean material commodity output streams. Even when separation techniques are used, each output stream will contain a small amount of contamination. Some recyclers reprocess the materials multiple times in order to improve separation efficiency. The output streams from the recycling process can include ferrous metals, mixed metals, glass, mixed plastics, and mixed materials. These outputs are then sent downstream to smelters, refineries, landfills, incinerators, or commodity brokers. In general recyclers do not send any material to the landfill; however some of the materials that are sent to downstream processors may end up in a landfill at a later processing stage.

The greatest potential for exposure and health impacts associated with formal recycling of electronics is to the workers that are processing the materials and products. Metals and organics, including lead, cadmium, and mercury, may be released as fine particulate dust and fumes during crushing, shredding, and heating of electronic components and products [48]. A study conducted by MJC and Associates found that workers could be exposed to metals and other compounds, which can exist in particulate form, through inhalation during recycling processes [49]. Concentrations of beryllium and lead were measured in the work areas of e-waste recycling facilities in Canada exceeded occupational exposure limits identified by the American Conference of Governmental Industrial Hygienists. The assessment also evaluated potential environmental risks from the processing of electronic waste and found that the main pathways for this type of risk are contaminated water released from the recycling process and leaching of hazardous substances from electronics that are stored uncovered outside. Several measures can be implemented at the recycling facility to ensure worker safety and environmental protection. In most cases, proper handling and controlled pre-treatment of electronic devices can minimize the hazards associated with these substances. Implementing safety measures, such as air extraction and filtration, proper covered storage areas, and using personal protective equipment can reduce the risk of inhalation and potential exposure.

2.2.2 Informal Recycling

Informal or unregulated recycling typically occurs when e-waste is exported to developing economy countries. There have been estimates that 50-80% of collected e-waste in the U.S. is not recycled domestically but rather shipped abroad for processing and recovery [50]. There are two main reasons that e-waste is exported, either to provide a second useful life for electronics or to reduce the cost of recycling due to lower labor costs [25, 50]. Informal electronics recycling activities have been documented in many countries, including China, India, and Africa. Countries such as China and India face a rapidly increasing amount of e-waste, both from domestic generation and imported products and materials [25]. Many of these countries lack regulations or laws that address the recycling and disposal sector. Illegal disposal sometimes occurs under the disguise of charitable donations. The European Union (EU) Commission estimates that anywhere between 25-75% of second-hand goods exported to Africa are not in working condition and are unable to be reused [22]. A recent e-waste report from Ghana revealed that there is currently no infrastructure in place to process e-waste safely in Africa [51]. The report also notes that, while many of the electronic products that arrive in Ghana are in serviceable or usable condition, they will still ultimately be processed informally due to the lack of infrastructure to process or manage the reuse and refurbishment of the equipment.

Desire to recover valuable materials, such as copper and precious metals, for resale drives the informal recycling sector, creating a significant risk to human health and the environment due to the primitive and unsafe methods used to reclaim these materials [25]. For example, copper is recovered from wires by open burning to remove the plastic casing, which emits considerable levels of dioxins, furans and other toxins [35]. Printed circuit boards are treated to recover precious metals often using a chemical leaching process that uses hazardous mixtures of acid or cyanide.

To understand informal recycling and its impact on human health and the environment, the Basel Action Network (BAN) visited open burning sites in Asia where laptop components were being burned in order to recover precious metals. BAN has shown that the frequency and intensity of environmental and health problems due to exposure to the hazardous chemicals contained in e-waste have increased in those areas of the developing world where e-waste dumping is most prevalent [50]. Greenpeace collected samples from more than 70 industrial units and dump sites in China and India and found elevated levels of lead, tin, copper, cadmium, antimony, polybrominated diphenyl ethers (PBDEs) and polychlorinated biphenyls (PCBs) [52]. Other studies have found heavy metals in bodies of water near these informal recycling sites, thought to be attributed to acid leaching of printed circuit boards [35]. Burning electronic components at low temperatures in uncontrolled areas can cause dioxin, furan, and polycyclic aromatic hydrocarbon(PAH) emissions, hazardous to both the environment and the workers processing the equipment. Another side of unregulated recycling is the lack of recovery efficiency in the informal processing of e-waste. In addition to the negative impacts on the environment, there is also a greater loss of material recovery due to the primitive and inefficient techniques used, compared to formal recycling.

2.2.3 Refurbishment and Reuse

Refurbishment is the process of restoring a product or its components to like new conditions in order to be resold. In order for the refurbished product to be able to be reused it must be able to be restored to like-new functionality and appearance. Reuse occurs when the initial user donates the product to a second user or after a product is formally collected and then resold to a new user. Both of these options offer benefits to the consumer with the lower price point at which refurbished products or components are often sold. The sustainable benefits of refurbishment and reuse are the reduction in raw material consumption and manufacturing burdens due to the delay of purchasing a new product. One study found that reusing an old laptop can provide lifetime energy savings of almost 50% compared to the manufacturing and use phase energy required to produce a new laptop [53]. Upgrading computers has also been considered as a strategy for similar reasons; Williams has suggested that the environmental benefits from reusing computers far outweigh the benefits of recycling [35].

For many products the manufacturing stage of the life cycle is the most energy and resource intensive; refurbishing or reusing the product can reduce the environmental impacts over the life cycle of the product by reusing existing materials rather than extracting new materials to manufacture a replacement product. However; for products that use a significant amount of energy in the use phase, like electronics, it is important to understand the trade-off between increased energy efficiency of new products and refurbishing older ones. Small changes in the use phase energy efficiency can outweigh the savings gained from refurbishing a product. If the use phase energy is significant, and the technology improvements improve the energy efficiency of new products, it may be better to replace products earlier [9, 14]. The potential benefits of refurbishment and reuse can be negated when the product is not as energy efficient as a newer model and an alternative EoL management pathway may be the more sustainable choice. There are also challenges in refurbishing due to the condition and variety of the products returned, which requires that the entire remanufacturing system be flexible and adaptable in order to be able to manage the product mix efficiently.

2.2.4 Landfill

The USEPA reports that in 2007 more than 80% of EoL consumer electronics were disposed of in landfills, an estimated 1.84 million tons [21]. A major concern of landfill disposal of electronics is the loss of valuable materials. As mentioned previously, these products contain valuable materials that are not recovered when disposed of in a landfill. The electrical and electronic equipment industry is considered responsible for 10 - 20% of the overall environmental impact of consumer goods with respect to the depletion of non-renewable resources [54]. While there may be no additional energy or materials used to process the laptop in the landfill, there will be energy and materials spent to manufacture new products and materials.

Some studies have suggested that there could be a potential hazard to workers and the environment when electronics are disposed of in landfills. Exposure of hazardous materials related to electronic products to landfill workers depends on several factors including the condition of the materials received, handling practices, and how much the materials are processed or crushed [55]. Another concern is that when e-waste is sent to a landfill it can lead to the creation of hazardous leachate, which has the potential to seep into the ground or drain into surface water, where it could negatively impact the environment and other food and water sources. Leachate is defined as "liquid that has passed through or emerged from solid waste and contains soluble, suspended, or miscible materials removed from the waste" [56].

Most landfill leachability studies in the literature have focused on the potential for discarded electronic devices to leach lead and other heavy metals. A study was conducted to measure leaching rates from 11 Florida landfills and focused on cathode ray tube (CRT) glass and printed circuit boards [57]. The results from the test were well below the regulatory standard for classifying waste as hazardous. Studies have been performed in the laboratory using the USEPA's toxicity characteristics leaching procedure (TLCP) test to determine leachability potential of e-waste. These laboratory tests have produced higher concentrations, however; leaching tests from actual landfills are likely a better measure for the potential environmental impacts than tests performed in a laboratory [35]. Leaching of toxic materials into groundwater or the surrounding environment has mainly been of concern around landfills that are not well managed or properly maintained. One study suggested that the risk of leaching of toxic materials in computers from well-managed sanitary landfills is minimal [35]. Measures to minimize potential risk to the environment and workers should be implemented in landfills. Controls can be used to prevent surface runoff, groundwater contamination, and potential air exposure. While releases to the environment and exposures to the general public are possible, strict regulations governing the construction and operation of solid waste landfills make this unlikely.

2.2.5 Incineration

Incineration may be used to recover energy from the waste material or to decrease the volume of the waste sent to landfills. While incineration reduces the hazardous potential of some substances, it may increase the toxic potential of others such as polyvinyl chloride (PVC) and brominated flame-retardants (BFRs). It concentrates substances such as lead, facilitating recovery or further management, but others are released into the environment through air emissions from the incinerator. Health and environmental impacts depend on the waste mix and emission controls in place at the incineration facility. Without proper emission controls, heavy metals such as lead, cadmium, and mercury may be released into the atmosphere during incineration and have the potential to bio-accumulate in the food chain, particularly in fish. This route constitutes the major source of exposure for the general public [22].

2.3 Overview of Material Recovery Facilities

This section provides further detail of the material recovery industry and the process flow within these facilities.

The landscape of the recycling industry has had amazing growth over the last decade. In a recent survey conducted by the International Data Corporation (IDC), of the 155 companies surveyed, 59% entered the EoL management industry in the last 10 years [58]. There are between 600 and 1000 companies in this industry; however the number of companies is always changing and difficult to determine due to the many mergers and acquisitions, as well as the numerous small companies that operate almost unnoticed. A substantial percentage of these organizations are small scale operations, often operating with fewer than 50 employees.

Material recovery facilities specialize in separating and recovering materials from electronic products. There is a wide range of business models within the electronics EoL management industry, utilizing an array of different combinations of these activities. These organizations also differ in the scope of products they collect and process, the processing methods and equipment they use, as well as their financing structure.

These facilities range in size and the amount of e-waste they process each year. The range of facility types in the EoL management industry can be characterized by the level of automation that is used within the facility. Facilities that focus on manual disassembly methods instead of using large automated equipment are not able to process as much e-waste (see Figure 2.4). The amount of waste processed primarily depends on the collection efficiency and the operating model of each facility. Some organizations focus on a single

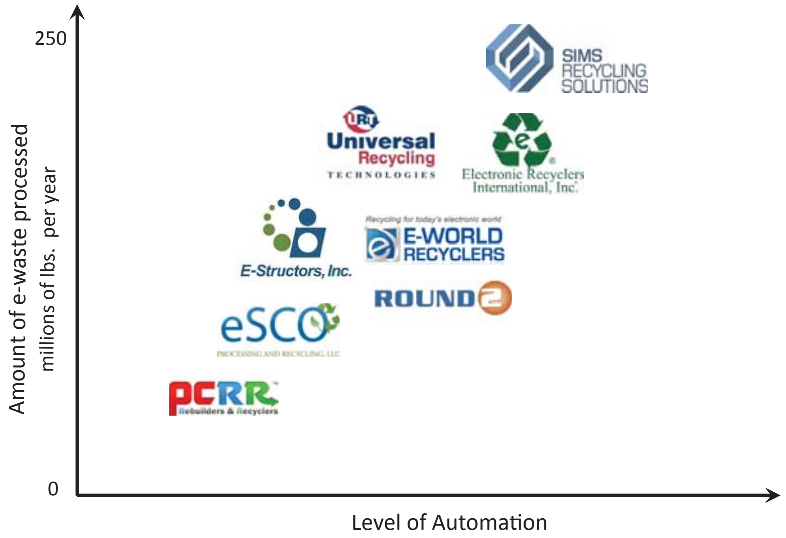


Figure 2.4: Comparison of automation level and amount of e-waste processed at material recovery facilities in the U.S.

activity such as product refurbishment and resale (e.g., an asset recovery business model) or mechanical or automated processing (e.g., a recycling business model), whereas other organizations engage in a combination of these activities [59].

There is also a variety of financing schemes, including financing from state government programs, from consumer fees collected at point of purchase, or from original equipment manufacturers (OEMs) of the products. The scope of products each facility processes can also vary significantly, especially depending on their main business model. For example, a company that focuses on recycling has the goal of recovering the most valuable materials from these products, so their collection focus would be on the products that contain the highest quality and quantity of valuable materials that can be recovered.

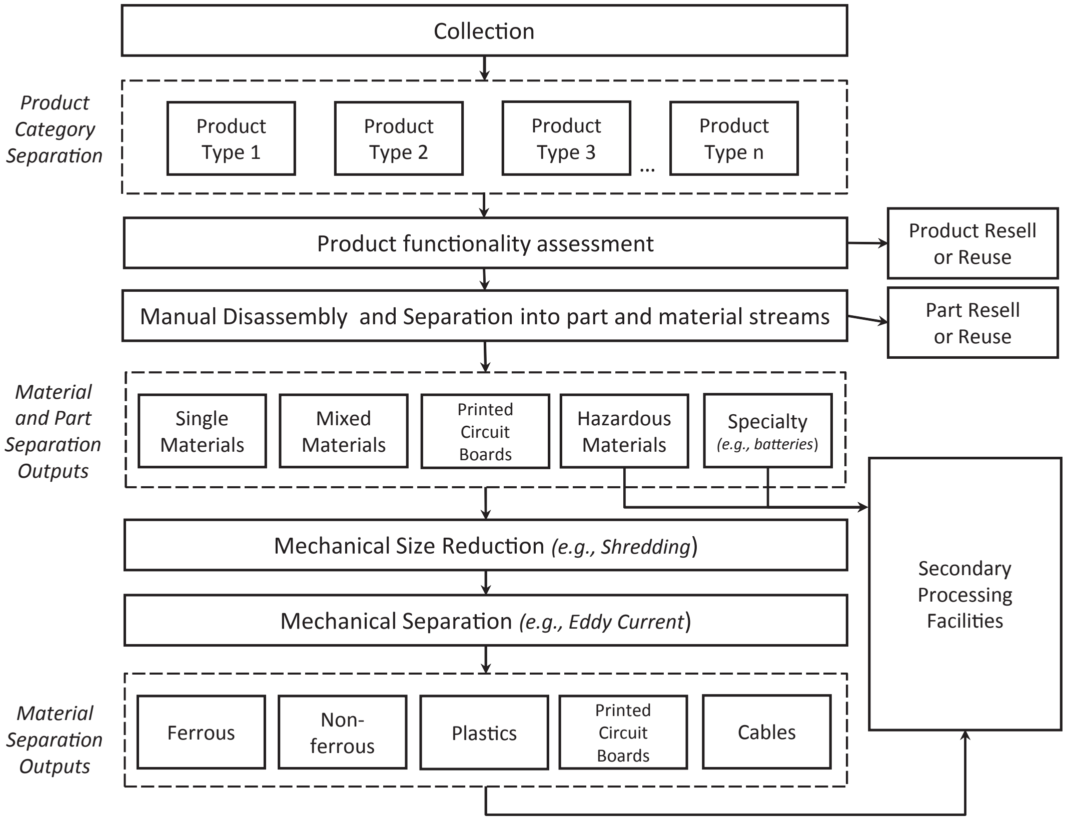


Figure 2.5: Diagram of process flow within a material recovery facility

The products and materials flow through several processing steps within these facilities, focused on disassembly, separation, and size reduction (see Figure 2.5). The products are first separated by product category or product type (e.g., displays, mobile devices). The products are then tested for functionality to assess if they can be resold or refurbished. The products that fail the functionality testing are then disassembled manually to remove components that are hazardous or need specialty processing (e.g., batteries). Next the remaining product and components are separated into single materials (e.g., laptop housing) and mixed materials (e.g., printed circuit boards). The components that are hazardous or require specialty treatment are shipped to secondary processing facilities downstream. The single material and mixed material streams are processed for size reduction. Mechanical shredding is often employed to reduce material size. These material streams are then separated mechanically using a variety of technologies which will be discussed in the following section.

2.4 Primary Processing Technology

There are two major types of technology equipment used in a primary processing facility as mentioned in the previous section: size reduction and separation.

Size reduction is employed in order to generate material streams that are uniform in both size and shape. Initial material liberation is also achieved during this process. In the industry size reduction is often referred to as shredding or grinding. The shredding equipment is characterized by its high torque and low speeds. These parameters are used to separate material slowly to minimize the potential for imbedding metal in plastic, which would increase contamination and impact the purity of the material output streams. Hammermills and shear shredders are the main types of size reduction equipment used in electronics recycling.

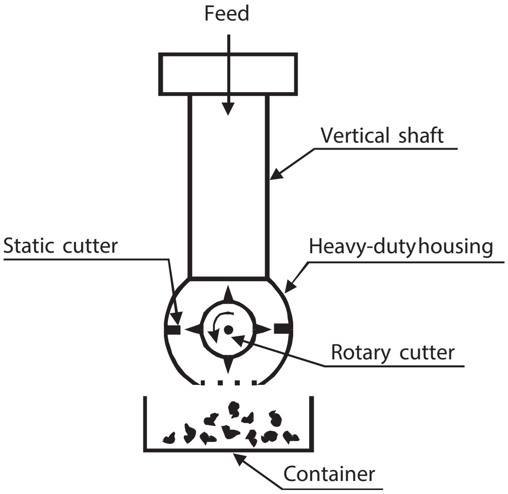


Figure 2.6: Schematic of horizontal hammer mill [60]

Hammermills can have either a horizontal or vertical rotor, but horizontal is the most commonly used (see Figure 2.6). They have a series of hammers that rotate within the machine and reduce the particle size when they collide with the infeed material. A screen is used to ensure size uniformity of the output stream. Material size distribution is determined by feed rate, hammer speed, and size distribution of incoming material stream.

Shear shredders consist of two horizontal, counter rotating shafts that have cutters to tear and shear the material (see Figure 2.7). Shearing forces and deformation are used to reduce particle size of the incoming material feed. These shredders typically operate within the range of 20 to 70 *rpm* [8].

Figure 2.7: Schematic of two shaft shear shredder mechanism [61]

The most common separation methods used in electronics recycling are magnetic separation, eddy-current separation, air separation, and triboelectric separation.

Magnetic separation is used to separate magnetic (i.e., ferrous) metals from a mixed material input stream using permanent or electric magnets. There are three possible systems that include magnetic head pully, drum, or magnetic belt. The belt magnet is the most common type of separation system used [62]. The particles move along a conveyor belt over the magnet and the ferrous particles adhere to the belt and the non-ferrous particles fall of the end of the conveyor due to gravity (see Figure 2.8).

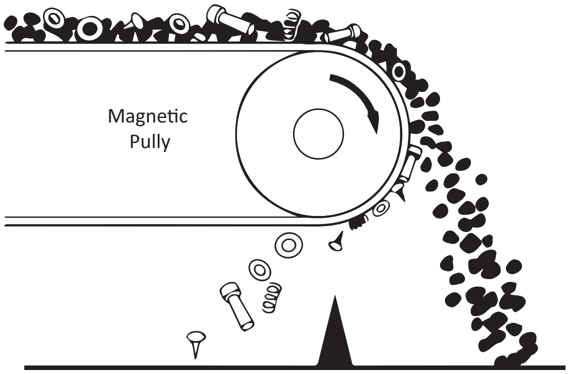


Figure 2.8: Schematic of magnetic separation system [63]

Eddy current separation is based on the conductive difference of materials and can be used to remove non-ferrous materials from non-metallic materials. This type of equipment is composed of an internal rotor and external drum. The internal rotor is comprised of magnets, either ferrite ceramic or rare earth magnets, arranged in alternating polarity. The internal rotor turns at high revolutions (over 3000 *rpm*), much higher than the outer drum, and produces an *eddy current*. The materials from the incoming stream react with the eddy current and are repelled based on their material properties and are separated in the bins below (see Figure 2.9). The repulsive forces exerted on the conductive particles are due to the interaction between the alternative magnetic field and the eddy current that is created [64].

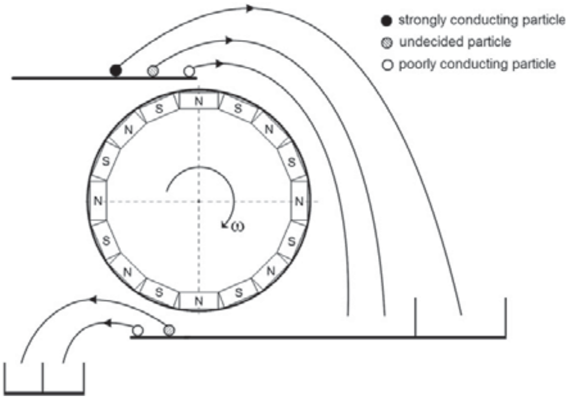


Figure 2.9: Schematic of eddy current separation [65]

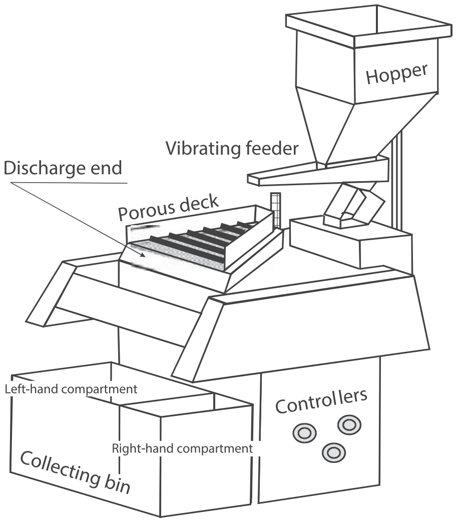


Figure 2.10: Schematic of air separation table [66]

The criterion for using the eddy current separator is based on the material properties ratio σ/ρ, where σ is the electrical conductivity of the material and ρ is the density of the material. The materials that have a higher ratio are more easily separated. Aluminum is one of the most easily separated material with a ratio of 13.1 $10^3 m^2/\Omega$ kg [65]. Magnetic and eddy current separation techniques are often used in combination in a separation system, to first separate the ferrous materials and then separate non-metallics and non-ferrous materials respectively.

Air separation is used to separate materials based on their respective aerodynamic characteristics (see Figure 2.10). These characteristics are a function of particle size, geometry, and density. The three types of separations systems are categorized by the equipment orientation; horizontal, inclined, and vertical. Air separation removes the light organic materials and separates lightweight materials from heavier ones.

Triboelectric separation uses centrifugal force to charge particles (see Figure 2.11). The materials with the highest affinity for electrons becomes negatively charged, while the other becomes positively charged. The materials are fed into the system and acquire opposite charges through interparticle contact. The charged particles are attracted to the oppositely charged electrode. A belt moves the particles to opposite end of the system to be separated.

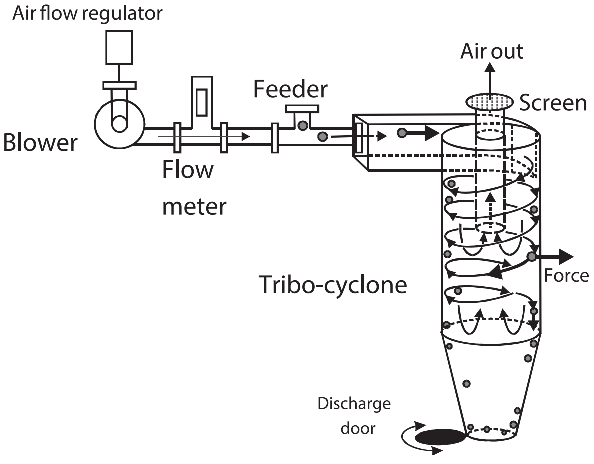


Figure 2.11: Schematic of triboelectric separation [66]

2.4.1 Material Separation Efficiency

In the U.S., the primary processing of e-waste is the most critical step in the processing of e-waste [62]. Activities that occur here have the greatest impact on the quantity and quality of materials that can be recovered from products.

Incomplete liberation and subsequent miss-sorting of materials results in the loss of minor metals in side streams (e.g., dust) from which they cannot be recovered for secondary processing [47]. The efficiency of the separation and size reduction processes is strongly related to the "quality" of the input or incoming stream of materials. In order to decrease

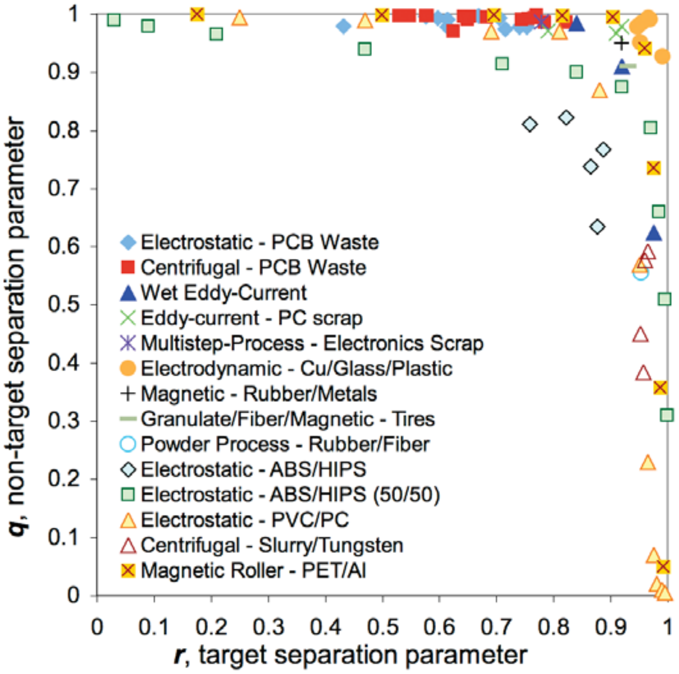


Figure 2.12: Separation performance parameters r and q for various recycling processes [68]

contamination in the input material stream, recyclers often incorporate manual disassembly methods in order to separate and process similar components and materials. Economic and technical limitations in separating materials and components are among the greatest obstacles to recover, recycle, and reuse products [67]. Even with these technical limitations, processing costs are often the limiting factor at these facilities. These costs include technology and equipment costs, labor costs, and resource costs. While manual disassembly improves the input stream quality, it is expensive and often not used extensively due to the associated labor costs.

A Bayesian material separation model has been used to characterize separation efficiencies of recycling processes [68]. This type of model assumes a binary mixture of the *target* material and the *non-target* material in the input stream. The separation efficiency of the target material is represented by r and the separation efficiency of the non-target material is represented by q . Figure 2.12 shows the performance of various separation processes based on the separation efficiency of the target and non-target materials. The various separation processes sort the particles based on their material properties as described in Section 2.4. Incomplete separation and sorting of materials results in significant material loss at each process step. Improving the recycling efficiency or performance of a system can be achieved through multiple steps, including individual process improvement, utilizing multiple separation steps, and optimizing operational parameters of a process or system [68]. Most work in this area has not been conducted at an industrial scale, but has still provided valuable insights into single process separation efficiency.

An industrial test indicated that the percentage of silver (Ag), gold (Au), and palladium (Pd) that could be recovered from circuit boards and copper fractions was only 12%, 26% and 26%, respectively [69]. Considering this, products that are high in material value, such as high grade circuit boards, should be removed prior to shredding to mitigate these losses. These materials can be shipped directly to a secondary processor (i.e., smelter) that can recover most of the metals with high efficiency (over 90%) [70]. This variation in recycling efficiency demonstrates the importance of using some level of manual disassembly methods to separate materials in order to improve material recovery. There is still a need for more industrial scale experiments to estimate material separation efficiency within these facilities. With these studies, more robust estimates of material recycling efficiencies could be determined.

2.5 Materials Recovery

Metals account for over 60% of the materials used in electronics, including iron, copper, aluminum, and gold. Steel and aluminum are typically removed manually because there is a high demand for these materials in the commodity markets. Copper is recovered from wiring and circuitry, and precious metals such as gold can be recovered from printed circuit boards. The metals used in the internal components are typically recovered via shredding and mechanical separation as described above. The recovered metals are baled and then sold to downstream secondary processors or metal brokers. The copper and precious metals are exported to be processed, because there are no secondary smelters in the U.S. The three most commonly used precious metals smelters are Boliden (Sweden), Noranda (Canada), and UMICORE (Belgium).

There has been recent attention on recovering rare earth metals from electronics, due to the heavy economic and environmental burden from mining these metals. There are processes available to extract rare earth metals from waste products; however most of them are still at the laboratory scale [71]. Methods have been developed to extract rare earths from metal alloys, like those in nickel metal hydride (NiMH) batteries, with over 97% laboratory recovery rates [72]. Initial findings show that recycling rare earths at an industrial scale may be technically feasible, but is not currently profitable. There has been suggestions to store these materials and components until the technology is mature enough to implement in material recovery facilities.

The processes to recover plastic through recycling are not as well developed as the recovery of metals. Even when reliable material streams exist, there are several barriers that hinder efficient recovery of plastics. This is largely due to the contamination from surface finishes and material mixing. The major concern in plastics recycling is the need to identify and separate the plastics found in electronics to reduce potential contamination in the output stream [62]. Co-mingling of plastic resins due to bulk shredding does not allow for the achievement of optimum material grade plastics for the commodity plastics market. Flame retardants used in electronic plastics may complicate recovery, separation, and reuse; brominated and phosphate based flame retardants are not compatible with each other so if both are present in the same recovered supply of a given plastic, the plastic will degrade during further processing.

Recyclers recover commodity plastics and send them to a broker or downstream recycler for secondary processing. Some recyclers may segregate plastics and then shred them to prepare them for a particular buyer or market, but plastics are typically kept in large pieces and baled before being shipped. There are three main types of processes used to recycle plastics: chemical, mechanical, and thermal. Chemical processing uses plastic waste as energy in the smelting process or as raw materials in petrochemical processes. Mechanical processing employs shredding and separation processes to recover material for new products or applications as described in detail in Section 2.4. When pelletized through mechanical recycling, engineering thermoplastics can sell for *dollars per pound* compared to *cents per pound* for container grade plastics [62]. Mechanical separation processes for plastics often require the different plastics to be liberated completely before sorting in order to optimize material purity [73]. Currently it is anticipated that scanner and optical sorting deices will progress and in the future may provide more efficient sorting of plastics and therefore more efficient material recovery, than current technology. Thermal processing uses plastic as an energy or fuel source.

2.5.1 Benefits of Material Recovery

Concern over increased resource consumption has brought attention to the opportunity to recover valuable materials through the collection and processing of waste electronic products and components. Interest in recycling has surged in recent years due to shifting material costs, environmental impacts of material production and disposal, and increasing regulations that focus on recycling efficiency and product recyclability [68]. Recycling is characterized by the collection and processing of materials in order to reclaim them to be used in new products and processes, thereby reducing the need for extraction and processing of virgin materials. The primary object of the recycling process should be to recover materials as efficiently and sustainably as possible. By improving material recovery from waste products and recycling technology efficiency, this new material stream can decrease the need for virgin raw materials.

Resource recovery is the primary benefit of recycling that is most often noted. The “cradle to cradle” strategy advocates for a closed loop economy in which materials are extracted from products at the end of their life and used as raw material for new products [74]. One way companies have started to consider this strategy is by understanding the potential for urban mining waste streams. The growing number of electronic products entering the waste stream has created what is commonly referred to as an “urban mine”. It has been said that the recycling of EoL consumer products will be the key to achieve the sustainable use of metals based on the quantity of products available to be recycled [70]. In order to show the benefits of urban mining there have been estimates comparing the concentration of metals in natural mines to urban mines. For example, the concentration of gold in a circuit board may be 40 to 800 times greater than found in natural gold ore [75]. Another estimation states that for primary gold mining the efficiency is 5 grams per ton of ore compared to 200 grams per ton of computer motherboards, or 300 grams per ton in mobile phones [30].

The recovery of value can only happen if the components and materials can easily be extracted from the processing stream and separated into their appropriate material streams. There is not only a technical limit of disassembly and separation, but an economic limit as well. Often the cost of disassembly will outweigh the value of products, components, and materials recovered, so that the product ultimately is processed by mechanical separation via shredding [76]. Shredding is a cost and time effective process for separation, however it often results in lower quality material streams compared to manual disassembly as discussed previously. Employing manual disassembly methods prior to automated processing can increase the purity of recovered material streams, promote the safe management of hazardous components, and improve overall materials recovery efficiency [76]. The main barrier to solely utilizing manual disassembly is labor costs. The increased miniaturization and complexity of consumer electronics has increased the difficulty and economic viability of manually disassembling products. To optimize material recovery efficiency, cost and time of disassembly should be considered.

Recycling of materials from e-waste can also contribute to energy savings when comparing the energy needed to produce virgin raw material to the energy needed to process secondary materials from waste products. Recycling thus reduces the amount of energy needed in the manufacturing of virgin materials in new products. EoL products in terms of both mass and numbers, represent a large source of potential material recovery [7]. One example of this is aluminum, which has been recently used as housing material for laptops. Ten times more energy is used to produce 1 kg of primary aluminum compared to secondary production from recycling, this increased demand for energy also increases the amount of emissions associated with primary production versus secondary production [77]. This difference in energy demand would increase when considering primary production of precious metals.

Primary metal production often involves a significant environmental impact, particularly for precious and special metals which are mined from ores that contain low concentrations of these materials. Due to these low concentrations, more earth needs to be removed in order to obtain technology and precious metals. Also, the degradation in ore quality compounds this problem. The increased efforts that are needed to mine these materials leads to increased energy consumption, emissions, land use, and waste. A related impact is the pollution from metals mining and the production of hazardous substances. Proper handling of hazardous substances during processing, manufacturing, and disposal is of major importance to sustainably manage electronic products.

Employing material recovery strategies that sustainably manage and process electronic products can maximize the benefits (e.g., resource recovery) and minimize the negative impacts (e.g., exposure to hazardous materials).

2.6 Strategies for Addressing Sustainability during the End-of-Life Phase

The waste hierarchy is a framework that ranks waste management options in order of most sustainable to least sustainable (see Figure 2.13). The waste hierarchy has been represented many ways, but the basic concept has remained the accepted framework for reducing waste by industry, governments, and academia.

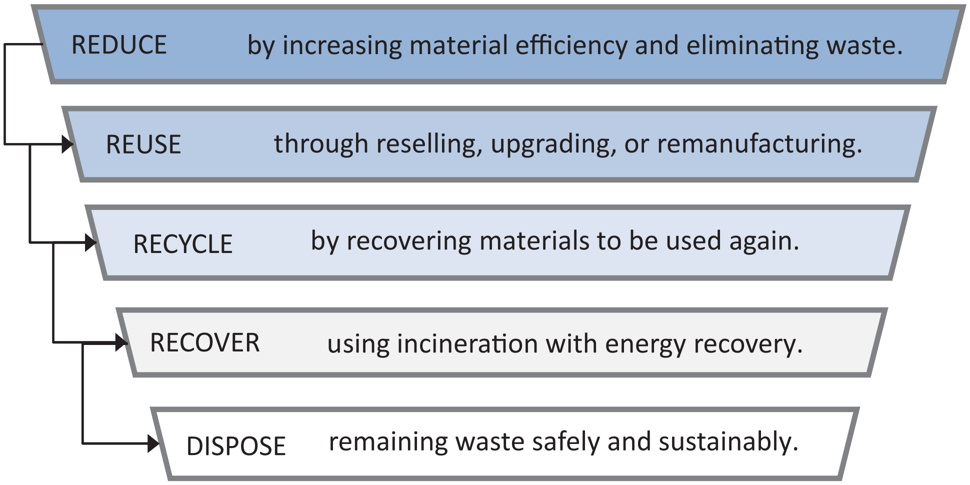


Figure 2.13: Waste hierarchy framework: methods to reduce waste organized in order of the most sustainable option at the top

The most preferable way to reduce waste is to reduce the amount of materials used to produce a product. Most of these techniques are incorporated at the design phase of the product life cycle. As you move down the waste hierarchy framework the value that can be obtained from the product diminishes [78]. Lifespan extension through reuse or repair maintains the original value of the product extending its useful life to a second user. Remanufacturing or refurbishing the product reclaims the functional components of the product to extend their lifespan and value to either be used in the original product form or a new product. Finally if the components are no longer functional and cannot be repaired the remaining materials and components are recycled in order to claim the individual materials within the product to be reused in the manufacturing of new products.

This section reviews strategies that have been developed in order to sustainably manage products during the end-of-life phase. During the last few decades, the electronics industry has undergone changes from research leading to advanced technology development and implementation of environmental legislation. There have been several studies addressing the life cycle environmental impacts of electronics at the product level. Most of these studies have not sufficiently addressed the EoL phase impacts, due to a lack of quality data and information about this stage. Other work has considered the potential for extending the lifespan of a product to delay it entering the waste stream. There has also been research focused on design for EoL which has discussed methods for modularity in order to upgrade the product or disassembly and design for recycling to make it easier to process at the EoL stage in order to maximize material recovery.

2.6.1 Legislation and Certification

Several international regulations have been enacted that impact the EoL phase of electronics, including: Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS), and Registration, Evaluation and Authorization of Chemicals (REACH) [4, 5, 79]. While these are not the only legislative initiatives that focus on e-waste, they are often the most noted and advanced.

WEEE Directive

The goal of the WEEE Directive (2011/65/EC) is to reduce the number of electrical and electronic products disposed of in landfills and municipal solid waste incinerators. The directive sets collection, recycling, and recovery targets for these products and imposes the responsibility for this on producers. Producers are defined as any organization that: manufactures and sells electrical and electronic equipment under his own brand, resells under his own brand which is produced by other suppliers, or imports/exports into a Member State. The producers are ultimately responsible for the collection, treatment, recovery, and disposal of their products at end-of-life, whether managed directly by the manufacturer or through the use of third party collection and recycling contractors. This directive covers all electrical and electronic equipment. The directive specifies what substances and components must be removed from all separately collected waste electrical and electronic equipment, including mercury-containing components such as backlight lamps, batteries, printed circuit boards than 10 cm^2 surface area in addition to printed circuit boards in mobile phones, plastics that contain brominated flame retardants, and liquid crystal displays (LCDs) with greater than 100 cm^2 surface area. The directive is currently being recast to focus on expanding products covered, increasing collection targets, and tracking of material to decrease sub-standard treatment and illegal exports within the EU and other countries.

RoHS Directive

The RoHS Directive (2012/19/EC) is a companion to WEEE with similar scope aimed at restricting the use of six hazardous materials in the manufacture of various types of electrical and electronic equipment and their components. RoHS is part of a legislative initiative to deal with the large quantity of toxic e-waste and the potential risks to health and the environment. The directive regulated the use of lead, mercury, cadmium, hexavalent chromium, and two types of flame retardants, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE), which now includes deca-brominated dipheyl ether (deca BDE), in new electrical and electronic equipment placed on the EU market after July 1, 2006. It is important to note that exemptions are included in the directive and will be reviewed periodically. Current exemptions related to computer equipment include the use of mercury in fluorescent bulbs, lead in CRT glass, lead in electronic components and fluorescent tubes, and lead in electronic ceramic parts. This directive was recast and enforced July 21, 2011 to expand the product categories covered, but did not eliminate any additional substances. However, the recast did highlight an additional four substances, including one flame retardant and three phthalates that are slated for further study under REACH (see below) and may be restricted in future revisions.

REACH

In addition to the directives outlined above, the European Parliament's Environmental Commission enacted a new regulatory framework for the Registration, Evaluation and Authorisation of Chemicals (REACH) entered into force in 2007. The goal of the REACH regulations is "to improve the protection of human health and the environment through the better and earlier identification of the properties of chemical substances [and] encourage the substitution of substances of very high concern (SVHCs) when alternatives have been identified". REACH imposes greater responsibility on industry to manage the risks from chemicals used in the manufacture of goods within the EU and to provide safety information on the substances registered that is publicly available. Manufacturers and importers are required to gather information on the properties of their substances, and to register the information in a central database. Unlike many U.S. regulations, restrictions can be imposed on specific chemicals based on findings of environmental persistence and bioaccumulation potential even if the data pertaining to toxicity is inconclusive or unknown. REACH does not ban chemicals, but identifies those with very high risk of human health and environmental impact through an evidence based process administered by the European Chemicals Agency (ECHA). REACH becomes important during the EoL phase when electronics are being processed and there is potential exposure to hazardous materials and chemicals. It is during this time that there is the most potential for people and the environment to be exposed to these chemicals as discussed previously in this chapter.

U.S. Legislation

The RoHS and WEEE Directives are driving environmental legislation in the U.S, including initiatives such as California's Electronic Waste Recycling Act and the Washington State Electronic Product Recycling Law. As of 2013, the majority of states in the U.S. have e-waste regulations including producer responsibility laws, consumer fees, landfill disposal fee, and bans on disposal and/or e-waste. Extended producer responsibility is the most prevalent as can be seen in Figure 2.14, as it requires manufacturers and retailers to provide or fund an EoL collection program for the products that they sell or manufacture within a given

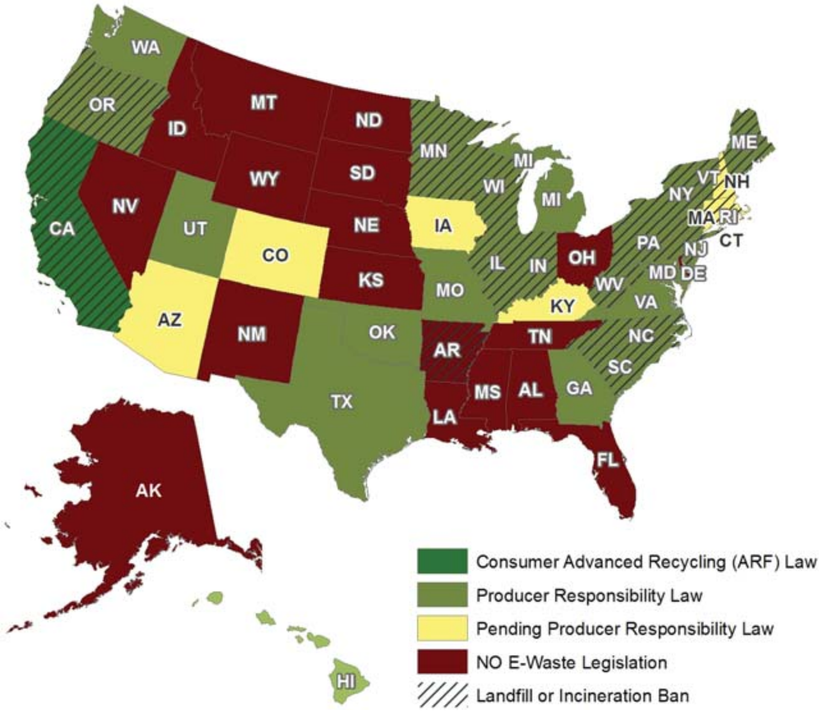


Figure 2.14: Map of e-waste regulation by state in the U.S. [80]

year. What is required from the producer varies by state. California is the only state that imposes a fee on the consumer when they purchase new electronic products based on the product's display size. The fees collected are then distributed to recyclers operating in the state. Arkansas collects a fee on all solid waste disposal and uses a portion of the funds to support a recycling program. Massachusetts and New Hampshire ban certain types of equipment from being disposed in landfills.

There have been many criticisms of the state laws that they do not support an integrated collection network of EoL products and the different rules, targets, and scopes create inefficiencies and additional compliance cost to organizations. This has been challenging for both EoL processors as well as product manufacturers for many reasons including the management of the changing laws and requirements in each state. In the U.S. there is also federal regulation, although not as extensive as state legislation.

Certification Programs

There are two main certification standards that have been adopted in the EoL management industry. R2 was developed in 2006 in a joint effort by the USEPA and the Institute of Scrap Recycling Industries (ISRI). There are almost 300 facilities certified to the R2 standard, primarily in the U.S. and Canada, but also in China, India, Malaysia, Singapore, Mexico, and the United Kingdom. The second certification program is e-Stewards certification which was created by the Basel Action Network (BAN). The e-Stewards certification prohibits the export of certain hazardous materials to non-OECD countries. The primary facilities certified to this standard are in the U.S., but also include sites in Canada, Mexico, and the United Kingdom.

2.6.2 Life Cycle Assessment

Figure 2.15 shows the basic stages of a process flow of e-waste through the EoL phase as outlined previously.

Figure 2.15: Basic process flow during the end-of-life phase

Understanding of the EoL options for electronics is limited due to the complexity of electronic products,combinations of different plastics, complex composite materials and component assembly, as well as their integrated design, which makes them difficult to process at the EoL stage [81].

In 2005, a research team at Lawrence Berkeley National Laboratory (LBNL) performed a study to estimate the energy and greenhouse gas (GHG) emissions over the life cycle of a personal computer [82]. For the EoL stage of this study, the energy consumption and GHG emissions associated with disposing of personal computers in a California landfill were estimated using life cycle inventory (LCI) data. The energy consumption and GHG emissions of demanufacturing personal computers for recycling in California was estimated using publicly available facility data from Fujitsu-Siemens. Recycling “credits” associated with recycling the bulk materials from computers, CRT monitors, and LCDs was estimated using several publicly-available LCI data sources. The study suggested that extending the lifespan of the personal computer could reduce the GHG emissions over the life cycle of a personal computer.

Lu et al. explored the economic and environmental implications of notebook computer recycling in Taiwan [83]. They estimated that during its life cycle, a typical laptop computer emits 51 kg CO_2, 120 g methane and 240 mg N_2O, i.e., 54 kg CO_2eq. The distribution between life cycles was not evident in this study due to limited transparency, so no conclusions could be made about the impacts associated with the EoL phase.

Duan conducted a LCA study of a Chinese desktop personal computer! [84]. The study found that the impact during EoL treatment was greatly influenced by technology level and quality of treatment system used to process the e-waste. The study found that in the best case recycling scenario the environmental benefits are almost as high as the environmental burden of the worst case. Safely managing toxic substances during the recycling processes results in lowering the burden of EoL treatment of about 75-80%, and, thus, allows an overall benefit for the EoL treatment. The best case was recycling of all recyclable materials and components plus the use of a technology that minimizes any releases of toxic substances into the environment. The study also noted that reliable quantitative data on e-waste flows treated under conditions of any of these scenarios are not available. The paper did not publish any inventory results; it only aggregated Eco-Indicator '99 scores, which limits the transparency. The CO_2 distribution of manufacturing, use and EoL is approximately 40%, 65% and -5%, respectively. This is similar to ecoinvent data for a desktop using 100% CRT screens.

A study by Dell assessed the life cycle carbon footprint of a Dell laptop [85]. Generic data from the GaBi database was used to model the EoL scenario and a 75% recycling rate based on the WEEE requirement for electronics. The study modeled three EoL scenarios, 0%, 75% and 100% recycling of the product. With the 75% recycling rate the total carbon footprint of the laptop was reduced by about a 4% and with the 100% recycling rate the reduction was 9% over the life cycle. The portion of the laptop that was not recycled was assumed to be landfilled. The study notes that the reduction can be attributed primarily to the magnesium alloy chassis and precious metals, especially gold.

Due to a lack of quality data and information about the EoL stage of products, this life cycle phase has not been well represented in many LCA studies in general, which is even truer for electronic products. LCA is not the most appropriate method for addressing material recovery efficiency within the EoL phase; however some aspects of LCA could be leveraged and can provide a very good overview on a product's impact on the environment and help identify key areas of improvement. LCA delivers a quantified result on environmental performance but does not provide information regarding how product designs can be improved [39].

2.6.3 Design for End-of-Life

In spite of increased awareness of e-waste issues, many electronic products are still designed with materials that are not easily recycled or in a manner that makes them difficult to disassemble and separate into pure material streams during the EoL processing. This section addresses product design decisions that can influence how a product is managed at the EoL phase.

Design decisions made during the product design and development stage define product properties and affect the performance of the subsequent stages of the products life cycle, including the EoL stage [86]. These decisions made in the early stage of the product life cycle have a great impact on efficiency of product disassembly, material separation, and purification during EoL processing. The economic and technical limitations of separating materials and components are among the greatest obstacles to recover, recycle, and reuse products [67]. Designing products that can be efficiently processed during the EoL phase will improve the product life cycle sustainability.

Design for the Environment (DfE) is a method used by designers to reduce life cycle costs and mitigate negative health and environmental impacts [17]. This approach includes physical design specifications such as material selection and assembly architecture, and influences how the product is handled during the EoL phase when products are disassembled and processed. The manufacturing and raw material stages of the laptop life cycle are resource intensive, and decisions made in the product design stage can help ensure those materials are efficiently reclaimed at the EoL phase.

A related effort is Design for Recycling (DfR), which focuses on product attribute decisions that improve recycling efficiency and quality of recovered materials. Product properties that are relevant to recycling and for disassembly are product structure, material composition, joining techniques, means for disassembly and re-usability. Several DfR guidelines and strategies for computers have been outlined in literature, industry, as well as eco-labels [87]. However, there is no conclusive data on how effective these guidelines are at improving product recyclability or which ones are the most important to consider with respect to recycling efficiency.

Several studies have been conducted in order to survey recyclers and disassemblers in order to understand what DfR guidelines are most effective at improving the recyclability of a product. In 2008, Dell surveyed recyclers in order to rank product design attributes relative to their importance to recycling. The results of the survey found that the design criteria which are more desired are uniformity of plastic resins, avoidance of metal inserts in plastics, and use of common screws [88]. Masanet prioritized DfR guidelines for plastic components in order to investigate the effectiveness of design for recycling guidelines. This work was based on site visits and interviews with computer disassemblers and plastic recyclers, both manual and automated, in the U.S. and Europe [87]. The study found that the criteria with the highest design priority are as follows: use of ISO labeling standards for plastics, limiting the use of paints, and not incorporating molded or glued metal parts within the plastic components. The Green Electronics Council (GEC), in collaboration with the National Center for Electronics Recycling (NCER) and Resource Recycling, Inc. conducted a project to understand the obstacles that electronics recyclers and refurbishers face and how product design could enhance the EoL value proposition [59]. Reducing impacts associated with hazardous materials was identified as the highest priority product design criteria during the study. Specific design recommendations were determined for better identification and ease of removal of components containing hazardous materials, including external markers, color coding, and elimination of these hazardous materials.

Design principles have also been developed to decrease the materials used in order to reduce the environmental value connected to those materials and the amount of effort needed to process the product at EoL. Materials that are potentially hazardous should be replaced or reduced and the use of heavy metals should be avoided when components with less toxic substances are available. This strategy also incorporates dematerialization, the concepts of volume and weight reduction [89].

Several studies have focused on the ease of disassembly and developed criteria to reduce the time or effort that it takes to disassemble a product. Moyer et al. provides a survey of recycling practices and the complexity of disassembly [90]. Manual disassembly techniques using innovative disassembly tools have shown substantial improvement in disassembly times. Huisman outlined the main improvement to aid in material recovery as increased possibility of plastic recycling of the housings and decreasing disassembly time [89]. More recent research has addressed modularity and the use of common components across a product family [91]. This work suggested that sharing the product platform could benefit both the design process as well as the EoL stage of the product life cycle.

2.6.4 Product Lifespan Extension

The rise in e-waste is also of concern as technology advances and more and more consumer electronics are on the market. The variety of product types, reduced lifespan, and technical obsolescence are all contributing factors to the amount of consumer electronics entering the EoL phase.

The lifespan or useful life of a product has been defined as the length of time from product purchase until the product no longer meets the original function. As technology advances, older products become obsolete and consumers want to upgrade their equipment. In 1998, the National Safety Council Study estimated about 20 million computers became obsolete in one year. According to the USEPAs most recent estimates that number has more than doubled by 2007 [21]. Product lifespan is a fundamental variable in understanding the environmental impacts associated with the life cycle of products. The lifespan can be composed of several stages, including a reuse stage, prior to reaching a final disposal stage. The first use stage consists of use by the initial purchaser of the product after which it can be stored, disposed of, or reused by a second user. If the first user of the laptop resells or donates a functioning laptop, the laptop continues its useful life with the second user. Understanding the lifespan of a laptop is important when determining when the EoL phase of the laptop begins.

Laptop computers are usually not replaced because they no longer function, but because the user would like to upgrade for more functionality [92]. A study by IBM found that the technological lifespan of a personal computer in an industrial environment is 2 to 3 years, and that businesses begin the transition to newer technology equipment between 3 to 5 years from original date of purchase. Other studies have suggested similar lifespans for laptops in residential applications, which range from 2.5 to 5.5 years [93,94]. The lifespan of a laptop is short compared to other durable goods, which is mainly attributed to advances in technology and computer performance. For example, the lifespan of a television has been estimated to be 8-12 years and large appliances 10-15 years [95,96].

The short lifespan of these products exacerbates the environmental impacts associated with production and disposal of these products due to production of replacement products and the increasing amount of e-waste. The lifespan of a product can potentially counterbalance the environmental impact from product manufacturing by extending the replacement cycle time, which decreases the need for virgin materials along with the extraction and refinement burden related to producing manufacturing-ready materials [93]. Additional manufacturing costs related to energy consumption and emissions are also avoided.

Some possible measures proposed in the literature to extend the lifespan of electronic products are to provide extended warranties, replacement parts, and options to upgrade the product to increase functionality. However, there is little data to support the route for success of these measures. One study by Williams suggested that providing secondary markets for used personal computers would increase their useful life [92]. This is based on the fact that computers are normally disposed of long before they stop working and not all users require the high performance of new machines. There have also been studies on consumer behavior and how to encourage consumers to extend the life of purchased products. Nes and Cramer describe four motivations consumers have for replacing a product: wear and tear, improved utility, improved expression, and new desires [97]. Cooper identified four potential methods to delay product replacement: adding value during the life cycle, avoiding purchasing through leasing, use of products through a service provider, and shared ownership [98].

Product users are the sole decision-makers in deciding when and how to retire a product. In making the retirement decision, they consider many issues, including convenience, product age, product functionality, product features, and the product's continued usefulness to their needs [21, 93]. As such, there is a high variability in the timing of end-of-life decisions made by product users, which influences the age distribution of returned products and their continued functionality.

2.7 Conclusion

This chapter provided an overview of the end-of-life management phase of consumer electronic products. The EoL pathways were presented including the potential impacts associated with each one. While reuse and refurbishment are prioritized over recycling in terms of the waste hierarchy, there is still debate whether lifespan extension is beneficial when considering the life cycle energy impact. This is due to the likelihood of increased energy efficiency of a new product as discussed in Section 2.6.4. An overview of the processing technology used to recycle these products was discussed, including the importance of recycling efficiency. The amount of material that is successfully recycled from a product greatly depends on the steps and processes employed at material recovery facilities. If materials are unable to be efficiently separated into their respective material streams, then those materials are lost. The benefits of material recovery from e-waste were outlined, including the recovery of valuable materials, energy savings, and pollution avoidance. While e-waste is a complex, mixed material waste stream; it is one of the most valuable. In addition, the hazardous materials within these products need to be safely and sustainably managed. Finally, the main strategies that have been used to address the EoL phase of consumer electronics were discussed. Legislation is a driving force of change within this life cycle phase and industry. Many global and state initiatives are expediting improvements with product collection, material safety, and recovery rates. While LCA methods are useful, currently, they are not practically implemented by EoL operators due to limited data availability and the time commitment required. Design for EoL has a long history, but there is still not conclusive data as to what guidelines are most effective when addressing the recyclability of a product. This refers to the detailed guidelines that would be needed for a designer to implement at the product design phase. There are however, several agreed upon design for recycling themes including, material compatibility, and this will be discussed in more detail in Chapter 4.

There are several barriers that have limited improvements in the management of the EoL phase of electronics. Due to the young nature of the recycling industry it is especially difficult to characterize due to the variance in business models, recovery methods, and data availability. Currently, data collection beyond revenue based metrics is not widely used within industry. This will have to be addressed in order to make progress within this industry. It is also the first step in developing the information feedback loop between designers and EoL practitioners. With this, we can make forward progress towards an ideal closed loop economy through better recovery of materials, improved product designs, and information exchange throughout the supply chain.

Chapter 3

Assessment of End-of-Life Pathways of Consumer Electronic Products

The goal of the research presented in this chapter was to develop a representative set of the most common pathways (i.e., reuse, refurbish, recycle) that consumer electronic products follow during the end-of-life management phase within the U.S. In order to do this a framework was developed to assess the characteristics of material recovery facilities that process electronic equipment. A survey was used to collect primary data from these facilities. The information provided by each facility was then mapped using a material flow analysis model that was developed to identify the most common pathways followed by each consumer electronic product category.

3.1 Introduction

Resource use is important in our society to enable new technologies and advancements, as discussed in Chapter 1. At the same time the extraction, use, and disposal of these resources contributes to environmental degradation and reduction of non-renewable resources [9]. Global consumption of resources has grown exponentially over the past century. The move towards a closed-loop economy would be an ideal system to sustainably manage resource use.

Bridging the gap between the end-of-life (EoL) practitioners and product manufacturers within the consumer electronics industry is necessary to move towards this more ideal and sustainable system. As mentioned in previous chapters, electronic products contain both valuable and hazardous materials. Recovering the value and safely managing the toxins is the upmost priority during EoL processing of these products. Due to the valuable material content, electronic products present an opportunity that is ideal for moving towards a closed loop economy. The concept of *urban mining* has gained traction in the last several years because of this opportunity. Urban mining is the mining of waste products in order to reclaim valuable materials to be reused in new products or applications. While recycling has always been motivated by this, products are often managed incorrectly and valuable materials can be lost in the process. Concern over resource scarcity and rare earth metals has also motivated this concept.

In order to sustainably manage these products during the EoL phase we must first understand the current state of the recycling industry. An important strategy that is underutilized in this stage of the product life cycle is the implementation of an information feedback loop from EoL management programs and facilities to product manufacturers and designers. In order to improve information exchange from the EoL stage throughout the product life cycle, it is necessary to develop a standardized system for information and data exchange. Another barrier to implementing this sort of system is the lack of data collection within the EoL management phase. The current focus of data collection at these facilities is motivated by the requirements of state regulations. States that have extended producer responsibility laws require programs and facilities to report mass based collection metrics. States that have landfill bans require the programs to certify that none of the equipment detailed by the regulation was disposed of in landfills. While these metrics are important, additional indicators are needed in order to better characterize program performance and the product and material flows through the end-of-life phase.

3.1.1 Review of End-of-Life Management Phase

Chapter 2 discussed the end-of-life management phase in detail. This section is presented here to review the basic flow of e-waste products through the EoL management phase, which is the focus of this chapter.

Figure 3.1 presents the product life cycle as described in Chapter 2 in addition to a more detailed diagram of the EoL phase. The diagram details the basic process flows that a product and its materials follow through collection and processing to the final stage in the product life cycle. This can include landfill disposal, incineration with or without energy recovery, and secondary processing (e.g., smelter facility).

When a product is no longer of value to a user they have three main options for discarding the product.

- Informal reuse - sell or give the product to another user
- Curbside collection - dispose of the product through local waste management
- Formal collection - send to a third party for formal management and processing

Once a product is returned through a formal collection route the next step in the management phase is primary processing which occurs at material recovery facilities (MRFs). In the U.S., the primary processing of e-waste is the most critical step in the processing of e-waste [62]. The ultimate fate of the collected products is decided at these facilities. In this stage, decisions are made on how to treat and process the products collected, based on their condition, potential economic value, and the current processing technology available. Once

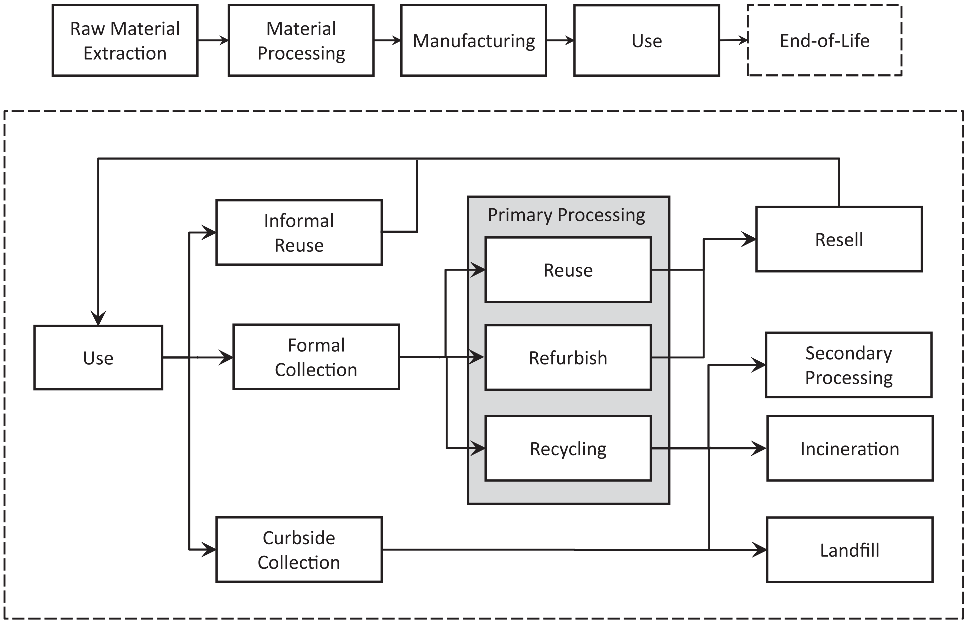


Figure 3.1: Diagram of end-of-life management phase that details the basic process flows that a product and its materials follow through collection and processing to the final stage

the products reach this stage, there are three main pathways that they can follow: reuse, refurbish, or recycle. Reuse, also known as direct reuse, includes products or components in working condition that can be sold or donated to secondary user. Refurbishment includes any products or components that can be reused after efforts are made to return them to a functioning product. A plug and play test is typically used to identify penetrability of products and components. Currently reuse and refurbishment at the component level has not been widely adopted, but industry experts have noted that it is currently being developed in the industry.

3.2 Mapping Product and Material Flows

The previous section discussed the importance of managing electronic products during the EoL phase with the goal of moving towards a more sustainable materials market. In order to do this, a better understanding of the current EoL management system is necessary. One method that can be used to characterize the current system and material flows within that system is material flow analysis.

3.2.1 Material Flow Analysis

Material flow analysis is a method of quantifying the mass of a material or product of interest as it moves throughout specified temporal and economic or geographic boundaries [99]. It is to make a systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the final sinks of material [100]. MFA builds on earlier concepts of material and energy balancing and is complementary to life cycle analysis and input-output models. The first material flow accounts on the national level were presented in the early 1990s for Austria and Japan. MFA in literature has commonly focused on material stocks of high volume materials, high value materials, or toxic materials. MFA is widely used in research on waste management at the substance level as a tool to trace the ows of particular materials and to manage the resource use of these materials creating closed loops in the economy.

Process-based MFA studies deliver indicator values for a systems characteristics, performance, and potential impacts [101].This method focuses on system comprehension rather than direct impact in order to develop a system understanding and explore areas of potential improvement.

Previous research has employed MFA to track waste flows of various consumer products. Binder and Mosler used MFA to analyze the consumption and mass of waste flows of short-life goods such as PET and aluminum bottles in Santiago de Cuba [102]. Streicher-Porte conducted a material flow analysis of personal computer recycling in the informal recycling sector in Dehli, India [101]. Hischier combined MFA with simplified LCA to determine the environmental impact of a Swiss take-back and recycling system [103]. Huisman evaluated the performance of various recycling scenarios and equipment based on environmental performance [104]. Lam and colleagues linked material flow analysis with environmental impact potential based on metal content using computers and televisions as a case study [29]. Several studies were done by Reuter and Van Schnaik using flow analysis focused on e-waste and EoL automobiles [105]. Chancerel conducted an assessment of WEEE pre-processing and focused on the precious metal flows in a German facility [69]. Oguchi also used MFA to determine the fate of metals contained in WEEE [106]. Gregory used MFA in order to analyze the material recovery system for leaded glass in CRTs [107]. Material flow analysis has also been used to predict the amount of obsolete equipment. Liu conducted this type of study in Beijing, China in order to inform future planning of collection systems [108]. Yu used MFA to forecast the amount of obsolete personal computers on a global scale [109]. Kwak and colleagues conducted an e-waste stream analysis of a computer refurbishing facility in Illinois in order to understand the variability of incoming product streams based on product characteristics, including product type, manufacturing age, and weight [91].

While these studies have provided a good foundation, they were limited in scope and often limited to one facility or used secondary data sources. Most MFA studies use market-wide statistics that do not capture the technical details of the system that are needed to provide actionable insight into the system.

There have been several studies that have evaluated the performance of EoL management systems. Gutowski and Dahmus used information theory to compare product material mix and predict the likely EoL path of a product [110]. Gregory and Kirchain developed a framework for evaluating the economic performance of four North American electronics systems [111]. Fredholm developed a framework to evaluate recycling systems based on collection rates, operating models, and economic performance [112]. Kwak and colleagues conducted and e-waste stream analysis at an e-waste collection center in order to assess product quantity and age [91].

Previous research has shown that material flow analysis can be used to assess waste management systems, as it considers the material and product flows entering and leaving the system. In order to sustainably manage electronics in the EoL phase of the life cycle you must understand the amount and type of products in the system as well as the EoL pathways they follow. Having accurate data on the types and quantity of consumer electronics items collected is important to understand the type and variety of products that are being collected and the potential materials that could be recovered from these products.

However, there are challenges to obtaining material flow data within the EoL management industry. The development of this type of system is stalled due to critical data gaps and challenges of characterizing such a young, diverse industry. Characterizing the flow of e-waste within the U.S is challenging due to lack of available data from EoL management facilities. In addition, the short history and variety of business models employed within this industry also make it difficult to evaluate. Electronic recycling has a short history, so there is not a broad and fixed infrastructure in place, making these types of assessments difficult [62]. Data collection and sharing is not a common practice within this industry. Exacerbating this shortcoming, recycler performance is typically assessed using indicators that do not consider key factors that influence recycling performance (e.g., inflow quality, product mix, or downstream material yields). Ideally this would be addressed in a detailed system-wide analysis. Unfortunately, time and expense preclude this approach beyond the occasional case study. While one-off studies provide valuable insights, they do not fill the operational need for continuous feedback and regular benchmarking within this industry.

As recycling systems become more widespread, understanding system performance becomes even more critical, both to enable improvement of existing systems and to design and implement new ones [110]. The importance of tracking these flows has been noted in literature as high priority due to the potential impact recycling processes have to contribute to the sustainable management of resources [100]. Pehlken also recognizes the importance of assessing these flows regarding their environmental impact including energy savings and material efficiency. The variety, variability, and condition of products entering the system creates mixed material flows and the composition of the incoming flow is often unknown and complex [100,113,114]. Attaining a sustainable materials market requires understanding the nature and magnitude of the flows within the system [115].

3.3 Assessment Methods

In order to sustainably manage electronic products in the EoL phase, we must first understand the current state of the industry, as discussed in the sections above. This section details the development of the assessment framework that was used to compare material recovery facilities. The primary goal of the assessment was to develop a representative set of the most common pathways that are followed during the EoL phase for each product category.

By understanding the mix and quantity of products that are being collected at material recovery facilites, in addition to the pathways they follow through these facilities and decision points, we will be able to better characterize the EoL phase. Previous work as discussed at the beginning of this chapter has focused on quantifying the amount of products collected at facilities; however, they have not considered the pathways that they follow within a facility, that determine the EoL fate of the product. Currently, there is not a good understanding of the percentage of products that follow each EoL pathway (i.e., recycle, reuse, refurbish) within these facilities or the EoL management industry as a whole. For example, what is the percentage of laptop computers that is refurbished versus directly sent to reuse within a facility? Are mobile phones more likely to be reused or recycled?

In order to address these needs within this industry, research is presented here that uses material flow analysis methods to map product flows within a material recovery facility. The flows were mapped according to collection method and the EoL pathway followed by each product category. A quantitative assessment of product flows was conducted and insights into the mechanisms and pathways were identified. This assessment was done using data collected from 14 material recovery facilities operating within the U.S. EoL management industry. The study identified facilities across the U.S. that varied in size and operating models in order to capture the diverse business models used in this industry. From these assessments, a representative set of the most common EoL pathways followed by product category was determined in order to better understand the flow of e-waste within the EoL management industry in the U.S. based on current industry practices.

The focus of this work is the formal collection and processing of e-waste as depicted by the boundary line in Figure 3.2.

Products collected through a formal collection system are sent to material recovery facilities for processing in order to recover value, depending on the condition of the product when it arrives at the facility. During formal processing of e-waste, three major categories have been identified as potential EoL pathways based on the fate of the product: reuse, refurbish, and recycling. These pathways can be followed at the component or whole product level through the facility.

3.3.1 Development of Assessment Framework

As mentioned previously, an assessment framework was developed to characterize the EoL management phase of consumer electronics in the U.S. (see Figure 3.3 below). The frame-

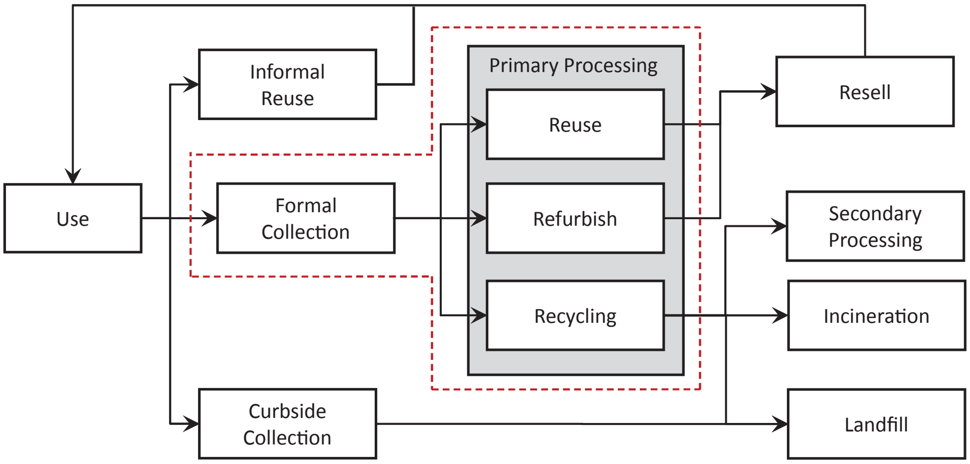


Figure 3.2: System boundary: the formal collection and processing of e-waste during the end-of-life management phase

work consists of five sections: facility overview, operating model and process flows, product flows, collection methods, and facility resource use. The primary objective of the proposed framework is to assess product flows of consumer electronic products in the U.S. to determine the percentage of products (by product category) that follow each available end-of-life pathway in a material recovery facility. Additional information about the facility was included in the framework to understand the operating model, processes and process flows performed at the facility, and facility level resource use.

The facility overview section of the framework provides basic facility information including facility size and location and the number of employees at the facility. The operating model and process flows section was included to understand how the products move through the process flow within the facility. This also provides insights into the operating model of the facility. For example, does the facility focus more on recycling or refurbishing of equipment?

Products ready for the end-of-life are collected through a variety of collection methods. The framework segments these methods by the consumer and business sectors, to better identify the collection performance of each of these sectors.

The product flows section identifies the incoming product mix collected by each facility. Then the mass percentage of each product category is determined based the end-of-life pathway it follows.

The final section of the framework focused on resource use in the facility in order to provide a high level assessment of the energy used to process these products during the EoL phase. While the focus of this work was not an environmental assessment, some findings are presented later in this chapter on the results of the energy assessment.

Facility Overview	
Facility Location	City, State
Facility Size	Area (ft^2)
Organization Size	Number of employees
Program Certified	List of certifications
E-waste Processed	Mass (lbs.) per year

Operating model and Process Flows	
Processes performed (e.g., manual dissassembly, shredding)	
Description of basic process flow within the facility	
Detailed process flow for a product category (e.g., laptop)	Process description
	Manual or automated
	Type of equipment used
	Number of operators
	Process inputs (e.g., electricity)
	Process outputs (e.g., hazardous waste)

Product Flows	
Incoming product mix	Mass percentage by product category
End-of-life pathways of incoming product mix	
Whole system reuse	Mass percentage by product category
Component reuse	Mass percentage by product category
Whole system refurbish	Mass percentage by product category
Component refurbish	Mass percentage by product category
Recycling	Mass percentage by product category

Collection Methods	
Consumer Sector	Retail Return
	Collection Program
	Direct from Consumers
	OEM takeback program
	Other
Business Sector	Direct from OEM
	Enterprise (Small/Med/Large)
	Government Agencies
	Academic Institutions
	Other

Facility Resource Use	
Facility Inputs	Electricity (kWh)
	Natural Gas (m^3)
	Water (gallons)
	Other
Facility Outputs	Hazardous waste (lbs.)
	GHG emissions (CO_2 eq.)
	Landfill waste (lbs.)
	Waste water (gallons)
	Other
Transportation	Fuel purchased
	Mileage

Figure 3.3: Framework developed to assess material recovery facilities based on five key categories: facility overview, operating model and process flows, product flows, collection methods, and facility resource use

3.3.2 Product Scope

The following product categories were included in this study:

- Desktop and laptop computers (including liquid crystal display (LCD) and cathode ray tube (CRT) technologies)
- Monitors (including LCD and CRT technologies)
- Mobile devices (including mobile phones and tablet computers)
- Televisions (including LCDs, Plasma, and CRT technologies)
- Digital Video Disc (DVD) players and Video Cassette Recorders (VCR)

These products were chosen due to the ability of EoL management facilities to track these products through the process flow and they are representative of a broad range of consumer electronic products that are most common in the marketplace today. In 2010, more than 62% of e-waste collected was from computing and ICT equipment [58]. It is important to note that while CRT technology is not currently used in new products; many CRT products are still being collected through e-waste streams.

3.3.3 Collection Methods

The collection methods were divided into two subcategories: the consumer sector and the business sector. Tables 3.1 and 3.2 describe these collection methods in more detail.

Table 3.1: Description of consumer sector collection methods evaluated in this study

Consumer Sector Collection Methods
Retail Return - Consumer returns product to a brick and mortar retail location
Collection Program - Consumer returns product to a local e-waste collection event
Direct from consumers - Consumer returns product directly to EoL management program
OEM Takeback program - Consumer returns product to OEM via mail or other means

Table 3.2: Description of business sector collection methods evaluated within in study

Business Sector Collection Methods
OEM - OEMs return products directly to EoL mgmt program
Enterprise - Businesses return products through contracts with EoL mgmt program
Government - Gov't agencies return products through contracts with EoL mgmt program
Academic - Institutions return products through contracts with EoL mgmt program

The segmentation of collection methods by business and consumer sector was done in order to distinguish between the amount of products brought to collection by the consumer versus business sector. The most common collection methods within the consumer sector are retail return, collection program or event, direct from consumers, or an OEM takeback program. In the business sector the most common methods are direct return from an OEM or returns from organizations including businesses, government agencies, and academic institutions.

3.3.4 Material Flow Analysis Model

This section describes the material flow analysis model that was developed to map the product flows through collection and subsequent EoL pathways within a given facility (see

Figure 3.4). The dashed line represents the system boundary of this study. Secondary processing, incineration and landfilling of e-waste were excluded; however, if a facility directly sent materials to either a landfill or incineration facility that data was captured.

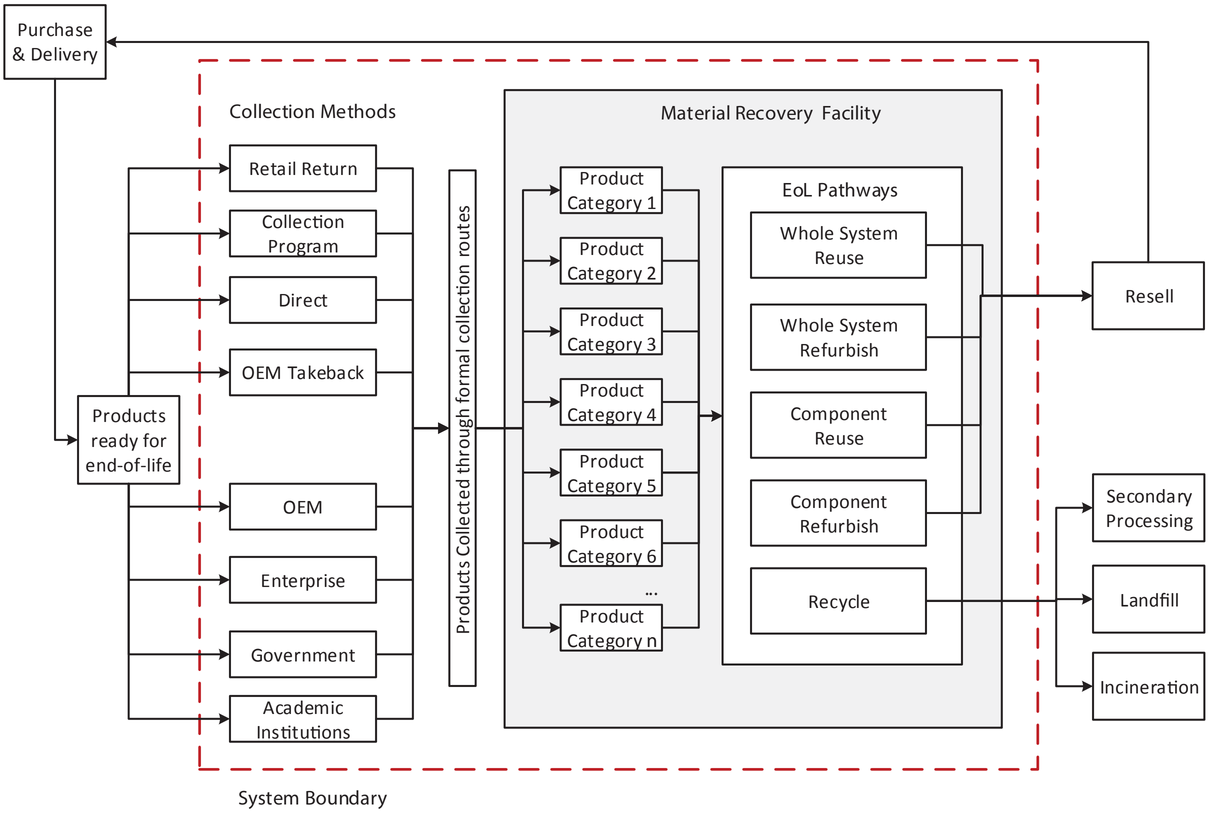


Figure 3.4: Material flow analysis model and system boundary used to map product flows through collection and end-of-life pathways within each material recovery facility

Initially products are collected by material recovery facilities through a variety of collection methods as described in the previous section. The products collected are then organized and separated into bins by their respective product category. The products are then sent to a station to be inspected and tested for functionality. Depending on the condition of the product it is then sent downstream in the facility to either whole system reuse, whole system refurbish, or part harvesting. The products that follow the reuse and refurbishment pathways are then sent downstream to be directly resold or reconditioned in order to be resold. The products that are not in working condition to be reused or refurbished are then sent to part harvesting. Products sent to part harvesting are then separated into components and parts to be further processed. The components that are still in working condition are then sent to part reuse and refurbish. The remaining equipment, components, and parts are sent to recycling.

The material flow analysis model presented in Figure 3.4 was expanded to account for the actual pathways that products follow within a material recovery facility. Figure 3.5 presents the resulting system analysis that was used to map the mass based flows of products through collection and EoL pathways by product category based on the description above. The system analysis was developed based on information gathered by conducting informational interviews with material recovery facility managers and EoL management programs.

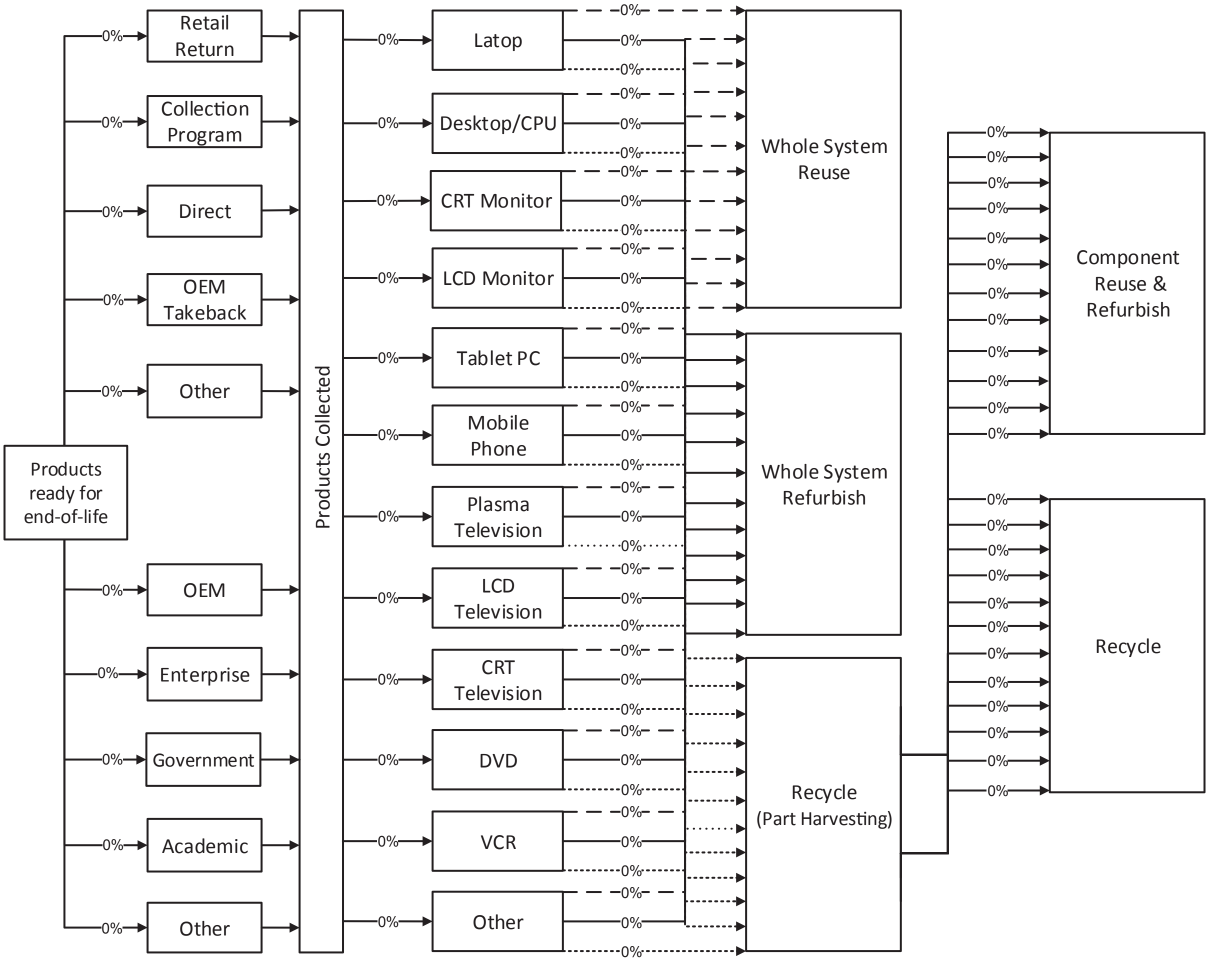


Figure 3.5: Expanded material flow analysis model used to map product flows through collection methods and end-of-life pathways in material recovery facilities for this assessment

3.3.5 Survey Development and Data Collection

Facility surveys were used to collect the data to assess each facility and model the product flows, based on collection methods, EoL pathways, and incoming product mix. The collection of primary facility data is a key contribution of this work. The survey was developed using input from experts in the field including OEMs and EoL practitioners in order to use terminology and processes consistent within industry. Data from the facilities was collected through a series of surveys and phone interviews. The phone interviews were conducted at the beginning and end of the survey process. During the first phone interview an overview of the research was presented and the survey questions were reviewed. This was done in order to clarify any survey questions and provide details regarding the requested data. Once the survey was completed a follow-up phone interview was done to clarify any questions regarding the submitted data.

The survey consisted of four main sections based on the assessment framework that was developed. A brief overview of each section is described below.

> **Section 1** - Facility information: Facility size, location, mass of e-waste processed, operating model, and certifications
>
> **Section 2** - Material Flows: Incoming product mix, collection methods, product flows for each EoL pathway
>
> **Section 3** - Process flow: Details of processes and process flows at each facility
>
> **Section 4** - Resource use: Facility level energy data

The first section of the survey was developed to understand the system architecture of each facility including the type of facility, location and size of facility, product scope, and processes performed at the facility as well as the amount of e-waste processed per year. The second portion of the survey focused on how the products flowed through the facilities and what EoL pathway they followed. The pathways were identified and mapped for each product category that was assessed. The third section of the survey asked facilities to provide detailed information regarding the process flow at each step as the products move through the facility. This section was included to give additional insight into the main process steps that are performed at each facility. The final section requested data on resource use in the facility in order to provide a high level assessment of the energy used to process these products during the EoL phase. While the focus of this work was not an environmental assessment, some findings are presented later in this chapter on the results of the energy assessment.

3.4 Assessment Results and Discussion

This section discusses the data analysis and results of the assessment of material recovery facilities that was conducted. The data was collected through primary survey data for each facility. As described above a material flow analysis was used to map the flow of e-waste products that enter each facility through collection routes and subsequent pathways. The results presented are based on data collected from 2011. Ideally, data would be collected over a longer time period; however, for this study it was limited to one year in order to minimize data collection intensity and time required from each survey participant.

Survey requests were sent to thirty-five facilities with a response rate of 40%. A total of 14 facilities responded to the survey and of those three were small, six were medium, and five were large based on the number of employees: small (1-15), medium (15-30), and large (30-65). The operational footprint was also determined for each facility and ranged from 7,000 to 150,000 ft^2. A past survey that was conducted by the International Data Corporation (IDC) to profile the recycling industry within the U.S. [58]. The survey responses indicated that this industry primarily comprised of facilities that operate with 10 or less workers representing 50.5% of the industry.

3.4.1 Overview of Participating Material Recovery Facilities

Recent studies have suggested that material recovery facilities are primarily concentrated in the Midwest, New England, and Western regions of the U.S., each of which accounts for approximately one-quarter of recycling companies [62]. Figure 3.6 shows the number of facilities throughout the U.S. that participated in the survey categorized by region. The majority of the facilities were located in the Mountain and Midwest regions, with four facilities from each. There were two participating facilities in the New England and the West, and one facility from both the Southwest and Southeast regions. This representation of facilities closely aligns with distribution of total material recovery facilities in the U.S.

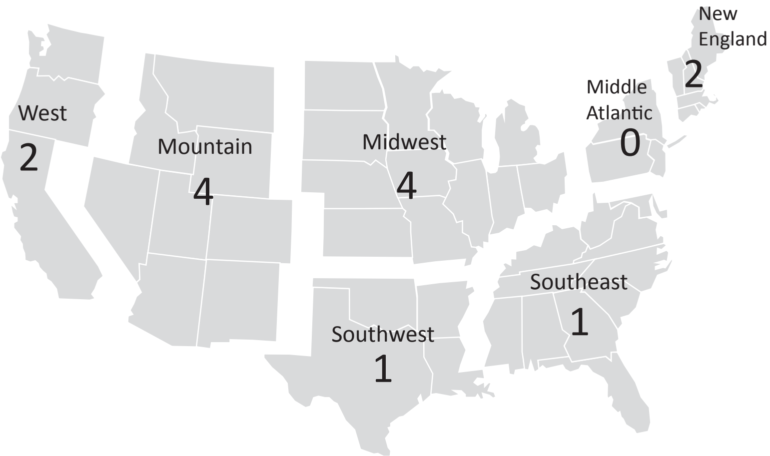


Figure 3.6: Material recovery facilities surveyed categorized by U.S. regional location

Table 3.3 provides an overview of the basic processes used at each facility A through N. The processes include, collection, manual disassembly, automated disassembly, functionality testing (products and components), refurbishing, reuse, and recycling.

Table 3.3: Overview of basic processes performed at each facility A through N

Basic Processes	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**
Collection	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Manual Disassembly	X	X	X	X	X	X	X	X	X	X	X	X		
Automated Disassembly	X			X		X		X	X	X	X	X		
Testing	X						X							
Refurbish/Reuse	X						X						X	X
Recycle	X	X	X	X	X	X	X	X	X	X	X	X	X	

The amount of e-waste processed at each facility over the past six years from 2007 until 2012 is presented in Figure 3.7.

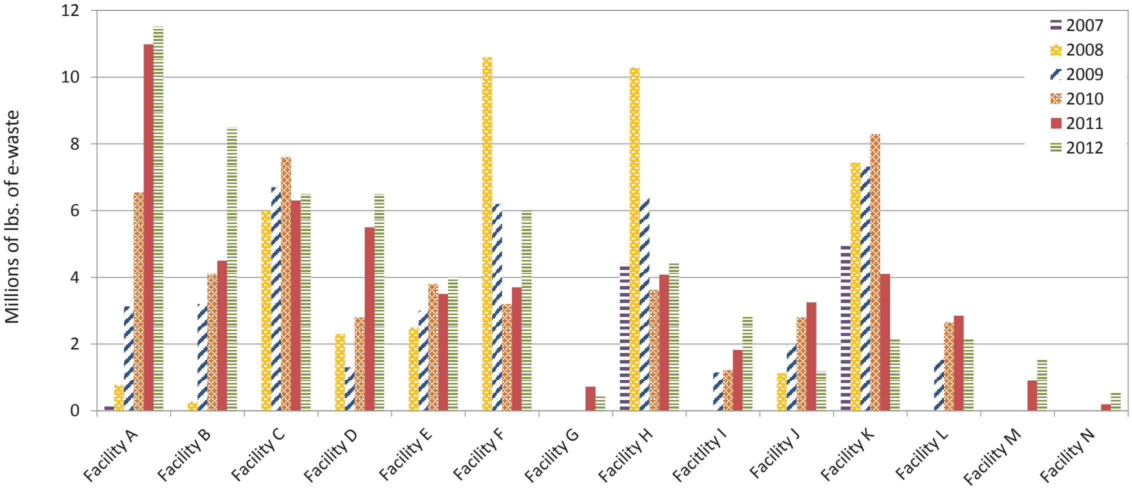


Figure 3.7: Mass (millions of lbs.) of e-waste processed per year at each facility (2007-2012)

The facility was not in operation the years for which data is not shown in the figure. The amount of e-waste processed at several facilities grew steadily from 2007 to 2012, which would be expected based on the growing amount of e-waste and collection systems. Facility A had the largest increase in e-waste collection over the six year period, with 60 times more e-waste mass collected in 2012 compared to 2007. However, it is interesting to note that this was not the case for all facilities. From this data it is difficult to determine what the cause of the decrease in the amount of e-waste processed at these facilities. Several of the facilities are young facilities so they are still developing their collection networks and this could be one potential reason for an unstable supply of e-waste. There were also several extended producer responsibility laws that were signed into law in 2007 and 2008, which could have affected the rise in collection in 2008 as shown in Figure 3.7. It has been noted throughout literature that the extended producer responsibility laws are one of the main motivators that drives collection. Figure 3.7 also provides a representation of some of the variation in the amount of e-waste processed between the facilities surveyed for this study.

To better understand the relationship between the age of the facility and the amount of e-waste collected at each facility, the results from Figure 3.7 are summarized in Table 3.4. The table shows the number of years each facility was in business, the total mass (lbs.) of e-waste process over the six year period (2007-2012), and the average mass (lbs.) of e-waste processed per year. The results show that the longer a facility has been operating, the more e-waste they collect and process on average each year. This is most likely due to the mature collection networks that these facilities have been able to develop over time.

Table 3.4: Comparison of the number of years each facility has been in business, the total mass (lbs.) of e-waste process over the six year period (2007-2012), and the average mass (lbs.) of e-waste processed per year at each facility

Facility	Years in business	Total (lbs.) 2007-2012	Avg. (lbs.)/year
Facility A	6	33,153,572	5,525,595
Facility B	5	20,570,000	4,114,000
Facility C	5	33,100,000	6,620,000
Facility D	5	18,400,000	3,680,000
Facility E	5	16,800,000	3,360,000
Facility F	5	29,700,000	5,940,000
Facility G	2	1,147,077	573,539
Facility H	6	33,248,672	5,541,445
Facility J	5	10,341,090	2,068,218
Facility K	6	34,320,084	5,720,014
Facility L	4	9,208,084	2,302,021
Facility M	2	2,474,000	1,237,000
Facility N	2	759,000	379,500
Facility I	4	7,009,871	1,752,468

3.4.2 Collection Methods: The Consumer and Business Sectors

It has been noted in literature that the majority of e-waste products collected for EoL treatment is from the business sector. This proved to be the case for the facilities that were surveyed as part of this study. Figure 3.8 presents the percentage of products collected at each facility from the business and consumer for each facility.

On average the quantity of products collected from the business sector was 64% compared to 36% from the consumer sector. The majority of products collected at each facility from the consumer sector were from either a collection program (11%) or state mandated OEM

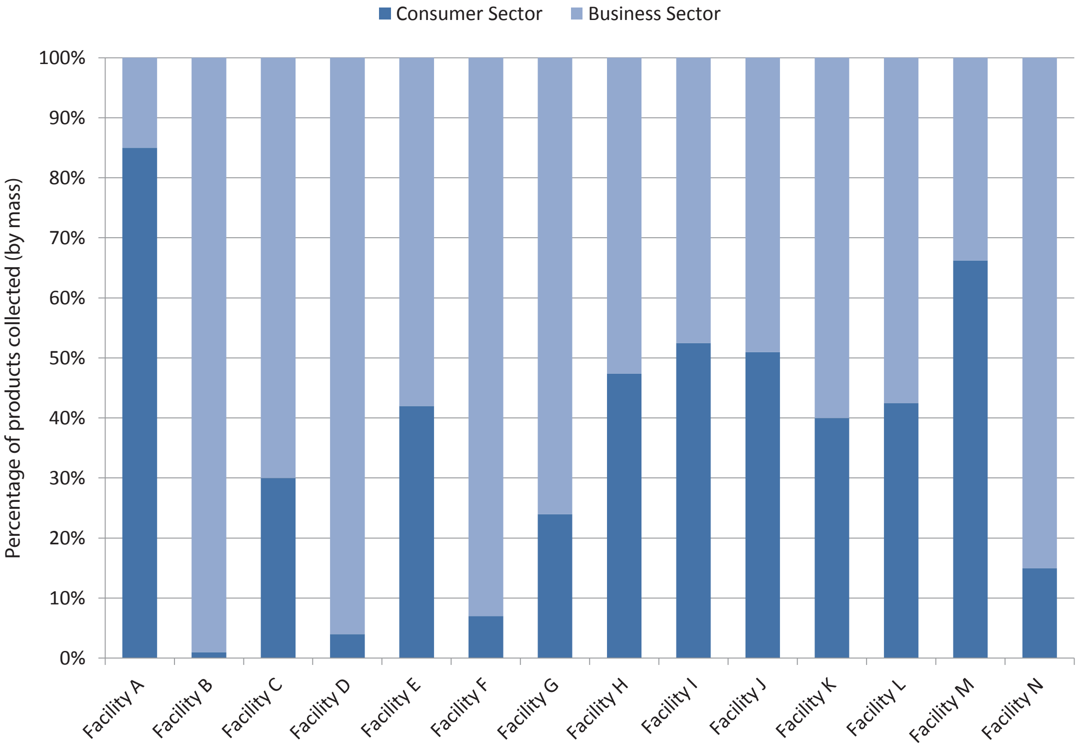


Figure 3.8: Comparison of percentage of products collected via the consumer and business sectors for all facilities for the year 2011

takeback programs (17%). For the business sector the majority of products (26%) were collected based on contracts that the EoL management facility had with local business to return products when they upgrade their computing and electronic equipment.

In 2012 alone, the average U.S. household spent $1,312 on electronic products according to a study conducted by the Consumer Electronics Association [20]. Sales to the consumer market represent the majority of electronic product purchases [58]. Considering this large market share, the survey results show that there is opportunity and a need to increase collection of e-waste from consumers, therefore increasing the amount of e-waste processed at each facility and the recovery of materials.

There are several barriers that prevent consumers from dropping off these products when they are no longer useful to them. Lack of consumer knowledge around the EoL phase of products is a main concern within the industry. As discussed in Chapter 1, many consumers store their old electronics for many reasons, not knowing where to dispose of these products or concern over data security. One study by Gattuso produced similar findings for obsolete computers, about 75% are stored in peoples homes, approximately 14% percent are recycled or reused, and 11% end up in landfills [45]. Consumer awareness and incentives could encourage e-waste recycling and ultimately divert products from landfills and storage to reclaim valuable materials. The development of more efficient collection channels will be necessary to facilitate a more sustainable EoL management system.

3.4.3 Incoming Product Mix

As discussed previously, the second section of the survey collected data on the incoming product mix processed by each facility. Each facility provided the mass (lbs.) of incoming e-waste by product category for 2011. Of the e-waste processed in 2011 at each facility the mass based percentage of each product category is presented in Figure 3.9.

In addition to the product categories included in the scope of this assessment (see Section 3.3.2), material recovery facilities collect a variety of electrical and electronic equipment. The *other* product category represents this additional equipment, which could be automated teller machines (ATM) machines, electronic medical devices, or other waste electronic equipment. This represents the largest category by weight of incoming products for several facilities. This is likely due to the fact that this type of equipment is often large and weighs more compared to other products, for example ATM machines or checkout equipment from retail stores.

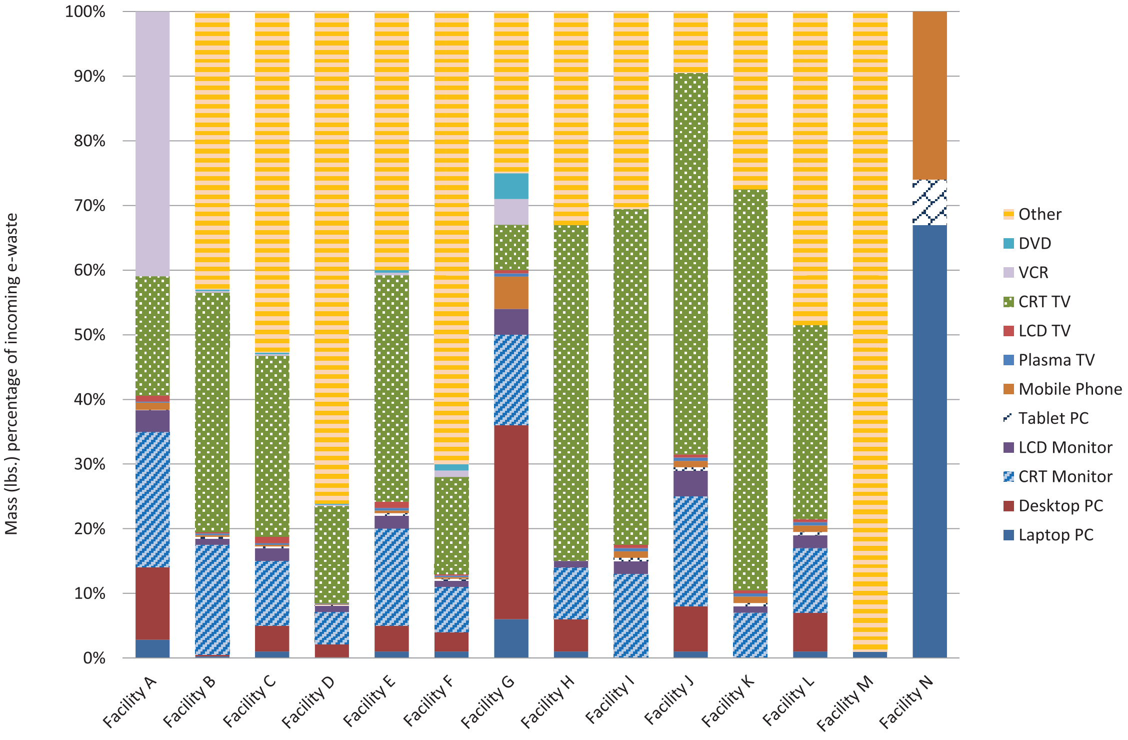


Figure 3.9: Percentage of incoming e-waste by mass (lbs.) for each product category at each facility for the year 2011

After the other category, the majority of equipment collected by mass was CRT televisions and monitors, followed by desktop computers. As evidence that older equipment that has been out date for many years is still being collected for EoL management. Also CRT equipment is much heavier than newer technology which skews the data when only accounting for mass based collection. One of the main concerns that arise from the large amount of CRT collection is that currently there are stockpiles of this type of equipment. This is mainly due to the limited secondary uses for leaded glass which is found in the screens of the CRT equipment and lack of available processing facilities. In 2013, several processors abandoned warehouses with more than 10,000 tons of CRT equipment and glass [116]. While this issue is currently limited to CRTs, it could potentially foreshadow future challenges for the recycling industry. As technology develops and different materials are used.

Currently these facilities do not collect data by number of units; this is often due to time constraints in addition to mass based reporting metrics that are required by state takeback laws. Mass is not a good indicator to use when assessing the product mix of the incoming e-waste stream due to the varied mass of products and continued size reduction of technology products that are placed on the market.

In order to gain more insight into what products are being collected, the mass based distribution was used to estimate a volume (by units) based distribution. The average mass of each product was estimated using market data and literature [34,83,117–119]. Figures 3.10 and 3.11 shows the average product mass for each product category that was evaluated. Due to the large variation in product mass between product categories, the results are presented in two charts. Figure 3.10 presents the average product mass (lbs.) data for product categories that weigh more than 10 lbs. Figure 3.11 shows the average product mass (lbs.) data for product categories that weigh less than 10 lbs.

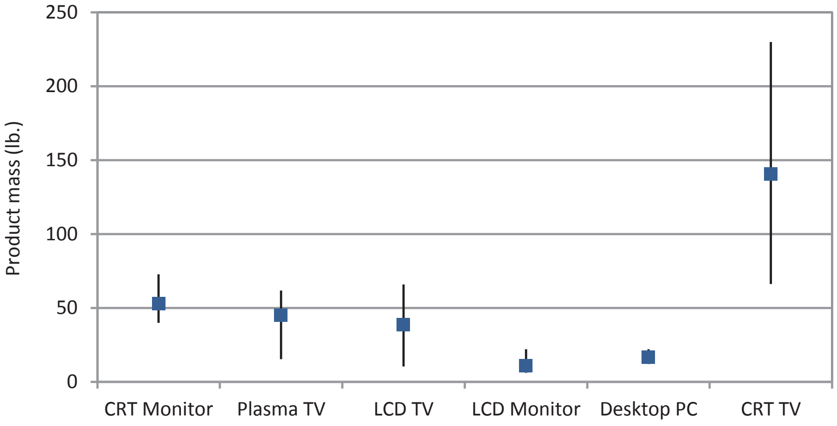


Figure 3.10: Average product mass by category for products that weigh more than 10 lbs.

Using the average product weights the number of units of collected for each product category was estimated. The data presented in Figure 3.12 provides a more accurate assessment

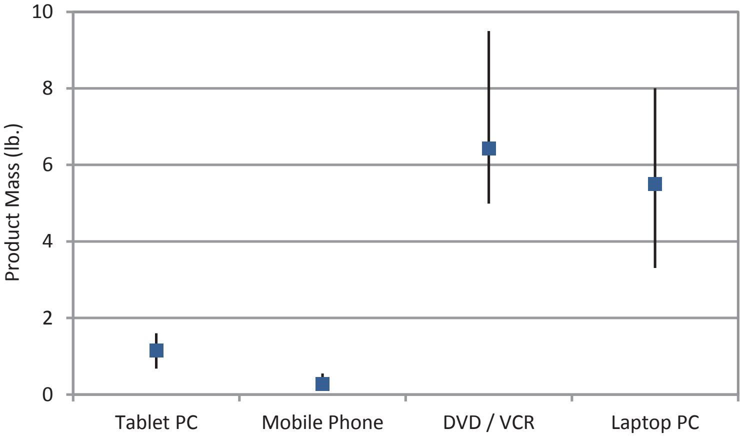


Figure 3.11: Average product mass by category for products that weigh less than 10 lbs.

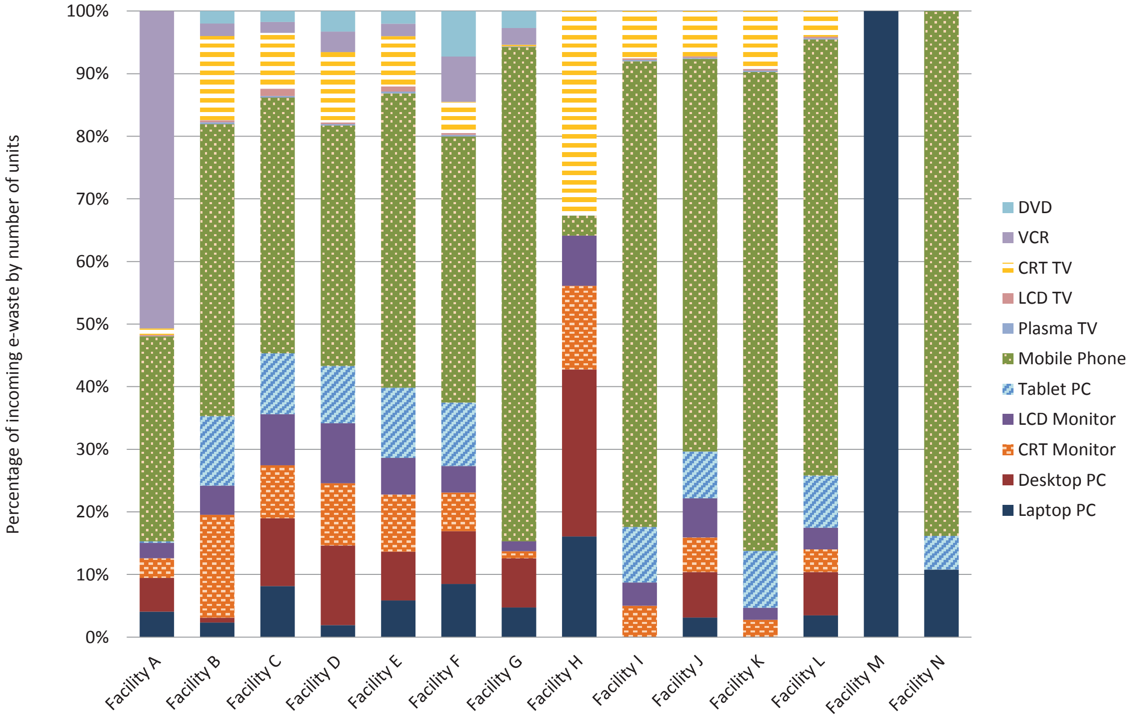


Figure 3.12: Percentage of incoming e-waste by number of units for each product category at each facility for the year 2011

of the incoming mix of products at each facility. Based on number of units mobile phones make up the largest portion (often over 35%) of incoming products for almost all facilities. This is an interesting insight as mobile phones have a significant amount of valuable material per product mass compared to other product categories because they are primarily composed of printed circuit boards, which contain the most valuable materials within the product. Mobile phones also have short lifespans compared to the other products. Recently the lifespan of a mobile phone within the U.S. was estimated to be 18-22 months, the shortest compared to other countries [120]. Consumers are also more likely to donate or recycle mobile phones compared to other electronic equipment because they are easy to drop off at collection points and are often not as expensive an investment as other product categories.

3.4.4 Mapping Product End-of-Life Pathways by Product Category

In order to improve the EoL management system it is important to understand the pathways that these products follow within the system as discussed earlier in this chapter. This section uses the data collected from the survey to map the product flows through each EoL pathway by product category based on the material flow analysis model developed in Section 3.3. The analysis assessed the percentage of products, by product category, that are reused, refurbished, or recycled within each material recovery facility. The goal of this assessment was to determine if a representative set of EoL pathways could be identified based on the most common pathways followed by each product category.

Figure 3.13 shows the percentage of incoming products that followed each end-of-life pathway (reuse, refurbish, and recycle) in each material recovery facility. The results of the material flow analysis show that most products that enter the formal collection and processing system are not in the condition to be directly reused without repair. There were only four facilities that reported products that were directly sent to reuse. The majority of the product that are collected are sent to recycling either at the facility or downstream to another facility that focuses on recycling. This was true even for facilities that focus more on the repair and refurbishment of products. This is most likely due to the condition of the products that are collected because they are not in a working condition to make it economically viable to refurbish or repair.

Next, the average percentage of products that follow each end-of-life pathway by product category was determined based on aggregate flow data from the participating facilities (see Figure 3.14).

This shows that of the product categories that were most likely to go directly to reuse were laptop computers and CRT monitors. These results were different than what was expected. Due to the age of CRT monitors and reduced market demand, it was surprising that they were reused at all. Perhaps there is still a demand for this type of equipment in secondary markets. On average, the majority of products within each product category were recycled. While a large percentage of products was expected to be sent to recycling, it is

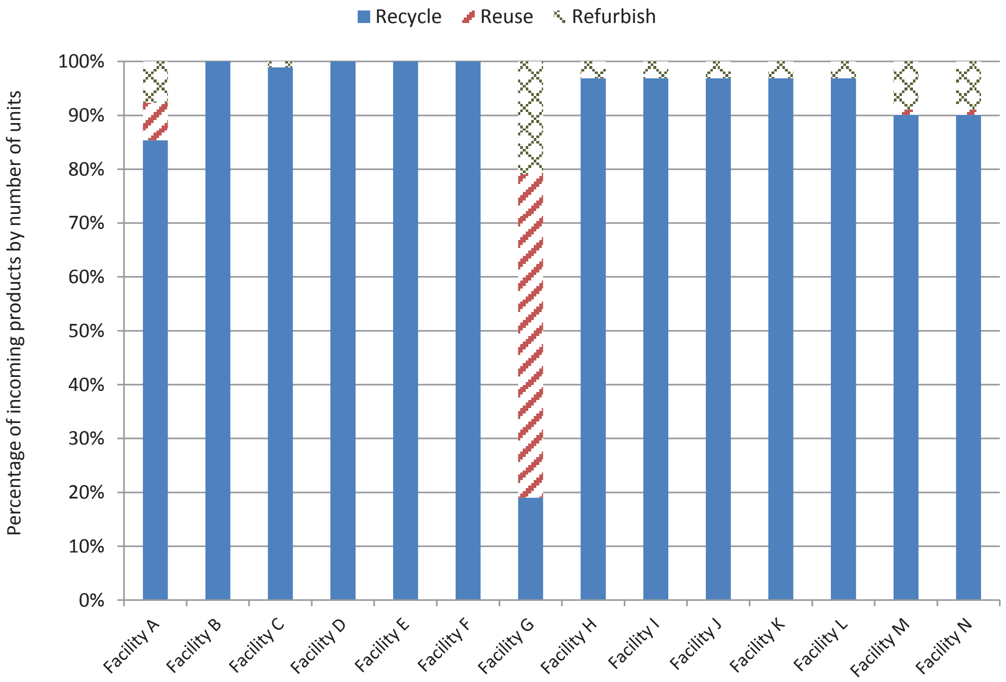


Figure 3.13: The percentage of incoming products that followed each end-of-life pathway in each material recovery facility

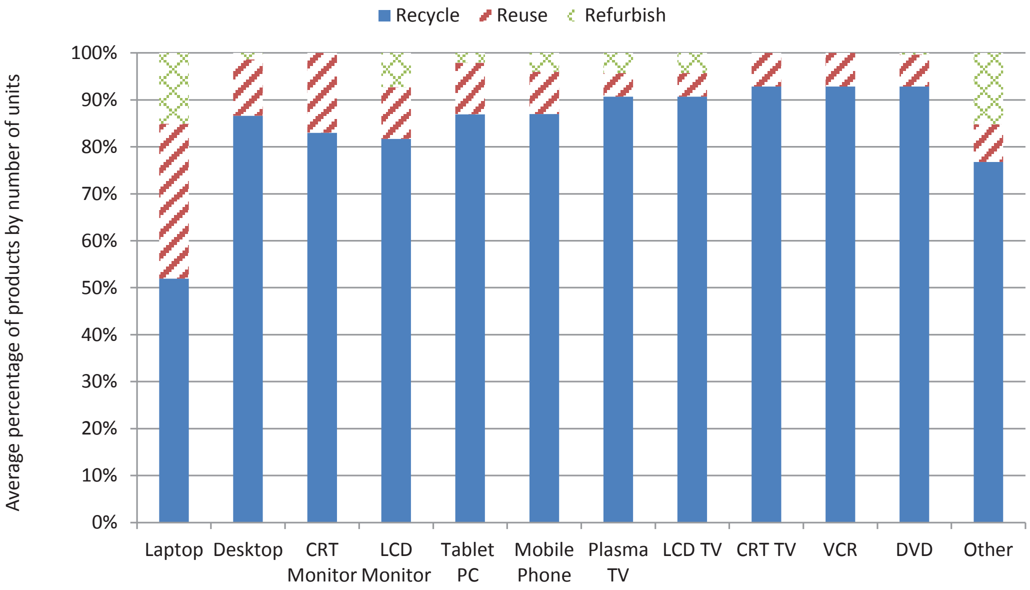


Figure 3.14: The average percentage of products by product category that followed each end-of-life pathway

interesting that more products did not follow the reuse and refurbish pathways, even when the facilities focused on the refurbishment and repair of equipment.

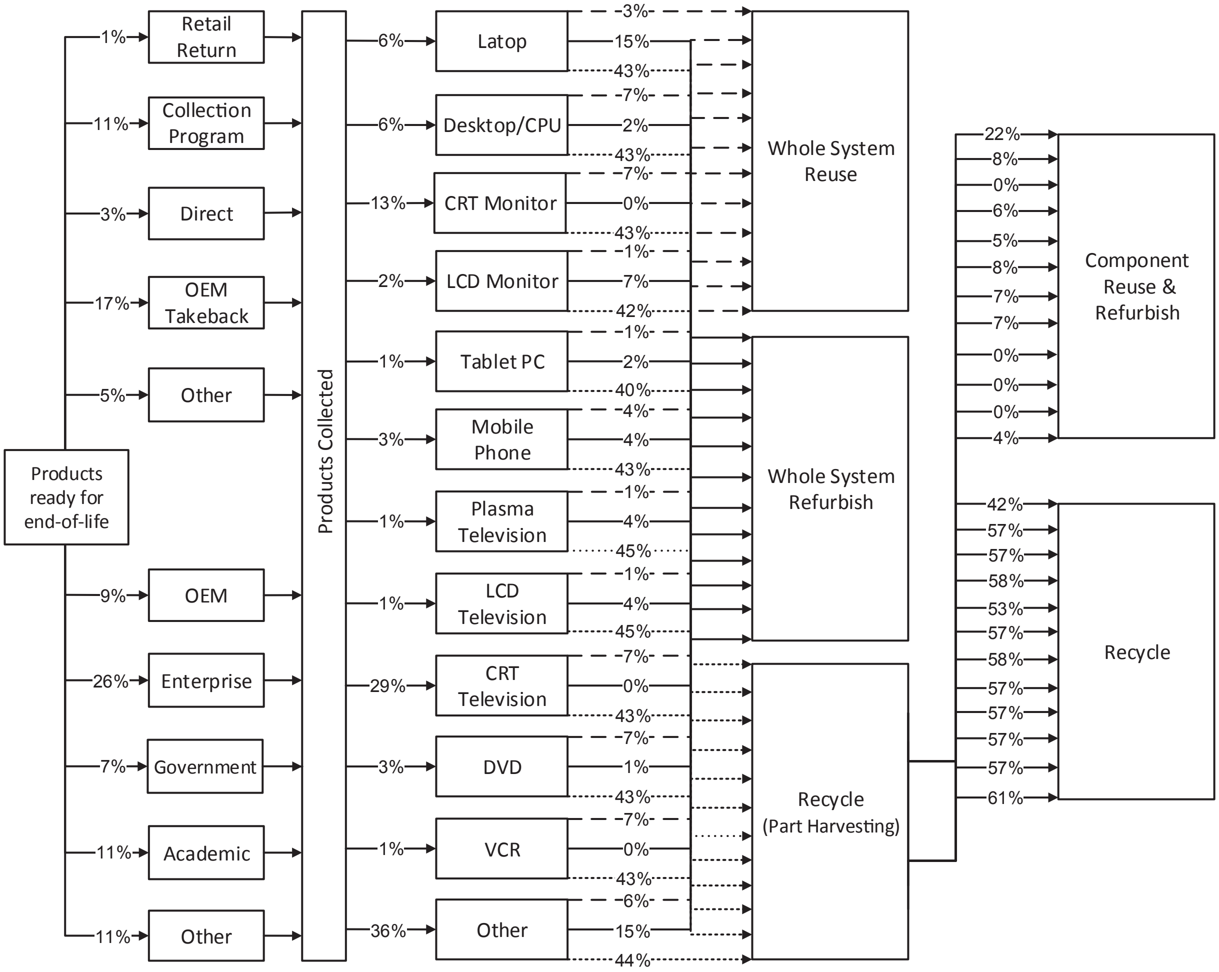


Figure 3.15: The most common end-of-life pathways that each product category follow within a material recovery facility

Finally a representative set of common pathways for each product category was mapped to the material flow analysis model based on aggregate facility data. The results of this are presented in Figure 3.15. Since the data used to map the flows was averaged across the facilities the flows do not add up to 100%. From this assessment you can see the percentage of each product category that folows the detailed end-of-life pathways, whole system reuse, whole system refurbish, component reuse, component refurbish, and recycling. For the flows that are leaving each product category the flow legend is as follows. The top dashed line represents the percentage of units from that product category that flows to whole system reuse. The second solid line represents the percentage of units sent to whole system refurbish. The last, smaller dashed line, represents the percentage of units sent to recycling.

There has been much research that has focused on designing products to be reused; however within the formal collection routes, are products actually being reused or refurbished? The results of this assessment show that once products enter the formal collection stream, most of the products go directly to recycling. It is important to note that reuse of products often occurs in the informal sector as described earlier in this chapter. Future work should focus on the decisions made within these facilities to understand why more products are not being reused and refurbished.

3.4.5 Facility Level Energy Assessment

Primary processing of e-waste is often not accounted for in the product life cycle assessment as mentioned in Chapter 1 due to the low impact compared to the manufacturing phase of the product life cycle. However, as the amount of e-waste created increases exponentially, the importance of understanding the resource use associated with processing e-waste will be even more important. Energy is consumed for different purposes within each facility. Energy is used by the heating, ventilation and air conditioning (HVAC) systems, lighting systems, office equipment, and processing equipment. Size reduction and separation equipment are energy and maintenance intensive operations [8]. Ideally process level energy data would be obtained from these facilities; however there are current limitations due to data availability and lack of sub metering data within these facilities.

An initial facility level resource assessment was conducted for each facility using primary data collected through the survey process described in Section 3.3. While the assessment framework provided information for major resources used at each facility, the focus of this assessment was electricity, as that is the primary resource used during the primary processing of e-waste.

The energy and resources consumed at each material recovery facility varies based on facility size and location, types of processes performed, process efficiency, and the total amount of e-waste processed. The electrical energy intensity was determined based on facility size and is presented in Figure 3.16. The energy intensity for each facility ranges from 0.5 to 82.6 kWh per m^2 of floor space.

There are evident trends within the electricity data as depicted in Figure 3.16. Facility A through G are the largest consumers of electricity, while facility H through N used significantly less. Facility D had the highest electrical energy intensity of 86.2 kWh per m^2 with respect to floor space. This difference could be attributed to the HVAC system energy requirement due to facility location or the energy required by equipment used to process e-waste. The HVAC system in a facility can consume a large amount of energy especially based on facility location and regional temperatures. Facilities with similar processing characteristics that are located in areas with extreme seasonal temperatures would use significantly more energy for their HVAC system. Recent studies of traditional manufacturing facilities have shown that in addition to external temperature, processing activity in the facility can

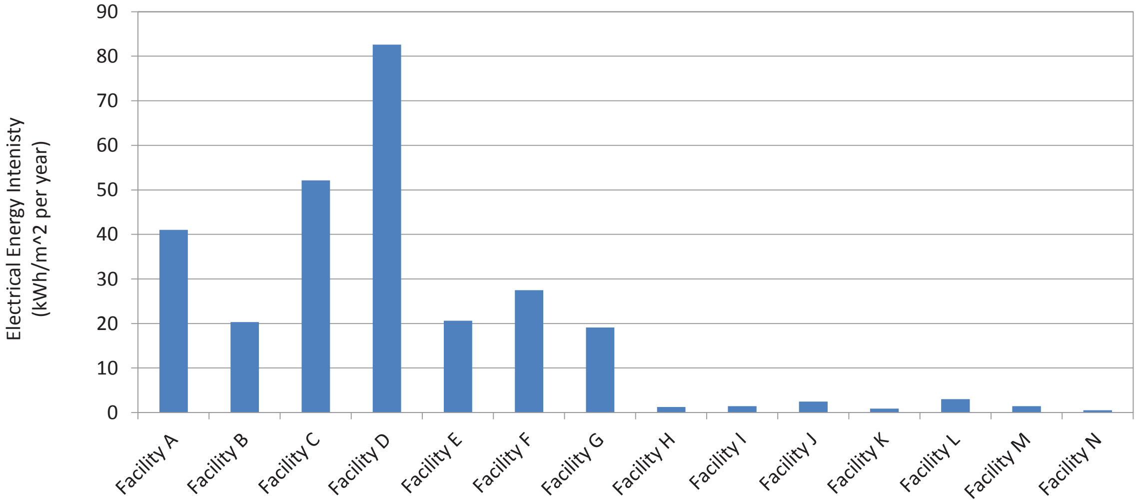


Figure 3.16: Electrical energy consumption (kWh/m^2) per year for each facility for the year 2011

impact HVAC load requirements [121]. Within the U.S. temperatures regional temperatures can range from below zero to over 100°F, as depicted in Figure 3.17 and 3.18.

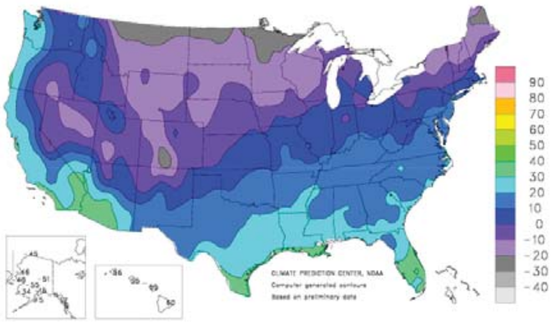


Figure 3.17: U.S. Regional Climate Map - Extreme minimum temperature (°F) [122]

The electricity use and the amount of e-waste processed at each facility were compared. The results of this comparison are presented in Figure 3.19. The electrical energy intensity was also determined based on electricity used per mass of e-waste processed, which ranged from 3.6 to 88 Watt hours per pound. This indicator shows that the electricity used to process e-waste is highly variable between facilities.

At first inspection, there is not a clear relationship between the amount of e-waste processed and electricity used at each facility. To better understand the relationship between the amount of e-waste processed and electricity used at each facility, we must consider the operating model and main processes performed at each facility. It was hypothesized that the

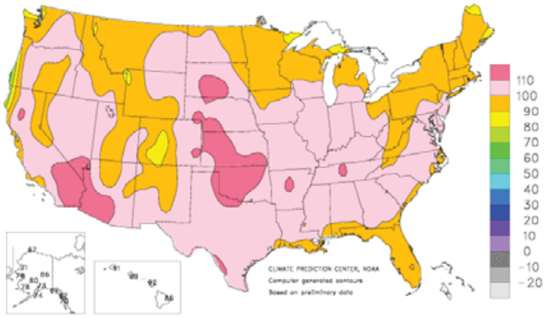


Figure 3.18: U.S. Regional Climate Map - Extreme maximum temperature (°F) [122]

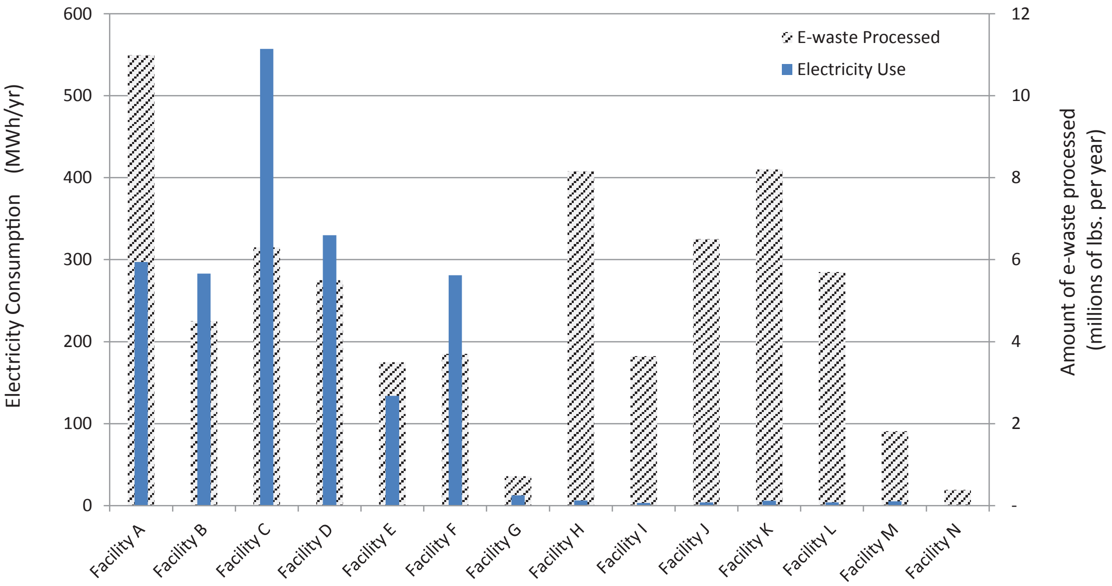


Figure 3.19: Comparison of electricity consumption (MWh/yr) and mass (millions of lbs.) of e-waste processed per year for each facility for the year 2011

amount of energy used at a facility that primarily focuses on manual disassembly would be lower than a facility that incorporated automated disassembly, due to the energy intensive equipment that is often used in the later. In order to address this hypothesis the process flows of each facility were examined to determine the effect of operating model on facility level energy distribution. Facilities H through N focused on manual processing and disassembly methods, which requires less electricity than those facilities that use mechanical equipment to process materials. Nearly every facility is unique in its process flows but may utilize similar technologies and systems. Future work should examine the interdependencies and decision points that occur within these facilities.

3.5 Summary and Need for Future Work

Understanding the pathways that the products follow in the EoL system is necessary in order to sustainably manage products in this phase of the life cycle. The information gathered can be used to inform product manufacturers and designers in order for them to better understand the EoL fate of the products they create.

The analysis in this chapter provides new results for material flows of consumer electronic products in the formal EoL management sector in the U.S. The data in this study was gathered from a limited number of facilities; however the assessment framework that was developed can be used for a broader assessment of this industry which is necessary in order to develop a more robust characterization of product flows. The framework developed extends beyond previous frameworks that have evaluated the performance of material recovery facilities and includes tracking products through the end-of-life pathways by product category. Also, this research provided primary data from facilities to map product flows, while previous work has relied on estimates of products sales or one off facility studies.

This study was based on current data of several facilities within the U.S. and provided useful insights into the recycling industry. However, the electronics and recycling industries are both ever-changing and there is a need for consistent data reporting to facilitate continuous feedback and benchmarking in order to improve overall system efficiency. Technology and product types are evolving and continuous information gathering will be necessary. Collaboration between key stakeholders will be necessary in order to develop sustainable management system of electronics when they reach their end-of-life within the U.S.

Current indicators used within the industry are not good measures of true performance. Common metrics in practice include the amount of material sent to landfills and mass of products collected. As shown by the analysis in Section 3.4, by evaluating the incoming mix of products collected using mass (lbs.) misrepresents the actual percentage of products collected. Mass based collection metrics also make it difficult to map the product flows to end-of-life pathways within a facility.

In order to move towards the ideal closed-loop system better sustainable indicators will need be not only developed but implemented across the industry. Implementation of mass balance metrics that consider the incoming flow of product compositions and the output streams of these facilities could be the first step. Mass balance metrics can be used in this industry sector to gain a more representative data of incoming and outgoing material streams within these facilities. These metrics could provide measures of system performance that allow quantitative comparisons and benchmarking within the industry. The implementation of standardized metrics within this industry would provide data to assess system performance based on operating models to inform the planning of new facilities and opportunities for existing ones.

The research was conducted using best available data based on current EoL management practices and product types. As mentioned previously in Chapter 1, the technology landscape is ever changing as technology develops and consumer demands evolve and there is a need for consistent data reporting and benchmarking within the industry to better facilitate improvements of EoL product management.

As mentioned in previous chapters a large portion of these products are stored or disposed of in landfills. Future work should identify methods to encourage product collection and engage users in this process. Improving collection mechanisms would in turn improve the quantity of products formally processed, ultimately increasing product reuse and material recovery.

Lack of data regarding the EoL management of electronic products makes it difficult to identify potential improvements within this industry. In order to facilitate this, a systematic process for data collection and information exchange between stakeholders throughout the supply chain is must be developed. There are challenges of implementing this type of information feedback loop. As with most industries there is concern with sharing proprietary information and managing data security. Collecting such a large amount of accurate data to represent this industry was one of the most challenging aspects of this work. With the incorporation of a systematic process to collect consistent, industry accepted key performance indicator data would allow for a more in depth analysis to understand the variability and interdependences within these systems.

Despite these challenges it is important to understand how these products flow through the system and what materials are recovered. Developing a better understanding of this system will allow for improvements in product design, material recovery, and information exchange throughout the supply chain. While these products are ultimately treated as materials during the EoL phase they need to be characterized as products in order to provide valuable information back to designers and product manufacturer. In order to do this, a mass flow analysis was conducted for each material recovery facility.

Future work should extend the research developed here to gather more robust data on the outflows of the material processing facilities and consider product composition to evaluate the value of materials reclaimed and identify areas for opportunity. Estimations could be made regarding the material content of the incoming flow of products based on average material content of each product. Understanding the evolving product composition (e.g., identifying the quantity of valuable materials or location of potentially hazardous materials) is critical to support decision making in this life cycle phase and the product design stage.

E-waste enters these facilities as whole products, but as the waste moves through the facility the products are transformed into component and material fractions that are treated downstream, this makes it challenging to track product flows through the end-of-life pathways.

Chapter 4

Product Recyclability Model for Consumer Electronic Products

This chapter reviews previous literature and research that has addressed the importance of evaluating product recyclability of consumer electronics. From the literature, several criteria have been identified that should be considered to determine the *true* recyclabilty of a product. Based on these findings, a product recyclability model was developed for consumer electronic products.

4.1 Product Recyclability

The attention to the rise in e-waste, along with regulations have put significant pressure on consumer electronic original equipment manufacturers (OEMs) to manage their products in an environmentally responsible way during the end-of-life (EoL) phase of the product life cycle. One aspect of this is that OEMs are motivated to improve their product designs to become more suitable for recycling and material recovery processes in an effort to reduce their overall environmental impact. Ideally, a product is designed to be recycled, reused, or remanufactured during the EoL phase, in order to reduce the demand for non-renewable resources and to keep products out of the waste stream. If a product cannot be reused or remanufactured, recycling is the next best option in order to reclaim any valuable materials from the product. This is particularly important regarding electronic products due their high value material composition. Allwood notes that recycling materials from mixed-material products discarded in mixed waste streams is the most challenging, but potentially the largest and most valuable [14]. However, even with this increased awareness many products are still designed with characteristics and materials that make them difficult to disassembly and recycle [39].

Evaluating the recyclability of products is the most common method used by stakeholders in producer responsibility to determine the environmental performance of products in the EoL phase [104]. Recyclability indicators are important and useful tools in order to assess performance; however, consistent methods need to be used in order to create meaningful comparisons. There is no current standard for measuring product recyclability. Most methods that are used by industry are internal methods and often proprietary. Comparisons between product families, categories, and OEMs are a valuable benchmark, but without consistent reporting techniques these comparisons are not meaningful.

The most common method to calculate recyclability is a mass-based approach; although not the only criteria to ensure efficient design, it is an important and commonly used metric. With the many factors that influence how recyclable a product is at the EoL phase, it can be difficult to calculate this measure beyond the theoretical value of recyclability. Due to this, there is not one defined method for calculating the recyclability of products within industry. This chapter presents a new approach for calculating the recyclability of consumer electronic products and discusses insights and methods for developing a more robust indicator.

Alignment and input from key stakeholders in the industry as well as current industry standards and efforts was an integral part of this work. This work was done in collaboration with The Sustainability Consortium and its member organizations. This chapter discusses the methodology and model that was developed to calculate the recyclability of consumer electronic products. The model aims to provide guidance and consistency in metrics used to determine recyclability of a product. It provides information for OEMs and EoL management facilities to exchange, which is the first step in improving the EoL management process and recovery of materials.

Many definitions have been proposed for recycling, recyclability, and recycling rates. As discussed in detail in Chapter 2 recycling has two distinct stages. The first stage of recycling (primary processing) is the recovery of scrap material and parts from EoL products and the second stage (secondary processing) is the technical extraction and processing of materials from the scrap materials and parts. Recycling is defined by the EU as "the reprocessing in a production process of waste materials for their original purpose or for other purposes, but excluding energy recovery" [5]. The federal trade commission, FTC considers a product recyclable if "it can be collected, separated or otherwise recovered from the solid waste stream for reuse, or in the manufacture or assembly of another package or product, through an established recycling program" [123]. For the purposes of this dissertation several terms need to be defined in order to provide consistency in language and definitions throughout this chapter.

Recycling - the process of extracting materials from EoL products in order to re-enter the raw material phase to be made into a new product, using current process technology that is widely available.

Recyclability - the ability of EoL products to be recycled, those materials from a product that are expected to enter the recycling stream.

Recycling Efficiency - the of mass output of target material from a recycling process as a percentage of the total mass input.

Recyclability Rate - the recyclable mass of a product as a percentage of total product mass.

4.2 Background and Literature Review

The most common environmental performance indicator of recycling activities used is the mass-based fraction of materials that can be recycled [124]. For example, the automotive sector determines vehicle recyclability based on the percentage of materials by mass that is recyclable or reusable. Mathieux defines the total recovery indicator (TRI) as the product mass share (%) that can be extracted for re-use, recycling, energy recovery and disposal [125]. This conventional mass-based approach to recyclability where each the mass of each material recycled contributes equally to the recyclability score, irrespective of its nature, is weak in nature. This method does not consider actual recycling efficiencies and the factors that affect them. It is more closely linked with the "theoretical or ideal case" which would be defined as the full material recovery, where every material is recovered in its initial amount and grade quality. With the many factors that influence how recyclable an electronic product is at the EoL phase, it can be difficult to calculate this measure beyond the theoretical value of recyclability. Due to this there is not one defined method for calculating the recyclability of products within industry; however several methods have been proposed in literature.

Several studies suggest value-based metrics, stating that the economic value of a secondary material could be a signal of its recyclability and a better measure than a purely mass based assessment [104, 126, 127]. Huisman suggests that calculations based on mass-based recyclability could be misleading, especially when materials are present in low amounts, but with high environmental and economic values such as precious metals [104].Huisman along with Stevels developed the QWERTY (Quotes for environmentally WEighted RecyclabiliTY and Eco-Efficiency) method to improve environmental performance of EoL products [104]. This method aims to minimize costs against maximal environmental recovery in end-of-life treatment. QWERTY attributes environmentally weighted recycling scores to the recycling of products, using life-cycle assessment (LCA) data.

Villalba proposed a recyclability index that is a measurement of the ability of a material to regain its valued properties through the recycling process [128]. While the index depends on the intrinsic and extrinsic properties of the material, it was assumed that the value the market places on the recycled material is a reflection of how well the material recovers its properties after it is recycled. With this assumption, the recyclability index could be calculated based on how much the material devalues or degrades during the recycling process. For example, a material that has a recyclability index of 1 means that there is no difference between the recycled and the virgin raw material. The recycled material is able to regain all the properties the material had in its virgin form, and this is reflected by similar market value of both materials [128]. Atlee and Kirchain expanded on the value-based metrics and developed a value retention index [124]. The method provided a recyclability factor based on the market value of the primary and secondary materials recovered from the product. Olivetti notes that previous work comparing LCA results and value-based metrics for several materials has indicated that value can be a proxy for environmental impact [126].

Several studies have addressed the performance of e-waste recovery processes. One study showed that recovery efficiency of metals and plastics from ICT equipment can determine whether a recycling activity leads to a net energy savings or burden, when compared to the energy expended during collection [129]. Studies have shown that a plastic recycling is typically one of the lowest revenue activities for disassemblers. The highest revenues were seen to come from reselling computers and components, and from recycling printed circuit boards to recover the precious metal content [87]. Another study analyzed the economic and environmental implications of a recycling system for notebook computers [83]. The study evaluated several different recycling scenarios from 0-100% recovery rate, and found that the impact to human health, ecosystem quality, and resource consumption increased with increased recovery rates. However; this study did not take into account the benefit or positive impacts caused by reduced need for virgin materials.

The *cradle to cradle* certification has identified that it is more desirable to have a product that is truly recyclable rather than one that contains a high recycled content but cannot then be recycled after use; therefore, recyclability is weighted twice as much as recycled content within their material reutilization score [74]. The material reutilization score is based on the inherent recyclability or biodegradability of the product, combined with the amount of recycled material and/or rapidly renewable content used in the product. This method uses a weighted average of the recycled/renewable content and recyclable/compostable content.

Several tools have been developed to evaluate different aspects of the end-of-life phase of products. Boks developed a Product Material Recycling Costs Model (PMRCM) in order to estimate EoL treatment costs to evaluate potential EoL scenarios [19]. Rose created the End-of-Life Design Advisor (ELDA) to determine the optimal EoL strategy for an electronic product based on environmental impacts [55]. Hultgren developed a tool that consists of a set of guidelines and strategies to be used as design strategies for recyclability [39]. The focus of this work was limited to internal metrics used by the Philips Corporation.

The literature discussed above has provided useful insights into the development of metrics and assessment of EoL impacts of electronic products. However, there are several barriers that prevent them from being implemented, for example, requiring extensive LCA data or an exhaustive list of design guidelines. While environmental assessment methods are useful, currently, they are not practically implemented by EoL operators due to limited data availability and the time commitment required, as discussed in Chapter 2. As LCA data becomes more accessible and product material compositional databases become standardized, these schemes will become more accessible. Another concern with the previous tools and methods developed is the large amount of detailed product composition data required to use the tool. Often product designers and OEMs need a simple tool that does not require detailed material data to be collected.

4.2.1 Industry Standards that Address Product Recyclability

There are several industry standards that aim to incorporate product recyclability criteria, but have yet to develop a standard methodology to do so. Several of the most notable efforts are Electronic Product Environmental Assessment Tool (EPEAT) and the International Electrotechnical Commission (IEC) [130, 131]. EPEAT is a global registry for greener electronic products and was developed through multi-stakeholder collaboration, including business, advocacy, government, and academia. It establishes a clear set of performance criteria for consumer electronics and is based on the 1680 family of Environmental Assessment Standards published by the Institute of Electrical and Electronics Engineers (IEEE). The recyclability criterion that is currently in the standard is limited to reducing the number of different plastics used in the product. The International Organization for Standardization (ISO) developed the ISO 22628 standard for road vehicles recyclability and recoverability calculation method describes the methodology for calculating recyclability and recoverability of a product [132]. It was originally intended for the automotive industry, but is often used in other sectors. The IEC recently released a new technical report IEC/TR 62635 that provides guidelines similar to ISO 22628 for recyclability rate calculation of electrical and electronic equipment. However, both of these standards are lacking in details and consistency to be able to be used for industry wide product category benchmarking. The performance of the recycling process used and recycling efficiency of materials are not considered in the calculations and are left to the discretion of the user. The lack of consistency that these standards offer, discourages them to be used to make product comparisons.

4.3 Development of Product Recyclability Model

This section details the methods used to develop the product recyclability model that included mass and value based indicators to quantify the recyclability of a consumer electronic product. Considerations to include design-based criteria in the model are discussed in Section 4.9.

4.3.1 Approach Used to Develop the Model

Based on the findings from literature, it has been shown that only using a mass-based indicator to determine product recyclability can be misleading because it does not consider the materials that are present in low quantities. As mentioned previously, value-based metrics have been proposed in previous literature suggesting that the economic value of a secondary material could be a signal of its recyclability [126, 127]. Studies have also shown that the recycling efficiency is directly linked to product design and the material combinations and connections of the product [133].

With this summary of findings, we can conclude that an ideal recyclability model would combine mass, value, and design based criteria in order to obtain a more realistic and accurate view of how efficiently a product and its materials can be recycled. Figure 4.1 presents

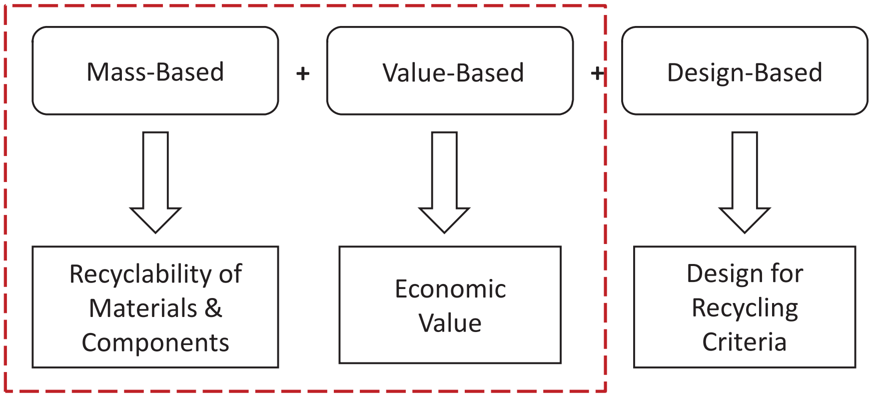


Figure 4.1: High-level overview of approach used to develop the product recyclability model

the approach that was used to develop a product recyclability model, which includes both mass and value based indicators (as outlined by the dashed line) to represent product recyclability. The mass-based indicator was developed based on the recycling efficiency of materials, recyclable material composition of common components, and the mass of materials and components that make up the product. This mass-based calculation is consistent with other product level reporting criteria (WEEE, EPEAT, IEC Technical Report) [5, 130, 131]. In order to determine the economic value of materials recovered from a product when it is recycled, the total scrap value of recyclable mass of the product is calculated.

This model can be used to calculate the recyclability of consumer electronic products at the EoL processing stage of the life cycle.

4.3.2 Model Structure

The product recyclability model is comprised of smaller component models and a database that includes the recycling efficiency and scrap value of materials used in electronic products.

As detailed in Figure 4.2, calculating the mass-based recyclability of the product has two parts: single materials recyclability (e.g., housing materials) and component recyclability (e.g., hard disc drive).

With the complexity of components and supplier based purchasing it is difficult for OEMs to provide detailed material information at the product level about the mass and type of materials used in components. Printed circuits boards are a classic example of this: the variety and complexity of these components require additional assessment in order to determine the composition and recyclable potential. In order to reduce the amount of data needed to use the recyclability model, component models were developed for the standard components found in consumer electronic products.

The component models are used to determine the recyclable mass of each component included in the product based on the material composition of each component and the recy-

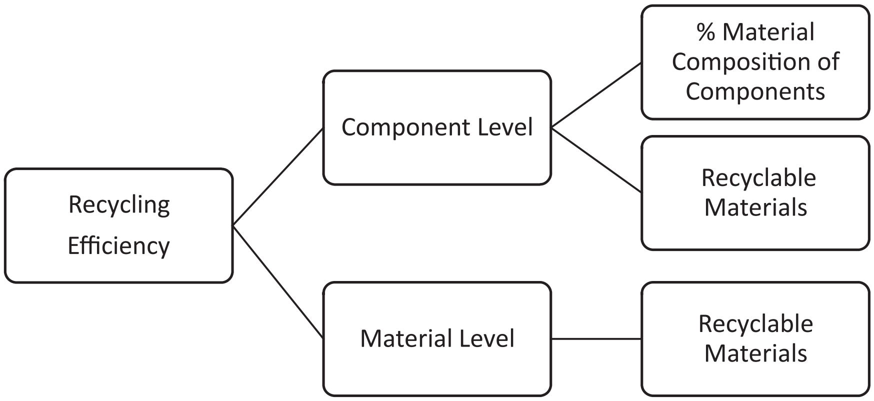


Figure 4.2: Recycling efficiency at the component and material level included in the model

cling efficiency of each material that makes up the composition. The models were developed for common components that are used in consumer electronic products. The following components models are included in the product recyclability model: hard disc drives (HDDs), liquid crystal displays (LCDs), optical drives (ODs), printed circuit boards (PCBs), batteries, and power supply units. The development of the component models is detailed in Section 4.5.

The system architecture of the model is presented in Figure 4.3 and shows the user inputs, model and database structure, and model outputs.

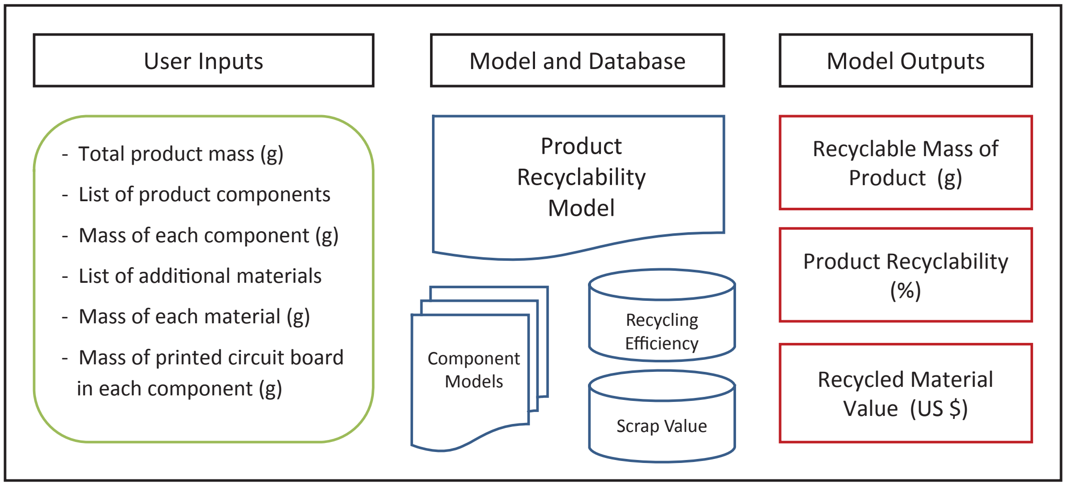


Figure 4.3: Diagram of system architecture of the product recyclability model and shows the user inputs, model structure, and model outputs

The model includes databases for recycling efficiency of each material, scrap value of secondary materials, and component composition models for common components as described earlier in this section. In order to use the model, the user collects the required product, component, and material data and inputs it into the user interface. The model results are then displayed and include the recyclable mass (g) of the product, the product recyclability (%), and the economic value (US $) of the materials that can be recovered from the product.

The following data is required by the user to input into the model:

a. Total product mass (g)
b. List of product components
c. Mass of components (g)
d. List of additional materials (*not included in component list*)
f. Mass of additional materials (g)
g. Mass of printed circuit boards (g) of applicable components (*if not available model will use component composition models to estimate mass*)

4.3.3 Model Assumptions

The following assumptions were used in the development of this model:

- Recycling efficiency of materials is based on current state-of-the-art recycling practices for size reduction and separation technology
- Component composition is representative of product categories
- Component material composition scales linearly with component mass
- Product material composition scales linearly with product mass
- Scrap value of materials is based on current market value

These assumptions were based on best available data for recycling efficiency and component composition, which will be discussed in detail later in this chapter. Mass-based scaling is commonly used for component composition within industry and literature. Scrap prices were determined from various sources using average price estimates.

4.3.4 Product Scope

The model was designed to be used for common consumer electronic products. The product categories included in the product scope of the model are listed below.

- Mobile devices (e.g., mobile phones, tablet computers)
- Laptop and desktop computers

- Monitors and integrated display units (Liquid crystal displays (LCDs))
- Televisions (LCD technologies)

The methods and data used in the model could be adapted to include additional product categories. For example, home appliances and medical devices would be appropriate product categories for model expansion due to the similarities in material composition, electronic components, and processing technology used to recycle these products.

4.4 Mass-based Recyclability Calculations

The foundation of the model is the mass-based approach as described in the previous section.

Equation 4.1 denotes the mass-based recyclability rate of a product.

$$RE_{cyc} = \frac{Recyclable\, mass\, of\, product}{Total\, product\, mass} \times 100\% \tag{4.1}$$

Commonly when using mass-based recyclability indicators, if a component or material is able to be recycled using a recycling process then that component is determined to be recyclable in its entirety. However, as mentioned previously, the recyclability rate of a product depends on numerous factors. One of the most important factors is the recycling efficiency of the materials present in the product. Recycling efficiency is the indicator used to estimate the quantity of material that can be recovered during a recycling process.

Recycling efficiency, R_{eff}, is defined as the mass of output materials,m_{output}, from a recycling process as a percentage of the total mass of input material,m_{input}, into the recycling process (see Equation 4.2).

$$RE_{eff} = \frac{m_{output}}{m_{input}} \times 100\% \tag{4.2}$$

The two main variables that affect recycling efficiency are the processing technology used during recycling and the design attributes of the product. Quantifying the material losses during preprocessing and the impact of material combinations and product design is necessary to evaluate the process efficiency and identify potential improvements. These concepts are discussed in detail later in this chapter.

The model incorporates the recycling efficiency of each material used in the product in order to determine the total recyclability of the product (see Equation 4.3).

$$RE_{cyc(material)} = \frac{\sum_{i=1}^{n}(m_{(i)} \times R_{eff(i)})}{M_{total}} \times 100\% \tag{4.3}$$

Where m_i denotes the mass of the ith material, $R_{eff(i)}$ is the recycling efficiency of the ith material, and M_{total} is the total mass of the product.

Similar to Equation 4.3 for materials, Equation 4.4 denotes the recyclability rate used to calculate the recyclable mass OF a component.

$$RE_{cyc(component)} = \frac{\sum_{j=1}^{n}(m_{(j)} \times R_{eff(j)})}{M_{total}} \times 100\% \tag{4.4}$$

Where m_j denotes the mass of the jth material in a component, $R_{eff(j)}$ is the recycling efficiency of the jth material, and M_{total} is the total mass of the product.

Combining Equations 4.3 and 4.4 we have the total recyclability of the product using Equation 4.5.

$$RE_{cyc(product)} = RE_{cyc(material)} + \sum_{i=1}^{n}(RE_{cyc(components)(i)}) \tag{4.5}$$

4.4.1 Recycling Efficiency of Materials

For the single recyclable materials the recycling efficiency for different materials was estimated based on academic literature and industry reports [8, 69, 134, 143]. Expert interviews were also conducted in order to confirm the validity of these numbers. An example of the recycling efficiencies of common materials is presented in Table 4.1.

A material that has a higher recycling rate is not necessarily processed more efficiently than another. Recycling rates of materials tend to reflect two important characteristics: the degree to which materials are used in large amounts in easily recoverable applications (e.g., lead in batteries) or where high value is present (e.g., gold in electronics) [8].

Economic value is the main motivation for recycling materials from these products. Materials and parts that are easily accessible and have high value are often the focus of these recovery efforts. Currently, materials that are used in small quantities (e.g., rare earth elements) or have low value (e.g., plastics) are not recycled. However, with increasing raw material costs and concerns of resource recovery we can assume that these materials will have improved recycling rates in the future. The recycling process efficiency will vary from metal to metal, depending on the material type or grade for which a process is optimized, and although it is typically high it will never reach 100% due to thermodynamic and other limitations [135].

Table 4.1: Recycling efficiencies for common materials in electronic equipment

Material	R_{eff}	Material	R_{eff}
Aluminum	98%	Magnesium	39%
Antimony	89%	Manganese	53%
Arsenic	1%	Mercury	62%
Beryllium	8.5%	Nickel	57%
Cadmium	12%	Palladium	65%
Chromium	93%	PC/ABS	35%
Cobalt	68%	PET	90%
Copper	82%	Platinum	76%
Germanium	50%	PP	68%
Gold	93%	PVC	97.5%
HDPE	90%	Silver	97%
Indium	1%	Tantalum	21%
Iron/Steel	95%	Tin	75%
LDPE	90%	Titanium	91%
Lead	95%	Zinc	52%
Lithium	1%		

4.5 Development of Component Models

The component models were developed considering two main characteristics. First, the material composition of each component was determined as a mass-based percentage. As discussed in the model assumptions, previous literature has shown that the material composition of components and products can be estimated using a linear relationship between material composition and mass of component or product [136]. Second, the materials that are commonly recycled from each component during the EoL management phase were identified based on literature and expert opinion. From this the mass based material composition of each component was determined. Only the materials that are currently recycled in industry are included in the models.

The following components were included in the model: hard disc drives (HDD), displays, optical drives (OD), printed circuit boards (PCB), batteries, and power supply units. This section presents the detailed component compositions that are used in the product recyclability model.

4.5.1 Hard Drives

There are two types of hard drive technology, solid state disc (SSD) and hard disc drive (HDD). SSD are not included in this model due to lack of reliable data regarding material composition and recycling potential.

HDD are composed of platters using either glass or aluminum as the substrate material. The aluminum-based platters are usually used in a 3.5 inch format; 2.5 inch hard disk drives are primarily equipped with two or three glass-based platters. A single glass-based platter of 2.5 inch format weighs around 4.8 grams [137]. The materials that are recycled from the hard drives are shown in Table 4.2.

Table 4.2: Mass based percentage material composition of a hard disc drive (only including the materials currently recycled in industry) [138, 139]

Material	Glass HDD	Al HDD
Steel	14%	14%
Aluminum (Al)	67%	78%
PCB	7%	7%

There are other important materials that are not currently recycled because they are difficult to separate from the other materials, which can be attributed to the compact design of the hard disc drive. The steel cover on the hard disk drive is typically secured to the aluminum frame using adhesive. This type of connection requires intensive manual disassembly and due to labor costs it is not often employed. With this the materials inside the hard drive are most likely not recovered. The PCB is the easiest to remove and can be separated from the drive without having to disassemble the cover and frame.

Since the hard drive is completely disassembled other valuable materials are not recovered, such as rare earth metal. Because the rare earth magnets are not removed from the hard drive during recycling, the magnets attach to the steel material fraction during processing and are lost in the recycling process.

Another challenge is that material recycling of rare earths from these magnets is not available on an industrial scale. However, if the magnets could be separated they could be stored temporarily until this technology could be implemented on an industrial scale.

Improving the ease of disassembly of these components and developing the industrial scale recycling technology to process rare earth magnets would improve the economic viability of recovering these materials. This becomes even more important to focus on for electronics recycling as a large percentage of rare earth metals are used in electronic equipment. According to Kara et al., over 30% of the neodymium used in 2008 was destined for hard disk magnets [140].

4.5.2 Displays

Display screens are used in many consumer electronic products including monitors, televisions, computers, and mobile devices. Display technology has evolved over the past several years and currently liquid crystal displays (LCD) have the largest share of the market. While Cathode Ray Tube (CRT) displays are no longer sold, they are still in use and being collected at EoL management facilities. While the author realizes this is an important e-waste issue, it is outside the scope of this work.

When LCD displays are recycled the following materials are recovered: plastics, steel, aluminum, and printed circuit boards. Table 4.3 presents the recyclable composition for desktop and integrated display technologies.

Table 4.3: Mass based percentage material composition of liquid crystal displays (only including the materials currently recycled in industry) [8, 137, 141]

Material	Desktop Display	Integrated Display
Aluminum (Al)	3%	24%
Glass	10%	18%
PC/ABS	30%	27%
PCB	4%	4%
Steel	33%	10%

The backlight lamps are processed as hazardous equipment. Often the glass, mercury, and other luminescent substances are disposed of as hazardous materials [137]. Because of this, these substances are excluded from the model.

Display technology is also composed of several rare earth elements used in the background illumination; however, similar to hard drives, the rare earths metals used in the luminescent materials are currently not recycled. Currently, suitable separation and refining processes are not available for recovering the indium from the display units and the rare earths from the background illumination. As mentioned previously rare earths are currently not recovered from electronic products. As recycling technology develops and additional materials, such as rare earth elements, are able to be recovered the model will need to be updated to include these materials.

4.5.3 Optical Drives

Table 4.4 presents the mass based percentage material composition of optical drives for the materials that are currently recycled in industry.The materials that are recycled from an optical drive are the housing components and the printed circuit board. Table 4.4 presents the mass based percentage material composition of optical drives for the materials that are currently recycled in industry.

4.5.4 Printed Circuit Boards

From literature it has been shown that printed circuit boards (PCBs) are composed of 30% metals and from this it is commonly assumed that 30% of a basic printed circuit by mass is recyclable. Typically the rest of the PCB is incinerated for energy recovery to fuel the

Table 4.4: Mass based percentage material composition of optical drives (only including the materials currently recycled in industry) [8,89,137]

Material	Optical Drive
Aluminum (Al)	39%
PC/ABS	15%
PCB	8%
Steel	35%

smelting process when recovering the valuable metals. From this it is assumed that 70% of the PCB is energy recovered. However, due to the varying composition of different PCBs, further analysis was used to model the different types of boards used in various products and components. The material content of PCBs varies by the type, application, and product category. Tables 4.5 and 4.6 present the recyclable material composition of printed circuit boards by application and product category respectively [7,8,69,89,137–139,142].

The valuable materials in a PCB are the metals and more specifically the precious metals and those are what are commonly recycled. Research has shown that gold, silver, and palladium can be recovered with a high level of efficiency in the refining process [69,70,137]. The metals that are most commonly recovered from printed circuit boards are gold (Au), silver (Ag), palladium (Pd), copper (Cu), and nickel (Ni).

Table 4.5: Mass based percentage material composition of printed circuit boards by application (only including the materials currently recycled in industry)

Material	Motherboard	Memory Card	OD	HDD	Low Grade
Ag	0.08%	0.17%	0.22%	0.26%	0.03%
Au	0.02%	0.08%	0.02%	0.04%	0.01%
Cu	0.16%	0.16%	0.16%	0.16%	0.16%
Ni	0.02%	0.02%	0.02%	0.02%	0.02%
Pa	0.03%	0.02%	0.01%	0.03%	—

There are other metals that are present on the PCB that should be noted; however they are not currently included in the model as they are not recovered in the recycling and refining process. One example of this is tantalum (Ta) that is used in high capacity capacitors. Some suggest the Ta capacitors within a laptop computer could contain as much as 2 grams of Ta.

Table 4.6: Mass based percentage material composition of printed circuit boards by product category (only including the materials currently recycled in industry)

Material	LCD Monitor	LCD TV	DVD Player	Mobile Phone
Ag	0.13%	0.03%	0.01%	0.10%
Au	0.05%	0.01%	0.00%	0.10%
Cu	0.16%	0.16%	0.16%	0.16%
Ni	0.02%	0.02%	0.02%	0.02%
Pa	0.01%	0.00%	0.00%	0.60%

4.5.5 Power Supply Components

Batteries

The most common battery type that is used in consumer electronics is lithium-ion. The size of the battery depends on the quantity of cells. For example, a laptop computer typically uses an 8 cell battery. Table 4.7 presents the mass based percentage material composition of lithium-ion batteries for the materials that are currently recycled in industry.When recycling lithium-ion batteries, cobalt is the main material recovered.

Table 4.7: Mass based percentage material composition of lithium-ion batteries (only including the materials currently recycled in industry) [143]

Material	Li-ion Battery
Aluminum (Al)	5%
Cobalt	18%
Lithium	3%
Nickel	10%
Steel	12%

Power Supply Unit and Power Cord

Copper is the only recovered material from the power cord. The quantity of copper within a cord is assumed to be a function of cord length. A power cord is typically composed of a 25% plastic casing and 75% copper wire [94]. The printed circuit board from the power supply unit is recycled and was modeled using the low grade PCB composition presented in Table 4.6.

4.5.6 Example Calculation

This section presents an example calculation used to calculate the recyclable mass of a HDD to demonstrate how the printed circuit board component models were integrated into the other component models. For example, a HDD is composed of materials and a printed circuit board and the recyclable mass of the materials and printed circuit board are determined independently. Also, as mentioned above, the material composition of printed circuit board depends on the type of circuit board used.

The equation for calculating the recyclable mass of a hard disc drive is shown in Equation 4.6.

$$RM_{HDD} = RM_{Materials} \; + \; RM_{PCB} \tag{4.6}$$

Where:

$RM_{HDD} = total\, recyclable\, mass\, of\, hard\, disc\, drive$
$RM_{Materials} = total\, recyclable\, mass\, of\, materials\, in\, hard\, disc\, drive$
$RM_{PCB} = total\, recyclable\, mass\, of\, printed\, circuit\, board\, in\, hard\, disc\, drive$

$$RM_{HDD} = \sum_{i=1}^{n}(m_{(i)} \;\times\; R_{eff(i)}) + \sum_{j=1}^{n}(m_{(j)} \;\times\; R_{eff(j)})_{PCB} \tag{4.7}$$

$$RM_{Materials} = (m \;\times\; R_{eff})_{steel} \; + \; (m \;\times\; R_{eff})_{Al} \tag{4.8}$$

$$RM_{PCB} = (m \times R_{eff})_{Ag} + (m \times R_{eff})_{Au} + (m \times R_{eff})_{Cu} + (m \times R_{eff})_{Ni} + (m \times R_{eff})_{Pa} \tag{4.9}$$

4.6 Value-based Reyclability Indicator

As mentioned previously, the value of a material is a good indicator of environmental impact and resource availability. Economic value also represents the quality and demand for the materials recycled from these products. Due to the limited life cycle assessment data, the economic value of the material provides a proxy for the environmental impact. The value-based calculation would not only provide economic insight into the recycling process but the potential environmental impact of those materials as well. This is the motivation for included a value-based recyclability indicator in the model.

The model contains a database of scrap material prices, as discussed earlier in this chapter, in order to obtain a current economic value of the materials recovered from the product. The value-based recyclability is calculated based on current scrap market value of the materials recovered through recycling. The value-based metric was calculated according to (Equation 4.10) where v_i is the market value of the secondary material recovered from the recycling process and RM_i is the recyclable mass of the ith material, for all materials in the product from *1 to n*.

$$V_{rec} = \sum_{i=1}^{n} v_i(RM_i) \tag{4.10}$$

The author realizes that the value for the scrap recovered fluctuates with market conditions and should be updated in the model accordingly. The tool also displays the scrap value in U.S. dollar amount for all the materials that could be recovered through recycling of the product and components.

Table 4.8: Scrap value prices for various materials [144–147]

Material	USD/lb.	Material	USD/lb.	Material	USD/oz t
Aluminum	$1.14	Nickel	$5.73	Gold	$ 447.68
Antimony	$7.74	Tantalum	$168.56	Iridium	$ 400
Cadmium	$1.46	Zinc	$0.98	Neodymium	$ 3.58
Cobalt	$17.31	ABS	$0.74	Palladium	$ 731
Copper	$4.06	HDPE	$0.62	Platinum	$ 994.52
Indium	$343.14	LDPE	$0.67	Rhodium	$ 890
Iron/Steel	$0.26	PBT	$0.18	Ruthenium	$ 57
Magnesium	$1.47	PC	$0.81	Silver	$ 16.04

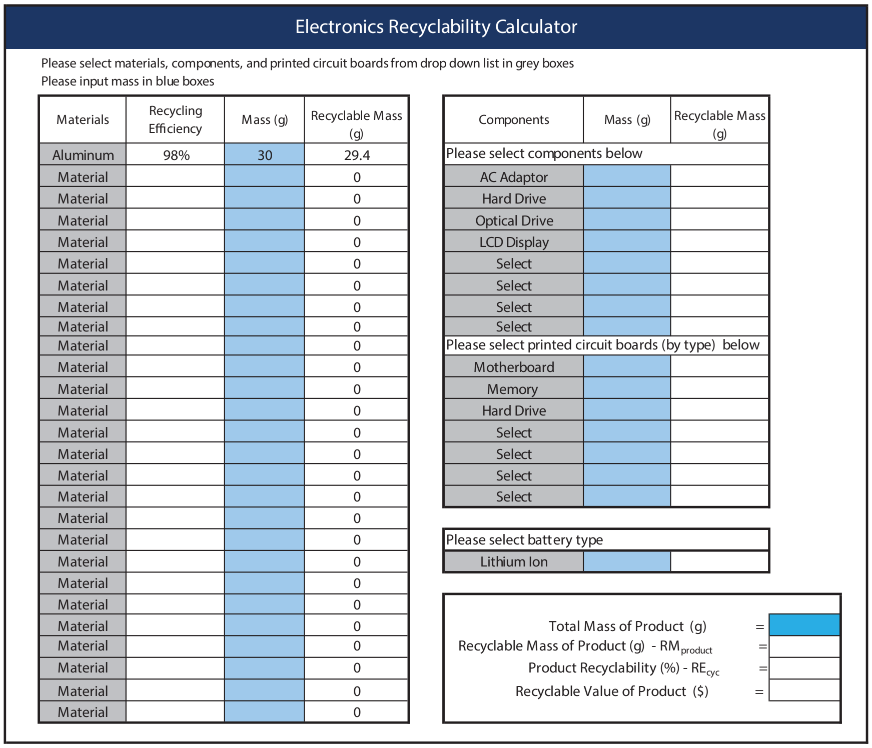
Table 4.8 presents the current scrap market value in U.S. dollars for a subset of the common materials recovered from electronic products.

4.7 User Interface

The model was constructed using Microsoft Excel as the platform. Once the data is collected by the user as described above they can input it into the model interface (see Figure 4.4).

The grey cells in Figure 4.4 use drop down menus, where the user can select the appropriate material, component, or printed circuit board. Then the user inputs the associated weight of each material, component, or printed circuit board in the corresponding blue cells. The user also inputs the total product mass in the corresponding blue cell. The recycling efficiency is then populated and the outputs are presented in the lower right hand corner of the interface and include the recyclable mass of the product (g), the product recyclabilty (%) and the recyclable value of the materials recovered from the product ($).

The user has several options when using the model and it can be flexible depending on how much and how detailed their product data is. For example, if the user does not have the mass of each printed circuit board within the product, the model can determine the mass based on the associated component compositions as described in Section 4.5. This was considered due to limited data and time availability of the potential user.



Electronics Recyclability Calculator

Please select materials, components, and printed circuit boards from drop down list in grey boxes
Please input mass in blue boxes

Materials	Recycling Efficiency	Mass (g)	Recyclable Mass (g)
Aluminum	98%	30	29.4
Material			0
Material			0
Material			0
Material			0
Material			0
Material			0
Material			0
Material			0
Material			0
Material			0
Material			0
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Material			0
Material			0
Material			0
Material			0
Material			0

Components	Mass (g)	Recyclable Mass (g)
Please select components below		
AC Adaptor		
Hard Drive		
Optical Drive		
LCD Display		
Select		
Select		
Select		
Select		
Please select printed circuit boards (by type) below		
Motherboard		
Memory		
Hard Drive		
Select		
Select		
Select		
Select		

Please select battery type		
Lithium Ion		

Total Mass of Product (g) =
Recyclable Mass of Product (g) - $RM_{product}$ =
Product Recyclability (%) - RE_{cyc} =
Recyclable Value of Product ($) =

Figure 4.4: Consumer electronic product recyclability model user interface

4.8 Verification of the Model

This section presents a laptop case study used to demonstrate the product recyclability model. The model was tested using a standard 15” laptop computer as an example product.

4.8.1 Laptop Case Study

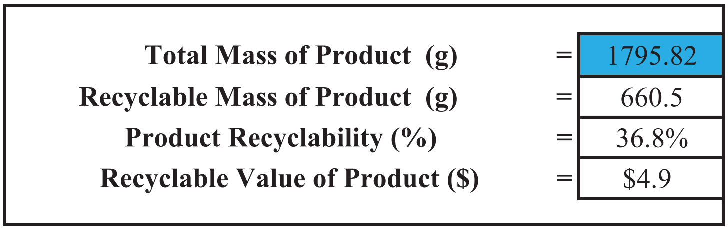
The data used for the laptop example was collected from a tear-down analysis performed by a researcher from The Sustainability Consortium. The laptop had a 15” integrated LCD display, six cell lithium-ion battery, aluminum HDD, and optical drive. The total mass of the laptop was 1795.82 grams. A summary of the bill of materials of the laptop is presented in Table 4.9.

The mass of each component, printed circuit board, and materials was entered into the model. The model outputs included the recyclable mass, recyclability, and scrap value of the product. For the laptop example the results from the model are presented in Figure 4.5.

These model results show that the 36.8 % of the laptop mass is recovered during recycling. The total value of the materials recovered is $4.90 per laptop. Considering the total product mass we can estimate the recyclable value of the laptop is $1.23 per pound.

Table 4.9: Summary of bill of materials that was used for laptop case study

Laptop Computer	
Printed Circuit Boards	**Mass (g)**
Motherboard	161.3
RAM Memory	12.4
Integrated Display	18.3
DVD Drive	12.3
HDD	5.2
Low grade	44.6
Components	**Mass (g)**
15” LCD Display	473.1
6 cell Li-ion battery	323.8
DVD Drive	145.1
Hard Disc Drive (Al)	62.6
AC Adaptor	127
Power cord	75
Materials	**Mass (g)**
PC/ABS Keyboard	111.4
Back Cover	173.1
Keyboard Support	138.54
Fan	12.08



Total Mass of Product (g) = 1795.82
Recyclable Mass of Product (g) = 660.5
Product Recyclability (%) = 36.8%
Recyclable Value of Product ($) = $4.9

Figure 4.5: Model results from laptop case study

These results were compared to a study that was conducted that estimated the recycling value of IT products under different market conditions [43]. The results from that study estimated that the recyclable value of a laptop could range from \$2.90 to \$8.00 depending on market conditions that affect scrap value prices. This comparison showed that the results from the model developed in this chapter are comparable to other estimations.

Future work should investigate multiple product case studies in order to compare model results across a broader variety of products and product categories. Currently the results are being presented to key stakeholders within the industry in order to receive feedback on the model to gauge applicability within the industry and validate results. Collaboration is a key characteristic of these efforts in order to develop valid, usable tools that can be implemented.

4.8.2 Sensitivity Analysis

A sensitivity analysis was conducted using the laptop case study data and results described previously to evaluate the impact of the model parameters on product recyclability. A Monte Carlo simulation was conducted using one thousand trials to evaluate the sensitivity of the most important parameters of the model. The parameters that were evaluated were the recycling efficiency of each material and the mass of the materials and components.

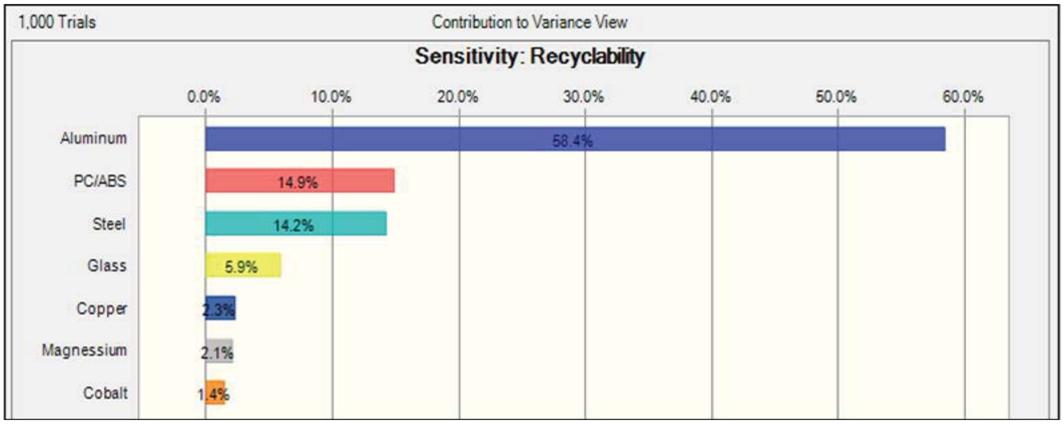


Figure 4.6: Results of sensitivity analysis - Contribution of material recycling efficiency to variance

First, the sensitivity of the recycling efficiency of each material was evaluated independently and the simulation results are presented in Figure 4.6. As expected the materials that contribute the largest percentage of product mass have the greatest impact on product recyclability. For the laptop example, these materials are aluminum (58.4%), PC/ABS (14.9%), and steel (14.2%).

A second simulation was conducted to evaluate both the recycling efficiency and mass of the materials and components. The results from this simulation are presented in Figure

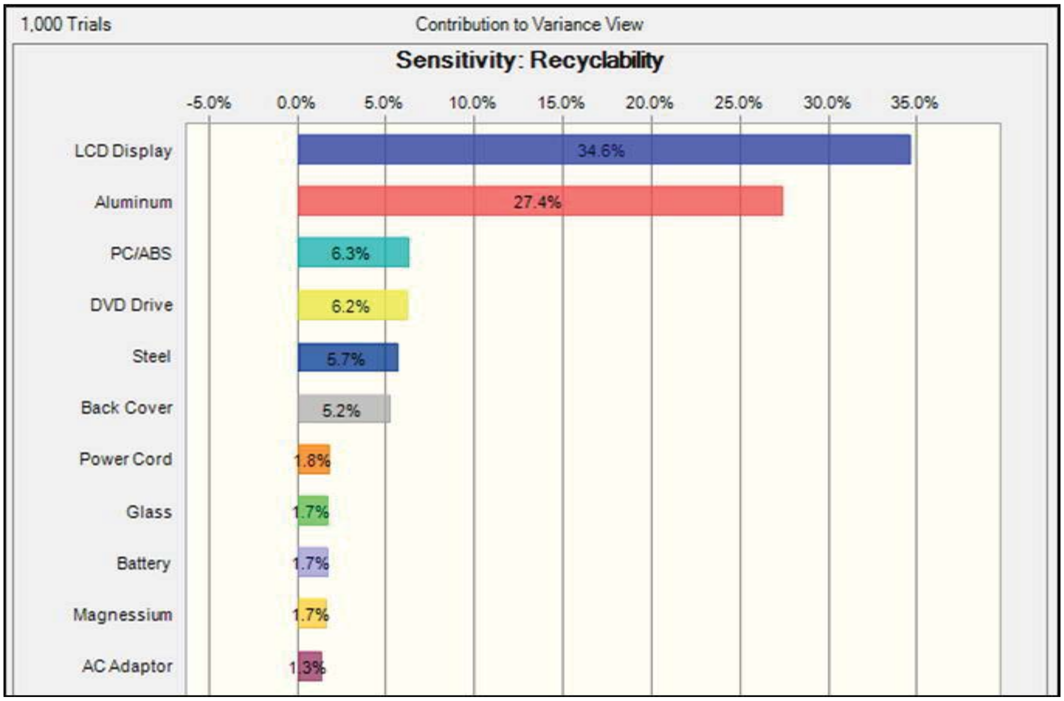


Figure 4.7: Results of sensitivity analysis - Contribution of material recycling efficiency and component to variance

4.7. The LCD display (34.6%) and aluminum (27.4%) had the greatest impact on product recyclability.

Future work should consider a more in depth analysis using several product case studies to consider variability within each product category and how it relates to product size.

4.9 Considerations for Implementing Product Design Criteria in the Model

One of the determining factors of how much material from a product is ultimately recovered is how efficiently it is disassembled and separated into the different material streams. The less contamination and "cleaner" the input stream is entering the shredder and secondary processing the more the recycling efficiency of that material increases. This contamination from both material combination and processing can result in accumulation of undesirable elements within the material stream; which can hamper further recycling [148]. Due to this the recycling efficiency of various materials fluctuates greatly even within a single facility. In order to account for this, design-based criteria should be included in a recyclability model.

There are several variables that affect recycling efficiency; technology level of recycling process, material separation and purification, and product design attributes. Product recyclability directly correlates to level of recycling efficiency of the system. How "clean" the input stream is in the recycling process directly correlates with recycling efficiency and therefore the amount of material that can successfully be recovered from a product through the recycling process. Product design attributes is one, if not the most important, determining factor of how clean the input stream is. Recycling efficiency is directly linked to product design and the material combinations and connections of the product [133].

In order to improve recycling efficiency of products two strategies can be used:

- Develop more efficient recycling processes and technology
- Design products that are easier to recycle

Of these, the development of easier to recycle products is expected to have the most significant effect [149]. Design for recycling (DfR) methods are often employed in the product design phase to ensure that the maximum amount of material can be reclaimed from the product during recycling. The material composition, types of connections, and product architecture all affect the degree of separation and subsequently the quality of material streams produced from pre-processing [105, 135]. Therefore the decisions made early in the design stage directly affect the recovery efficiency of materials in EoL processing and incorporating DfR techniques can ultimately lead to a higher efficiency of resource cycles. However, a systematic method has not yet been developed in order to consider DfR criteria when calculating the recyclability of a product. As mentioned at the beginning of this chapter, an ideal tool would incorporate mass, value, and design based metrics in product recyclability. This section discusses the main concepts that should be considered in order to develop a methodology to incorporate product design criteria into the model.

Several studies have been conducted in order to survey recyclers and disassemblers in order to understand what design guidelines are most effective at improving the recyclability of a product. However, there is no conclusive data on how effective these guidelines are at improving recyclability and there is no tool that provides a set of detailed design strategies for engineers with practical advice focusing on recycling and closing the materials loop for consumer electronics [39]. The existing guidelines in DfR can be described as an unstructured collection of many specific rules. Kriwet et al stated that the aim of researching the topic of DfR therefore should be to provide the designer with a set of guidelines that are simple, easy to apply and easy to evaluate [40].

As discussed in Chapter 2, design decisions made during product the design and development stage define product properties and affect the performance of the subsequent stages of the product's life cycle, including the EoL stage [86].These decisions made in the early stage of the product life cycle can impact the ease of product separation and purification for later reuse and recycling of components and materials. This section of the chapter prioritizes the most important design criteria for a product designer to consider when addressing product recyclability. The design criteria were categorized into material connection and material selection.

Product design has a significant impact on the liberation and separation efficiency of materials during recycling of a product. This research has identified three parameters that are most importance to consider when designing products to be recycled.

1. Material Compatibility - *Metals and plastics*
2. Separation Potential - *Quantity and type of connections*
3. Contamination - *Coatings, paints, and material mixing*

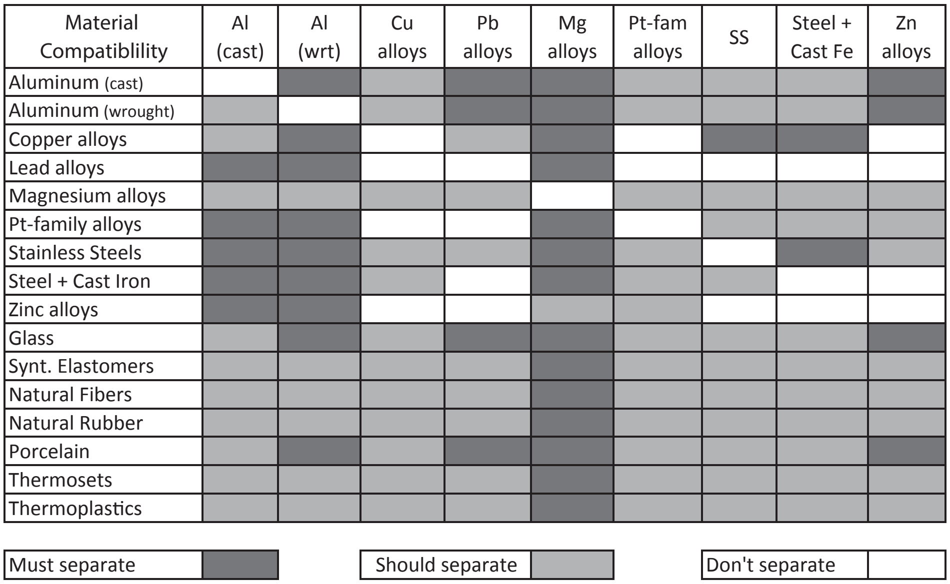
4.9.1 Material Compatibility

When recycling electronic products the amount of material that can be recovered from the product depends on the product material mix. These complex products contain many substances that are used in numerous combinations and are often closely connected [70]. With this it is important to consider material compatibility during the product material selection process.

Metals

The recycling of metals is highly developed. Metals differ greatly in their density and their magnetic and electrical properties, making separation comparatively easy. The value of metals, per kg, is greater than that of other materials used in electronic products. These factors help make recycling consumer electronics economically attractive. Technical challenges with recycling electronics stem from the complex material compositions and low concentrations of metals, which are dispersed in various amounts throughout the product and its components. These challenges become even greater when attempting to recover precious and critical metals, which are very valuable but often present in low quantities and concentrations. For example, the recovery of copper from a cable is much easier than recovering copper and other precious metals from a printed circuit board. However, due to their value the metals with the most economic incentive are usually the ones that are recovered in recycling. Specialized metallurgic processes are used to recover these metals effectively. Even with this specialized equipment, some loss to slag, dust, and other residues will inevitably occur during the process [47].

It is important to note that with appropriate technology other metals can be co-recovered. Similar to primary production, most metallurgic recovery processes have been developed based on the combinations of metal families found in primary ore sources [105]. The recovery of metals from combinations in products that do not occur in nature remains a challenge. With this, it is suggested to choose material combinations that are compatible with each other, especially when these materials are connected within a product. There have been some tools that have been developed in order to consider material compatibility. Castro developed a material compatibility matrix for metals based on material selection during the design stage of an automobile [150]. An adapted version of the matrix is presented in Figure 4.8.



Material Compatiblility	Al (cast)	Al (wrt)	Cu alloys	Pb alloys	Mg alloys	Pt-fam alloys	SS	Steel + Cast Fe	Zn alloys
Aluminum (cast)	□	■	▨	■	■	▨	▨	▨	■
Aluminum (wrought)	▨	□	▨	■	■	▨	▨	▨	■
Copper alloys	▨	■	□	▨	■	□	■	■	□
Lead alloys	■	■	□	□	■	□	□	□	□
Magnesium alloys	▨	▨	▨	▨	□	▨	▨	▨	▨
Pt-family alloys	■	■	□	□	■	□	▨	▨	▨
Stainless Steels	■	■	▨	▨	■	▨	□	■	▨
Steel + Cast Iron	■	■	▨	□	■	▨	▨	□	□
Zinc alloys	■	■	□	□	▨	▨	□	□	□
Glass	▨	■	▨	■	■	▨	▨	▨	■
Synt. Elastomers	▨	▨	▨	▨	■	▨	▨	▨	▨
Natural Fibers	▨	▨	▨	▨	■	▨	▨	▨	▨
Natural Rubber	▨	▨	▨	▨	■	▨	▨	▨	▨
Porcelain	▨	■	▨	■	■	▨	▨	▨	■
Thermosets	▨	▨	▨	▨	■	▨	▨	▨	▨
Thermoplastics	▨	▨	▨	▨	■	▨	▨	▨	▨

Must separate ■ Should separate ▨ Don't separate □

Figure 4.8: Material compatibility matrix for metals Adapted from adapted from [150]

More recently a "metal wheel" was developed that categorizes each metal by its base metal also known as a *carrier* metal [151]. The wheel was developed based on primary metallurgy but can be used to address metal compatibility during the design of product to ensure efficient recycling during the EoL process (see Figure 4.9).

The innermost ring shows the main carrier metals as described above. The three outermost rings show the potentially valuable elements associated with each carrier metal. The outermost ring contains compound elements that are generally lost in waste. The second outermost ring shows other valuable metals that may be recovered if economically viable and the next ring shows other carrier metals that are commonly recovered with the base metal. The recovery of these metals is much more complicated than described here, however this shows the potential of tools that could be developed in order to prioritize design and material selection criteria, at the same time improving product recyclability at the EoL phase.

The main metallurgy routes are copper/lead/nickel metallurgy (including metals), aluminum, and ferrous/steel. Once precious metals enter a steel plant or aluminum smelter it is almost impossible to recover them.

Plastics

Plastics are used in a variety of products and compose a large percentage of electronic products. Plastics pose several problems that hinder the recycling process including difficulties in separation and material contamination [152]. Plastics all have similar densities and no significant magnetic or electrical properties that make them easy to separate like metals.

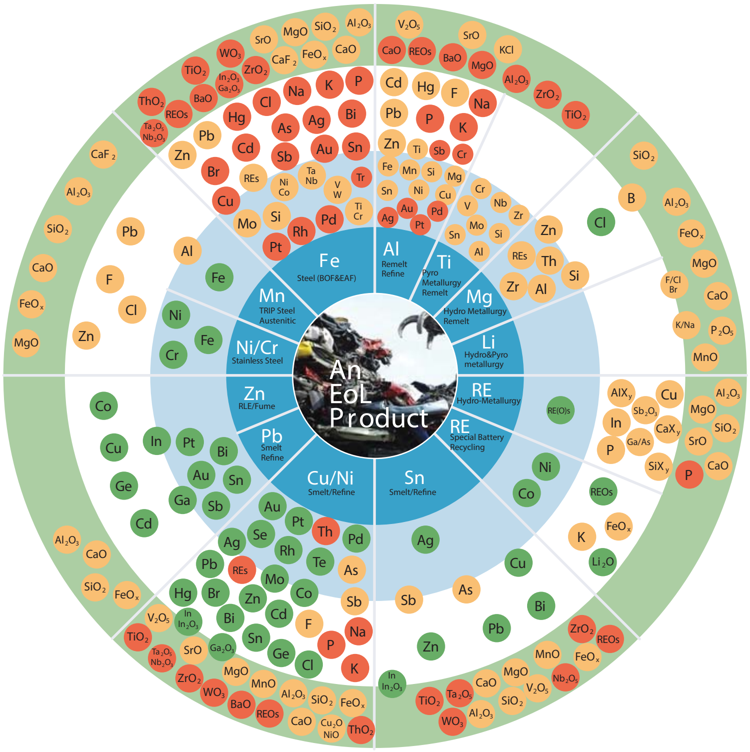
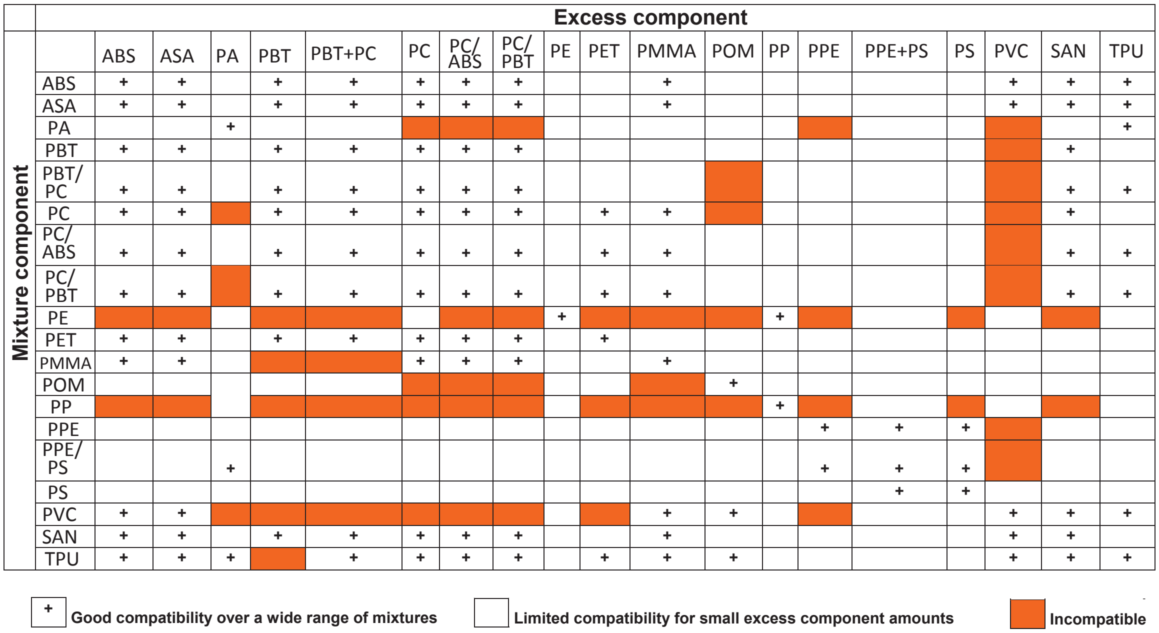


Figure 4.9: Metal wheel depicting metal compatibility based on primary metallurgy [8]

They can be identified by x-ray fluorescence or infrared spectroscopy, but these methods are often expensive. In fact, due to their complexity of plastics recycling, most plastics today are used in energy-recovery processes [153].

As mentioned previously the quality or grade of the incoming stream greatly affects the separation efficiency and material loss during the recycling process. The separation efficiency of plastics has been reported previously in literature for various plastics. The separation efficiency refers to the ratio of the amount of each plastic exiting the separation process to the amount of each plastic that entered the separation process. There have been several studies that addressed plastic bottles and film recycling to estimate separation efficiency. Schmidt & Strmberg reported a material loss of 3% for collected PET bottles in Switzerland, whereas Frees suggested a loss of 7.6% for LDPE film and PP bottles in Denmark [154–156]. Several studies by Dodbiba evaluated the separation efficiency of a mixture of polystyrene (PS), polyvinyl chloride (PVC), and polyurethane (PE) and found to be 67% [157]. It is important to note that, this efficiency is relatively high due to the grade of the input mixture which was around 96%. Separation efficiency for mixed material products, such as electronics, is much lower due to increased contamination in the input stream.

Thermoplastics that can be recycled can be ground into pellets and then used in the



	Excess component																		
Mixture component	ABS	ASA	PA	PBT	PBT+PC	PC	PC/ ABS	PC/ PBT	PE	PET	PMMA	POM	PP	PPE	PPE+PS	PS	PVC	SAN	TPU
ABS	+	+		+	+	+	+	+			+						+	+	+
ASA	+	+		+	+	+	+	+			+						+	+	+
PA			+			🟧	🟧	🟧						🟧			🟧		+
PBT	+	+		+	+	+	+	+									🟧	+	
PBT/ PC	+	+		+	+	+	+	+				🟧					🟧	+	+
PC	+	+	🟧	+	+	+	+	+		+	+	🟧					🟧	+	
PC/ ABS	+	+		+	+	+	+	+		+	+						🟧	+	+
PC/ PBT	+	+	🟧	+	+	+	+	+		+	+						🟧	+	+
PE	🟧	🟧		🟧	🟧		🟧	🟧	+	🟧	🟧	🟧	+	🟧		🟧		🟧	
PET	+	+		+	+	+	+	+		+									
PMMA	+	+		🟧	🟧	+	+	+			+								
POM						🟧	🟧	🟧			🟧	+							
PP	🟧	🟧		🟧	🟧	🟧	🟧	🟧		🟧	🟧	🟧	+	🟧		🟧		🟧	
PPE														+	+	+	🟧		
PPE/ PS			+											+	+	+	🟧		
PS															+	+			
PVC	+	+	🟧	🟧	🟧	🟧	🟧	🟧		🟧	+	+		🟧			+	+	+
SAN	+	+		+	+	+	+	+			+						+	+	
TPU	+	+	+	🟧	+	+	+	+		+	+	+					+	+	+

+ Good compatibility over a wide range of mixtures ☐ Limited compatibility for small excess component amounts 🟧 Incompatible

Figure 4.10: Plastics compatibility matrix [158]

input stream for injection molding, extrusion, or film casting. Some polymers after recycling are only suitable for down cycle. For example, polypropylene (PP) is commonly used for its good chemical and mechanical resistance, however even though it can be easily recycled, due to the chemical changes during recycling the secondary material is typically used in applications that require a lower tensile strength, such as furniture or toys. The major types of plastics used in electronic products are thermoplastics and thermosets. Thermoplastics can be re-melted and formed into new products, unlike thermosets. The engineering thermoplastics used in products have a high intrinsic value and when recycled they typically sell for dollars per pound as compared to cents per pound for bottle and container grad plastics [62]. Thermosets cannot be re-melted to form new products. Thermoplastics show better recyclability than thermosetting plastics.

Similar to metals, a plastic compatibility matrix has been developed [158]. The matrix shows plastic combinations that have good compatibility, limited compatibility for low amounts, and ones that are incompatible (see Figure 4.10). This matrix could be used for guidance during material selection of plastics.

While the material compatibility charts are a good first step, more work needs to done in order to adapt this information so it is accessible and useful to product designers. One key takeaway from this discussion is to maximize material compatibility during the material selection phase of the design process when possible. For example, printed circuit boards are often recycled based on copper metallurgy, so silver and gold can easily be recovered, however any aluminum that is present will be lost. With this it is important to minimize the presence of aluminum within the vicinity of these components. Another takeaway is to limit the number of different materials used in a product. Combinations of incompatible materials should be avoided to improve recycling efficiency of the materials.

In order to include material compatibility within the recyclability model a rating or weighting scheme could be used to develop a material compatibility index score. The index could be used in order to score a product based on the number of different materials in addition to the number of incompatible material combinations.

4.9.2 Separation Potential

Products that have metal and plastic parts that are easily separated will be able to have a higher percentage of material recovery than those that are difficult to disassemble into discrete material substances. This is especially important if the connections are between two materials that are not compatible as described in the above section.

Huisman noted that the main improvement to aid in material recovery was decreasing disassembly time [89]. Manual disassembly techniques have shown substantial improvement in disassembly times; however manual disassembly is often limited due to the expense of labor costs. Due to this products should be designed so that they can be manually disassembled within a reasonable amount of time. Also, the product should have connections and material compatibility combinations that would be able to be separated using mechanical or automated recycling processes as described in Chapter 2. The amounts of materials ending up in the ‘wrong output streams during recycling can be decreased by improving separation potential between material and component connections with the product architecture.

Identifying the types and quantity of connections in a product can provide insight into how efficiently the materials can be recovered during recycling. It is assumed that the fewer number of connections would increase the separation potential of the materials and components within the product.

Joints or connections can be categorized as two types, physical and chemical. A physical joint refers to a connection between two or more materials using a mechanical connection. A chemical joint refers to a connection between two or more materials using a chemical connection. These types of joints have also previously been classified as permanent (chemical) and non-permanent (physical). Connections can be quantified by this classification type, often physical joints are separately more easily during shredding processes than chemical joints.

Tseng and colleagues identified types of joints based on how the materials are connected [159]. The four types with their description are listed below.

- Zero joint joint between the same materials
- Point joint point connection that uses mechanical joining element (e.g., rivet)
- Line joint line connection (e.g., weld, adhesive)
- Surface joint surface connection (e.g., coatings, paints)

These were developed in order to assess the liaison intensity between parts of a product to assess product modularity. A similar method could be used to consider liaison intensity of the connections in a product. The assessment results could provide a rating scheme based on the quantity and type of connections. With this classification scheme the types of joints could be rated with respect to their separation potential using either manual or automated disassembly techniques. A connection index could be developed to consider these results based on a weighting scheme which could be incorporated into a design-based recyclability metric.

4.9.3 Material Contamination

In addition to material compatibility and separation potential, the potential material contamination should be evaluated. While many materials in EoL products are valuable, there are also hazardous substances that complicate EoL management and processing. Additional equipment is also needed in order to sustainably manage off-gases and effluents from smelter operations in order to ensure prevention of heavy metal and dioxin emissions. The reduction and ultimately elimination of hazardous substances within product should be considered to reduce potential material contamination.

Contamination may also occur in parts or components that contain adhesives, labels, or paint that increase the difficulty of recycling those materials. This is often the case with plastics parts that use metal inserts or fillers in order to improve the strength and durability of the material. Paints and coatings are often used for aesthetic appeal. This often unavoidable contamination relegates the recycled plastics to being down cycled into products such as benches or fillers in asphalt [160]. In some cases, one percent contamination is enough to ruin a batch of high grade plastics for recycling. The American Plastics Council conducted a study with an e-waste collection program and found that two-thirds of plastic parts collected were rejected for: metalized coatings, paint, or glass filler, lamination or labels that were difficult to remove, composite plastics high density-variable structural foam, or comingled plastics [134].

Material contamination can be evaluated by considering material mixing and compatibility as discussed previously. In addition, the use of hazardous substances, adhesives, labels, and other coatings should be considered when developing design-based criteria to be included in the recyclability model.

4.10 Summary

This chapter reviewed the methodology used to develop a product recyclability model for consumer electronics. A detailed review of recycling efficiency of materials used in electronic products was conducted in order to provide the most up to date accurate data for the model. Component composition models were developed and incorporated in the model for common components and printed circuit boards used in electronic products. This was done to alleviate the data required to use the model. The flexibility of the model allows the user to be able to decide the level of detail they include when using the model.

One of the most challenging aspects of developing a product recyclability model is the availability of a robust data set for recycling rates of materials. Further research is needed in order to develop a more comprehensive set of recycling rates that are representative of electronic product recycling. The processes and process efficiency during recycling can change over time and the model would need to be updated to reflect this.

Considerations to develop a design-based metric to be included were discussed. Future work should address the implementation of this in the model to provide a more accurate assessment of product recyclability.

One major barrier to encourage resource efficiency in the electronics industry is the absence of accurate information and feedback from the end-of-life phase throughout the rest of the supply chain [161]. The information exchange among end-of-life actors is the last and least developed perspective on end of life, and its implementation is scarce.

Atlee noted these different types of measures needed between recyclers and manufacturers [124]. OEMs have developed design guidelines in an attempt to quantify recyclability and in contrast, a recycler is more focused on process-based measures instead of product based. To be able to accurately capture the recyclability of a product; the new model that considers mass, value, and design metrics would need to have input from several actors across the supply chain. This would provide the opportunity for a better information exchange between designers, manufacturers, and EoL management facilities.

In order to improve e-waste processing at the EoL stage, designers need to understand the processes at the recycler level and recyclers need to be informed of product characteristics that may impact the EoL treatment activities. Creating this feedback loop between designers and EoL practitioners will better ensure that the product is efficiently and safely processed at the EoL in order to provide high material recovery rates. Transfer of product information from the designer to the recycler is necessary to allow recyclers to implement treatment that respects environmental and safety requirements, and optimize parts and material recovery.

OEMs can benefit from understanding the processes at material processing facilities and the decisions that are made at each step regarding how to efficiently process the product. Additionally, exchanging information about recycling efficiency will enable OEMs to more accurately calculate the recyclability of their products. Information regarding materials that are difficult to process or separate or any material incompatibility issues that affect the EoL management phase will allow OEMs to have continuous feedback that can be used during the product design phase. Information that is relevant to the EoL management facility would be details about the material composition and product architecture, such as hazardous materials, types of connections.

Important aspects of this analysis are the detailed component compositions that were developed. focusing on what materials are actually recovered from these products, and the recycling efficiencies of those materials. The approach developed can be used to provide guidance and consistency in metrics used to determine the recyclability of a product.

Chapter 5

Conclusion and Future Work

5.1 Research Contributions and Discussion

This dissertation presented an in depth review of the end-of-life (EoL) phase of consumer electronic products. This research developed methodologies and tools to inform strategies for consumer electronic products during the design and EoL phases of the product life cycle. The methods and tools presented provide an assessment of the EoL phase from a facility and product level perspective. Alignment and input from key stakeholders in the industry as well as current industry standards and efforts were an integral part of this work. Throughout the development of this work feedback was solicited from original equipment manufacturers (OEMs), non-government organizations (NGOs), government agencies, and end-of-life practitioners.

5.1.1 Summary of Key Contributions

Facility and material flows assessment

- Developed of assessment framework based on five key categories to evaluate e-waste material recovery facilities
- Developed material flow analysis model to map end-of-life pathways of electronic products through the end-of-life phase
- Characterized the end-of-life management phase of consumer electronics based on collection methods, incoming product mix, and material flow analysis

Consumer electronic product recyclability

- Created product recyclability model to determine the recyclable mass and economic value of materials recovered

- Developed methodology to determine product recylability based on the material and component levels of a product
- Developed component composition models to determine the mass based percentage of materials commonly recovered from those components
- Reviewed important considerations to include product design criteria in a future model

5.1.2 Assessment of End-of-Life Pathways and Material Recovery Facilities

Important conclusions and outcomes of this work were the development and implementation of an assessment framework used to characterize the end-of-life phase of consumer electronic products. The potential end-of-life pathways were characterized for each product category assessed including collection methods and the reuse, refurbishment, and recycling pathways. The majority of products collected was from the business sector, which presents an opportunity and need to develop more efficient collection channels within the consumer sector. The mass based collection metrics are also not appropriate to obtain a realistic view of the products collected, as shown in Chapter 3. The largest number of units collected at 90% of the facilities was mobile phones. The mass based collection metrics identified CRTs as the largest percentage of products collected. An initial facility level energy assessment was conducted, which showed the effects of employing manual versus mechanical processing within a facility. A deeper analysis should be conducted at the process level to provide more insight into the facility operations and resources used during the EoL management phase. The framework developed can be leveraged for future system wide assessments within the industry, which would allow for a quantitative comparison between systems.

5.1.3 Development of Product Recyclability Model

A product recyclability model was presented that incorporated mass and value based metrics to develop a more robust product recyclability assessment. The approach developed can be used to provide guidance and consistency in metrics used to determine the recyclability of a product.

With the complexity of components and supplier based purchasing it is difficult for OEMs to provide detailed material information at the product level about the mass and type of materials used in components. Due to this, product recyclability is often not accounted for during the design stage and is sometimes limited to a short list of materials restricted through regulations.

Component models were developed based on the recyclable material composition of various electronic components including hard disc drives, optical drives, displays, power supplies, batteries and printed circuit boards. The component models were developed using two criteria: material composition of each component and the materials that are commonly recovered from the components during recycling of the product. The printed circuit board models were developed based on location and application of each board. The flexibility of the tool was integrated in order to alleviate the amount of data needed to use the model, therefore making it easier to use and implement within industry.

The model was validated with a case study of a 15" laptop computer. These results show that only about one-third of the material mass of the laptop is recovered during recycling which equates to a value of $4.90 per laptop. The sensitivity analysis showed that aluminum and the liquid crystal integrated display had the greatest impact on product recyclability.

The methods and data used in the model could be adapted to include additional product categories. For example, home appliances and medical devices would be appropriate product categories for model expansion due to the similarities in material composition, electronic components, and processing technology used to recycle these products.

5.1.4 Considerations to Include Product Design Criteria in the Recyclability Model

This research also identified product design criteria that should be implemented into the recyclability model, including: material compatibility, separation efficiency, and material contamination. The two main variables that affect recycling efficiency are the processing technology used during recycling and the design attributes of the product. Quantifying the material losses during preprocessing and the impact of material combinations and product design is necessary to evaluate the process efficiency and identify potential improvements. More research is needed to understand the interactions between these two characteristics and how they affect materials recovery efficiency.

Many tools have been developed to evaluate design for the end-of-life criteria, but have yet to successfully be incorporated into a product recyclability indicator or tool. There is a need for accurate assessments of process technologies at material recovery facilities to collect primary data to better inform and quantify product recyclability. With this data advanced modeling and process simulations tools could be developed that are utilized both by product designers and EoL practitioners.

5.2 Future Work

Future work within this life cycle phase should focus on improving data collection within the end-of-life phase and communication throughout the supply chain focusing on key stakeholders including, product designers, manufacturers, EoL practitioners, and consumers.

5.2.1 Key Performance Indicators

The development of a systematic method for continuous assessment and data collection is necessary as technology continues to evolve. As our society moves towards cloud based computing and hardware as a service we can imagine that the EoL management landscape will change as well. Improved collaboration across the entire supply chain as mentioned previously will enable us to adapt to this ever changing system. However, the proper metrics and indices are needed in order to evaluate and communicate system performance.

Common tools, including life cycle assessment, material flow analysis, and economic evaluations, have been used independently to address the EoL management phase of consumer electronics. A more collaborative approach is necessary in order to obtain a truly sustainable system. One key performance parameter that should be tracked and measure is a complete mass balance of the EoL phase of these products. As discussed in Chapter 4, there is significant variability with material recycling efficiencies. A system-wide mass balance, including primary and secondary processing, would allow for improved estimates of incoming products streams and the materials that are able to be recovered from those products. Incorporating this type of assessment within facilities would provide continuous system feedback and enable improvement opportunities to be identified. While this type of assessment may take several years to implement, facilities should be encouraged to move towards measuring performance using these types of metrics.

Currently facilities track incoming products by mass, however as discussed in Chapter 3, this type of metric does not provide any insight into the quantity of units of each product category due to the variable product mass. This type of tracking and reporting is also encouraged by extended producer responsibility laws that require manufacturers to take back products based on a specified mass quantity. A combination of mass and volume based metrics would need to be incorporated in order assess incoming product mix at these facilities.

5.2.2 Consumer Engagement

One key stakeholder that is often ignored during the EoL phase is the product user. Engaging the user in the EoL phase would inevitably increase the amount of e-waste collected during this phase. A new method for Design for X should focus on Design for Consumer Engagement. This concept moves beyond consumer education and extends the reach to include the consumer. Often, information about where to recycle a product and disposal options is difficult to find on a companys website and not viewed by the consumer. Developing innovative strategies to reclaim products during the EoL phase would move us towards a closed loop economy. This is not to offset the burden of EoL collection to the consumer, but to provide positive incentives to sustainably manage products during the EoL phase.

5.2.3 Information Exchange

In order to achieve true resource efficiency and move towards a closed loop economy, there is a need for increased and active participation from all key stakeholders throughout the supply chain. The need for an information feedback loop between designers, manufacturers, and EoL practitioners was a theme throughout this dissertation. While sustainably managing products during the EoL cycle phase has gained interest, there is still a need for facilitating the implementation of these concepts in practice.

In order to improve e-waste processing at the EoL stage, designers need to understand the processes at the recycler level and recyclers need to be informed of product attributes that may impact the EoL treatment activities. Creating this feedback loop between designers and EoL practitioners will better ensure that the product is efficiently and safely processed at the EoL in order to provide high material recovery rates. Transfer of product information from the designer to the recycler is necessary to allow for the implementation of sustainable treatment processes for efficient material recovery.

OEMs can benefit from understanding the processes at material processing facilities and the decisions that are made at each step regarding how to efficiently process the product. Additionally, exchanging information about recycling efficiency will enable OEMs to more accurately calculate the recyclability of their products. Information regarding materials that are difficult to process or separate or any material incompatibility issues that affect the EoL management phase will allow OEMs to have continuous feedback that can be used during the product design phase. Information that is relevant to the EoL management facility would be details about the material composition and product architecture, such as hazardous materials, and type of connections.

Future work in this area should focus on improving data collection and exchange throughout the product supply chain. Data collection efforts should be focused on connecting the end-of-life phase practitioners with original equipment manufacturers. A systems level approach is needed in order to understand the interdependencies between product design and EoL facility performance characteristics. This is essential to facilitate progress towards a more sustainable materials recovery system.

Bibliography

[1] G.E. Moore. Cramming more components onto integrated circuits. *Electronics*, 38(8):114–117, 1965.

[2] Report of the World Commission on Environment and Development: Our Common Future. Technical report, United Nations World Commission on Environmentand Development, 1987.

[3] J. Rockström, W. Steffen, K. Noone, . Persson, F. S. Chapin, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. Schellnhuber, B. Nykvist, C. A. De Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley. Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*, 14(2):32, 2009.

[4] Directive 2011/65/EC of the European Parliament and of the Council. Directive on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS), 2011. Available from `http://ec.europa.eu/enterprise/policies/european-standards/harmonised-standards/restriction-of-hazardous-substances/index_en.htm` Accessed May 12, 2012.

[5] Directive 2012/19/EC of the European Parliament and of the Council. Directive on Waste Electrical and Electronic Equipment (WEEE), 2011. Available from `http://ec.europa.eu/environment/waste/weee/index_en.htm` Accessed April 22, 2012.

[6] K. Halada. Resource risk and posibility of recycling. In *Proceedings of OECD-UNEP Conference on Resource Efficiency*, 2008.

[7] C. Hagelüken. Towards bridging the materials loop: How producers and recyclers can work together. In *Proceedings of EU-US workshop Brussels*, 2012.

[8] M. Reuter, C. Hudson, A. van Schaik, K. Heiskanen, C. Meskers, and C. Hagelüken. Metal recycling opportunities, limits, infrastructure. Technical report, United Nations Environment Programme (UNEP),Report of the Global Metals Flows Working Group of the International Resource Panel of UNEP, 2013.

[9] S. Sahni, A. Boustani, T.G. Gutowski, and S.G. Graves. Reusing personal computer devices: Good or bad for the environment? In *IEEE International Symposium on Sustainable Systems and Technology*. Institute of Electrical and Electronics Engineers, 2010.

[10] Blake Alcott. Historical overview of the jevons paradox in the literature. In *The Jevons Paradox and the myth of resource efficiency improvements*, pages 7–78. Earthscan, London, England, 2008.

[11] W. J. Kramer, B. Jenkins, and R. S. Katz. The role of information and communications technology sector in expanding economic opportunity. Technical Report 22, Harvard University Kennedy School of Government, 2007.

[12] The Climate Group. Smart 2020: Enabling the low-carbon economy in the information age. Technical report, Global eSustainability Initiative (GeSI), 2008. Available from `http://gesi.org/files/Reports/Smart%202020%20report%20in%20English.pdf`, Accessed October 18, 2012.

[13] United Nations Environmental Programme (UNEP). Why take a life cycle approach? Technical report, United Nations Publication, 2004. Available from `http://www.unep.fr/scp/publications/details.asp?id=DTI/0585/PA`, Accessed October 18, 2012.

[14] J.M Allwood, M. F.Ashby, T.G. Gutowski E., and Worrell. Material efficiency: A white paper. *Resources, Conservation and Recycling*, 55(2011):362–381, 2011.

[15] T. Devoldere, B. Willems, J. Duflou, and W. Dewulf. The eco-efficiency of reuse centres critically explored: The washing machine case. *The International Journal of Sustainable Manufacturing*, 1(3):265–285, 2009.

[16] R.A. Frosch and Gallopoulos. Strategies for manufacturing. *Scientific American*, 261(3):144–152, 1989.

[17] T.E. Graedel and B.R. Allenby. *Design for environment.* Prentice Hall, 1997.

[18] B. Allenby. The ontologies of industrial ecology. *Progress in Industrial Ecology - An International Journal*, 3(1/2):28–40, 2006.

[19] C. Boks and A. Stevels. Theory and practice of environmental benchmarking in a major consumer electronics company. *Benchmarking: An International Journal*, 10(2):120–135, 2003.

[20] Consumer Electronics Association. Market research report: Trends in consumer electronic reuse, recycle and removal. Technical report, 2008.

[21] Office of Resource Conservation and Recovery. Management of electronics waste in the united states: Approach 1 and approach 2. Technical report, United States Environmental Protection Agency (EPA), 2008.

[22] M.K.S. Bhutta, A. Omar, and Y. Xiaozhe. Electronic waste: A growing concern in today's environment. *Economics Research International*, 2011.

[23] J. Watts. Lead poisining cases spark riots in China. *Lancet*, 374(9701), 2009.

[24] United States Environmental Protection Agency (EPA). Electronics waste management in the united states through 2009. Technical report, United States Environmental Protection Agency (EPA), 2011. Available from `http://www.epa.gov/osw/conserve/materials/ecycling/docs/fullbaselinereport2011.pdf`, Accessed April 24, 2011.

[25] R. Widmer, H. Oswald-Krapf, D. Sinha-Khetriwal, M. Schnellmann, and H. Boni. Global perspectives on e-waste. *Environmental Impact Assessment Review*, 25(5):436–458, 2011.

[26] Office of Resource Conservation and Recovery. Municipal solid waste in the united states. Technical report, United States Environmental Protection Agency (EPA), 2008. Available from `http://www.epa.gov/osw/nonhaz/municipal/msw99.htm`, Accessed April 24, 2011.

[27] M. Oguchi, T. Kameya, S. Yagi, and K. Urano. Product ow analysis of various consumer durables in japan. *Resources, Conservation and Recycling*, 52(3):463–480, 2008.

[28] R. Kahhat. Electronic waste: Environment and society. In *E-Waste management: From waste to resource*. Routledge Taylor and Frances Group, 2012.

[29] C.W. Lam, S. Lim, and J.M. Shoenung. Linking material flow analysis with environmental impact potential. *Journal of Industrial Ecology*, 17(2):299–309, 2012.

[30] F. Verhaeghe. Critical raw materials not your problem? In *Proceedings of 3rd International Slag Valorisation Symposium*, 2012.

[31] Y.J. Park and D.J. Fray. Recovery of high purity precious metals from printed circuit boards. *Journal of Hazardous Materials*, 29:2140–2146, 2009.

[32] B. K. Fishbein. Waste in the wireless world: The challenge of cell phones, 2002. Inform, Strategies for a better environment. Available from `http://informinc.org/reportpdfs/wp/WasteintheWirelessWorld.pdf` Accessed August 3, 2013.

[33] P. Kiddee, R. Naidu, and M.H. Wong. Electronic waste management approaches: An overview. *Waste Management*, 33(5):1237–1250, 2013.

[34] B.H. Robinson. E-waste: An assessment of global production and environmental impacts. *Science of The Total Environment*, 408(2):183–191, 2009.

[35] E. Williams, R. Kahhat, B. Allenby, E. Kavazanjian, J. Kim, and M. Xu. Environmental, social, and economic implications of global reuse and recycling of personal computers. *Environmental Science and Technology*, 42(17):6446–6454, 2008.

[36] J.B. Ayers. *Handbook of supply chain management.* Auerbach Publications, 2006.

[37] P. Li, J. Dahmus, S. Guldberg, H.O. Riddervold, and R. Kirchain. How much sorting is enough: Identifying economic and scrap-reuse benefits of sorting technologies. *Journal of Industrial Ecology*, 15(5):743–759, 2011.

[38] S. Kriebe. Current and new electronic waste recycling. In *E-waste management: From waste to resource*. Routledge Taylor and Frances Group, 2012.

[39] N. Hultgren. Guidelines and design strategies for improved product recyclability. Master's thesis, Chalmers University of Technology, Gothenburg, Sweden, 2012.

[40] A. Kriwet, G. Seliger, and E. Zussman. Systematic integration of design for recycling into product design. *International Journal of Product Economics*, 38:15–22, 1995.

[41] T. E. Graedel and E. M. Harper. A tale of three metals. In *E-waste management: From waste to resource*. Routledge Taylor and Frances Group, 2012.

[42] Committee on Critical Materials in Impacts on the U.S Economy, Committee on Earth Resources, and National Research Council. Minerals, critical minerals, and the U.S. economy, 2008. Washington, DC: National Academy Press.

[43] B. Brown-West. A strategic analysis of the role of uncertainty in electronic waste recovery system economics: An investigation of the it and appliance industries. Master's thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2010.

[44] S. Hamm and K. Hall. Building the perfect laptop. *Bloomberg Businessweek*, 2008. Available from `http://www.businessweek.com/stories/2008-02-13/building-the-perfect-laptop`, Accessed November 18,2013.

[45] D.J. Gattuso. Mandated recycling of computers: A lose-lose-lose proposition, 2005. Competitive Enterprise Institue (CEI). Available from `http://cei.org/pdf/4386.pdf` Accessed Novermber 18, 2013.

[46] International Association of Electronics Recyclers (IAER). Electronics recycling industry report, 2005.

[47] C. Hagelüken. Recycling of electronics scrap at umicore's integrated metals smelter and refinery. *Erzzmetall*, 59(3):152–161, 2006.

[48] Five Winds International. Toxic and hazardous materials in electronics: An environmental scan of toxic and hazardous materials in it and telecom products and waste, 2005. Final Report submitted to Environment Canada, National Office of Pollution Prevention and Industry Canada.

[49] MJC and Associates. Screening level human health and ecological risk assessment for generic e-waste processing facility, 2004. Prepared for the ICT Innovation and Computers for Schools Program, Industry Canada and National Office of Pollution Prevention, Environment Canada.

[50] J. Puckett, L. Byster, S. Westervelt, R. Gutierrez, S. Davis, A Hussain, and M. Dutta. Exporting harm - the high-tech trashing of Asia, 2002. Report by The Basel Action Network and Silicon Valley Toxics Coalition.

[51] Y. Amoyaw-Osei, O.O. Agyekum, J.A. Pwamang, E. Mueller, R. Fasko, and M. Schlue. Ghana e-waste country assessment, 2011. Report by the Secretariat Basel Convention e-waste Africa Project.

[52] K. Brigden, I. Labunska, D. Santillo, and M. Allsopp. Recycling of eleectronic wastes in China and India: Workplace and envrionmental contamination, 2005. Greenpeace International. Available from `http://svtc.org/wp-content/uploads/greenpeace.pdf`, Accessed April 24, 2012.

[53] T.G. Gutowski, S. Sahni, A. Boustani, and S.C. Graves. Remanufacturing and energy savings. *Environmental Science and Technology*, 45(10):4540–4547, 2011.

[54] O.F. Neto, G. Walther, J. Bloemhoff, J.A.E.E van Nunen, and T. Spengler. From closed-loop to sustainable supply chains: The WEEE case, 2007. Eramus University Working Paper. Available from `http://repub.eur.nl/publications/index/781685813`, Accessed November 18, 2013.

[55] C.M. Rose. *Design for environment: A method for formulating product end-of-life strategies*. PhD thesis, Stanford University, Palo Alto, California, 2000.

[56] Solid Waste Association of North America Applied Research Foundation. The effectiveness of municipal solid waste landfills in controlling releases of heavy metals to the environment, 2004.

[57] Y.C. Jang and T.G. Townsend. Leaching of lead from computer printed wire boards and cathode ray tubes by municipal solid waste landfill leachates. *Environmental Science and Technology*, 37(20):4778–4784, 2003.

[58] D. Daoud. Inside the U.S. electronics recycling industry, 2011. International Data Corporation. Available from `http://www.isri.org/CMDownload.aspx?ContentKey=b4870939-31cd-4110-9ce1-53ed3bc3a8bf&ContentItemKey=b02f4142-da79-44ba-bab4-4a631c06b4a3` Accessed May 12, 2013.

[59] W. Rifer, P. Brody-Heine, A. Peters, and J. Linnell. Closing the loop electronics design to enhance reuse/recycling value, 2009. Report from the Green Electronics Council in collaboration with the National Center for Electronics Recycling and Resources Recycling, Inc. Available from `http://science.house.gov/sites/republicans.science.house.gov/files/documents/hearings/021109Omelchuck.pdf`, Accessed April 22, 2012.

[60] G. Dodbiba, A. Shibayama, J. Sadaki, and T. Fujita. Combination of triboelectrostatic separation and air tabling for sorting plastics from a multi-component plastic mixture. *Materials Transactions - Special issue on new systems and processes in recycling and high performance waste treatments*, 44(12):2427–2435, 2003.

[61] FM Plastics Machinery. Shear shredder. Available from `http://fmplasticsmachinery.com/wp-content/uploads/2010/12/twoshaft.jpg`, Accessed October 1, 2013.

[62] H.Y. Kang and J.M. Schoenung. Electronic waste recycling: A review of U.S. infrastructure and technology options. *Resources, Conservation and Recycling*, 45:368–400, 2005.

[63] Western Process Equipment. Magnetic pulley. Available from `http://westproquip.com.au/equipment/magnetic-pulleys/`, Accessed October 1, 2013.

[64] J. Cui and E. Forssberg. Mechanical recycling of waste electrical and electronic equipment. *Journal of Hazardous Materials*, 99:243–263, 2003.

[65] M. Lungu. Separation of small nonferrous particles using an angular rotary drum eddy-current separator with permanent magnets. *International Journal of Mineral Processing*, 78(1):22–30, 2005.

[66] G. Dodbiba and T. Fujita. Progress in separating plastic materials for recycling. *Physical Separation in Science and Engineering*, 13(3-4):165–182, 2004.

[67] W. Knight and M. Curtis. Measuring your ecodesign [end-of-life disassembly]. *Manufacturing Engineer*, 81(2):64–69, 2002.

[68] M.I. Wolf, M. Colledani, S.B Gershwin, and T.G. Gutowski. Modeling and design of multi-step separation systems. In *IEEE International Symposium on Sustainable Systems and Technology.* Institute of Electrical and Electronics Engineers, 2002.

[69] P. Chancerel, C.E.M. Meskers, C. Hageluken, and V.S. Rotter. Assessment of precious metals flows during preprocessing of waste and electrical and electronic equipment. *Journal of Industrial Ecology*, 13(5):791–810, 2009.

[70] C. Hagelüken. Recycling of precious and special metals. In *Eco-Efficiency in Industry and Science*, pages 221–241. Springer Science, 2013.

[71] L. Meyer and B. Bras. Rare earth metal recycling. In *IEEE International Symposium on Sustainable Systems and Technology*. Institute of Electrical and Electronics Engineers, 2010.

[72] S. Rao. *Resource Recovery and Recycling from Metallurgical Wastes*. McGill University, Montreal, Canada, 1 edition, 2006.

[73] M.R. Gent, M. Menendex, J. Torano, D. Isidro, and S. Torno. Cylinder cyclone density media separation of plastic wastes. *Waste Management*, 29(6):1819–1827, 2009.

[74] McDonough Braungart Design Chemistry LLC. Cradle to cradle trademark guidelines. `http://www.mbdc.com/wp-content/uploads/2013/04/Cradle-to-Cradle-CertifiedCM-Trademark-Guidelines.pdf`, 2012.

[75] D. Bleiwas. Obsolete computers, gold mine or high-tech trash? *Resource recovery from recycling: U.S. Geological Survey Fact Sheet*, 2001.

[76] B. Willems, W. Dewulf, and J.R. Duflou. A method to assess the lifetime prolongation capabilities of products. *International Journal of Sustainable Manufacturing*, 1(12):122–144, 2008.

[77] Global Aluminum Recycling Committee. Global aluminum recycling - A cornerstorne of sustainable development, 2006. London, International Aluminum Institute.

[78] W. McDonough and M. Braungart. *Cradle to Cradle Remaking the way we make things*. North Point Press, New York, New York, 1 edition, 2002.

[79] Evaluation Regulation on Registration, Authorisation, and Restriction of Chemicals (REACH). European union regulation, 2007. Available from `http://ec.europa.eu/enterprise/sectors/chemicals/reach/index_en.htm` Accessed May 12, 2012.

[80] Delta Institute. Trends in e-waste legislation fact sheet, 2012. Available from `http://www.delta-institute.org/ewaste/emerging-trends/` Accessed October, 2013.

[81] J. Mueller, H. Griese, K. Schischke, I. Stobbe, G.A. Norris, and A. Udo de Haes. Life cycle thinking for green electronics: Basics in ecodesign and the UNEP/SETAC life cycle initiative. In *Proceedings of International IEEE Conference on Asian Green Electronics*. 2004.

[82] E. Masanet, L. Price, S. de la Rue du Can, R. Brown, and E. Worrell. Optimization of product life cycles to reduce greenhouse gas emissions in California. Technical report, California Energy Commision, PIER Energy-Related Environmental Research, 2005.

[83] L.T. Lu, I. Wernick, T. Hsiao, Y. Yu, Y. Yang, and H. Ma. Balancing the life cycle impacts of notebook computers: Taiwan's experience. *Resources, Conservation and Recycling*, 48(1):13–25, 2006.

[84] H. Duan, M. Eugester, R. Hischier, M. Streicher-Porte, and J. Li. Life cycle assessment study of a chinese desktop personal computer. *Science and the Total Environment*, 407(5):1755–1764, 2009.

[85] S. O'Connell and M. Stutz. Product carbon footprint assessment of dell laptop - results and recommendations. In *IEEE International Symposium on Sustainable Systems and Technology*. Institute of Electrical and Electronics Engineers, 2010.

[86] J. Olesen. *Concurrent development in manufacturing*. PhD thesis, Technical University of Denmark, Lyngby, Denmark, 1992.

[87] E. Masanet, R. Auer, D. Tsuda, T. Barillot, A. Baynes, and Les Ulis Cedex-france. An assessment and prioritization of "design for recycling" guidelines for plastic components. In *IEEE International Symposium on Electronics and the Environment*. Institute of Electrical and Electronics Engineers, 2002.

[88] P. Shrivastava, S. O'Connell, and M. Watson. Dell survey of electronic recyclers - results and analysis. In *IEEE International Symposium on Sustainable Systems and Technology*. Institute of Electrical and Electronics Engineers, 2005.

[89] J. Huisman. *The QWERTY/EE Concept: Quantifying Recyclability and Eco-Efficiency for End-of-Life Treatment of Consumer Electronic Products*. PhD thesis, Delft University of Technology, The Netherlands, 2003.

[90] L.K. Moyer and S.M. Gupta. Environmental concerns and recycling/disassembly efforts in the electronics industry. *Journal of Electronics Manufacturing*, 7(1):1–22, 1997.

[91] M. Kwak, S. Behdad, Y. Zhao, H. Kim, and D. Thurston. E-waste stream analysis and design implications. *Journal of Mechanical Design*, 133, 2011.

[92] E.D. Williams and Y. Sasaki. Energy analysis of end-of-life options for personal computers: resell, upgrade, recycle. In *IEEE International Symposium on Electronics and the Environment*. Institute of Electrical and Electronics Engineers, 2003.

[93] C.W. Babbitt, R. Kahhat, E. Williams, and G.A. Babbitt. Evolution of product lifespan and implications for environmental assessment and management: a case study of personal computers in higher education. *Environmental Science and Technology*, 43:5106–5112, 2009.

[94] European Commission DG TREN/D1/40-2005. Lot 3: Personal computers (desktops and laptops and computer monitors. Final Report (task 1-8). Technical report, Prepatory studies for Eco-design Requirments of EuPs, 2013. Available from `http://www.energimyndigheten.se/Global/F%C3%B6retag/Ekodesign/Ekodesign/Datorer/EuP_Lot3_PC_FinalReport.pdf`, Accessed May, 2013.

[95] G.L. Peralta and P.M. Fontanos. E-waste issues and measures in the Philippines. *Journal of Material Cycles and Waste Management*, 8(1):34–39, 2006.

[96] M. Oguchi, T. Kameya, T. Tasaki, N. Tamai, and N. Tanikawa. Estimations of lifetime distributions and waste numbers of 23 types of electrical and electronic equipment. *Journal of the Japan Society of Waste Management Experts*, 17(1):50–60, 2006.

[97] N. vanNes and J. Cramer. Product lifetime optimizations: A challenging strategy towards more sustainable consumption patterns. *Journal of Cleaner Production*, 14(15-16):1307–1318, 2006.

[98] T. Cooper. Inadequate life? evidence of consumer attitudes to product obsolescence. *Journal of Consumer Policy*, 27(4):421–449, 2004.

[99] E. van der Voet. *Substance from cradle to grave: development of a methodology for the analysis of substance flows through the economy and the environment region*. PhD thesis, Leiden University, The Netherlands, 1996.

[100] A. Pehlken, M. Rolbiecki, A. Decker, and K.D. Thoben. Contribution of material flow assessment in recycling processes to environmental management information systems. In *EnviroInfo 2010 Integration of Environmental Information in Europe*. 2010.

[101] M. Streicher-Porte, R. Widmer, A. Jain, H.P Bader, R. Scheidegger, and S. Kytzia. Key drivers of e-waste recycling system: Assessing and modeling e-waste processing in the informal sector in Delhi. *Environmental Impact Assessment Review*, 25(2005):472–491, 2005.

[102] C.R. Binder and H.J. Mosler. Waste-resource flows of short-lived goods in households in Santiago de Cuba. *Resources Conservation and Reycling*, 51(2007):265–283, 2007.

[103] R. Hischier, P. Wager, and J. Gauglhofer. Does WEEE recycling make sense from an environmental perspective? the environmental impacts of the swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE). *Environmental Impact Assessment Review*, 25(2005):525–539, 2005.

[104] J. Huisman and L.N. Stevels. Eco-efficiency of take-back and recycling, a comprehensive approach. *IEEE Transactions on Electronics Packaging Manufacturing*, 29(2):83–90, 2006.

[105] M.A. Reuter, A. van Schaik, O. Ignatenko, and G.J. de Haan. Fundamental limits for the recycling of end-of-life vehicles. *Minerals Engineering*, 19(2006):433–449, 2006.

[106] M. Oguchi, H. Sakanakura, A. Terazono, and H. Takigami. Fate of metals contained in waste electrical and electronic equipment in municipal waste treatment process. *Waste Management*, 32(1):96–103, 2012.

[107] J.R. Gregory, M.C. Nadeau, and R.E. Kirchain. Evaluating the economic viability of a material recovery syste: the case of cathode ray tube glass. *Environmental Science and Technology*, 43(24):9245–9251, 2009.

[108] X. Liu, M. Tanaka, and Y. Matsui. Generation amount prediction and material flow analysis of electronic waste: A case study in Beijing, China. *Waste Management Resources*, 24(5):434–45, 2009.

[109] J. Yu, E. Williams, M. Ju, and Y. Yang. Forecasting global generation of obsolete personal computers. *Environmental Science and Technology*, 44(9):3232–3237, 2010.

[110] J.B. Dahmus and T.G. Gutowski. What gets recycled: An information theory based model of product recycling. *Environmental Science and Technology*, 41:7543–7550, 2007.

[111] J.R. Gregory and R.E. Kirchain. A framework for evaluating the economic performance of recycling systems: A case study of north american electronics recycling systems. *Environmental Science and Technology*, 42(18):6800–6808, 2008.

[112] S. Fredholm. Evaluating electronic waste recycling systems: The influence of physical architecture on system performance. Master's thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2008.

[113] M.R. Galbreth. *Managing condition variablility in remanufacturing*. PhD thesis, Vanderbilt University, Nashville, Tennessee, 2006.

[114] V.D.R. Guide and V. Jayaraman. Product acquisition management: Current industry practice and a proposed framework. *International Journal of Production Research*, 38(16):3779–3800, 2000.

[115] G. Gaustad, E. Olivetti, and R. Kirchain. Toward sustainable material usage: evaluating the importance of market motivated agency in modeling material flows. *Environmental Science and Technology*, 45(9):4110–4117, 2011.

[116] J. Powell. Abandoned warehouses full of crts found in several states. *Resource Recycling*.

[117] A.S.G. Andrae and O. Andersen. Life cycle assessments of consumer electronics - are they consistent? *International Journal of Life Cycle Assessment*, 15:827–836, 2010.

[118] R. Kahhat, S. Poduri, and E. Williams. Bill of attributes in life cycle modeling of laptop computers: Results and trends from disassembly studies. Technical report, The Sustainability Consortium, 2011.

[119] BestBuy online retailer. Available from `bestbuy.com` Accessed August 3, 2013.

[120] R. Entner. International comparisons: The handset replacement cycle, 2011. Available from `http://mobilefuture.org/resources/international-comparisons-the-handset-replacement-cycle-2/`, Accessed November, 2013.

[121] N. Diaz-Elsayed. *Development of energy models for production systems and processes to inform environmentally benign decision-making*. PhD thesis, University of California, Berkeley, Berkeley, California, 2013.

[122] National Weather Service of the National Oceanic and Atmospheric Administration. Regional climate maps-USA. Available from `http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/regional_monitoring/usa.shtml` Accessed November, 2013.

[123] Federal Trade Commission. Guides for the use of environmental marketing claims. CFR 260.7. In *Federal Register*, volume 77. 2012.

[124] J. Atlee and R. Kirchain. Operational sustainability metrics assessing metric effectiveness in the context of electronics-recycling systems. *Environmental Science and Technology*, 40:4506–4513, 2006.

[125] F. Mathieux, D. Froelich, and P. Moszkowicz. Development of recovery indicators to be used during product design process: methods, potentialities and limits. In *Proceedings EcoDesign2011: Environmentally Conscious Design and Inverse Manufacturing*, pages 281–286. 2001.

[126] E. Olivetti, J. Gregory, and R. Kirchain. Original equipment manufacturer end-of-life equipment collection metrics. In *IEEE International Symposium on Electronics and the Environment*. Institute of Electrical and Electronics Engineers, 2008.

[127] G. Villalba, M. Seggara, A.I. Fernández, J.M. Chimenos, and F. Espiella. A proposal for quantifying the recycalbility of materials. *Resources, Conversvation and Recycling*, 37(1):39–53, 2002.

[128] G. Villalba, M. Seggara, J.M. Chimenos, and F. Espiella. Using the recyclability index of materials as a tool for design for disassembly. *Ecological Economics*, 50(2004):195–200, 2004.

[129] J. Dahmus, S. Fredholm, E. Olivetti, J. Gregory, and R. Kirchian. Modeling the economic and environmental performance of recyclign systems. In *IEEE International Symposium on Electronics and the Environment*. Institute of Electrical and Electronics Engineers, 2008.

[130] Electronic Product Environmental Assessment Tool (EPEAT). Part of the IEEE 1680 standards. EPEAT is managed by the Green Electronics Council, 2010.

[131] International Electrotechnical Commission. IEC/TR 62635 - Guidelines for end-of-life information provided by manufacturers and recyclers and for recyclability rate calculation of electrical and electronic equipment, 2012.

[132] International Standards Organization. ISO 22628:2002, Road vehicles - Recyclability and recoverability - Calculation method, 2012.

[133] A. van Schaik and M.A. Reuter. The time-varying factors influencing the recycling rate of products. *Resources, Conservation and Recycling*, 40(4):301–328, 2004.

[134] American Plastics Council. Plastics from residential electronics recycling: Report, 2000. A summary report from the electrical and electronics group of the American Plastics Council.

[135] M.B.G. Castro, J.A.M. Remmerswaal, M.A. Reuter, and U.J.M Boin. A thermodynamic approach to the compatibility of materials combinations for recycling. *Resources Conservation and Recycling*, 43(2004):1–19, 2004.

[136] E. Olivetti and R. Kirchain. A product attribute to impact algorithm to streamline it carbon footprinting. In *Design for Innovative Value Towards a Sustainable Society*, pages 747–749. 2012.

[137] M. Buchert, A. Manhart, D. Bleher, and D. Pingel. Recycling critical raw materials from waste electronic equipment, 2012. Commissioned by the North Rhine-Westphalia State Agency for Nature, Environment and Consumer Poretection.

[138] S. Mohite. *Disassembly analysis, material composition analysis and environmental impact assessment of computer disk drives.* PhD thesis, Texas Tech University, Lubbock, Texas, 2005.

[139] S. Boyd. *Life-cycle assessment of semiconductors.* PhD thesis, University of California, Berkeley, California, Berkeley, 2009.

[140] H. Kara, A. Chapman, T. Crichton, P. Willis, N. Morley, and K. Deegan. Lanthanide resources and alternatives, 2010. Oakdene Hollins Research and Consulting, United Kingdom Government Department for Transport.

[141] M. Zgola. A triage approach to streamline environmental footprinting: A case study for liquid crystal displays. Master's thesis, Massachusetts Institute of Technology, Cambridge, MA, 2011.

[142] A. C. Kasper, A. M. Bernardes, and H. M. Veit. Characterization and recovery of polymers from mobile phone scrap. *Waste Management and Research*, 29(7):714–726, 2012.

[143] Briefing Paper Factbase. Technical report, 2011 Battery Summit, 2011.

[144] Scrap material prices. Available from `www.metalprices.com` Accessed September, 2013.

[145] Scrap material prices. Available from `www.scrapindex.com` Accessed September, 2013.

[146] Scrap material prices. Available from `www.scrapmonster.com` Accessed September, 2013.

[147] Scrap material prices. Available from `www.mineralprices.com` Accessed September, 2013.

[148] H. Hatayama, H. Yamada, I. Daigo, Y. Matsuno, and Y. Adachi. Dynamic substance flow analysis of aluminum and its alloying elements. *Materials Transactions*, 48(9):2518–2524, 2007.

[149] Y. Hiroshige, T. Nishi, and T. Ohashi. Recyclability evaluation method (REM) and its applications. In *EcoDesign2011: Environmentally Conscious Design and Inverse Manufacturing*, pages 315–320. 2001.

[150] M.B. Castro, J.A.M. Remmerswaal, J.C. Brezet, A. van Schaik, and M.A. Reuter. A simulation model of the comminution-liberation of reycling streams: Relationships between product design and the liberation of materials during reycling. *International Journal of Mineral Porcess*, 75(3-4):255–281, 2005.

[151] M.A. Reuter and A. van Schaik. Opportunities and limits of WEEE recycling - Recommendations to product design from a reyclers perspective. In *Proceedings of Electronics Goes Green 2012+*. 2012.

[152] M. F. Ashby. *Materials and the Environment - Eco-informed Material Choice*. Elsevier, Oxford, UK, 2013.

[153] Plastics Europe. Plastics - the Facts 2012 - An analysis of european plastics production, demand and waste data for 2011.

[154] A. Schmidt and K. Strömberg. Recycling in LCA - system expansion in Danish, 2007. Danish Environmental Protection Agency.

[155] N. Frees. Environmental advantages and disadvantages of plastic recycling in Danish, 2002. Danish Environmental Protection Agency.

[156] T. Astrup, T. Fruergaard, and T.H. Christensen. Recycling of plastic: accounting of greenhouse gases and global warming contributions. *Waste Management and Resources*, 2009.

[157] G. Dodbiba, K. Takahashi, J. Sadaki, and T. Fujita. The recycling of plastic wastes from discarded tv sets: Comparing energy recovery with mechanical recycling in the context of life cycle assessment. *Journal of Cleaner Production*, 16(4):458–470, 2008.

[158] European Computer Manufacturers Association (ECMA) International. Environmental design considerations for ICT and CE products, 2008. Available from `http://www.ecma-international.org/publications/files/ECMA-ST/Ecma-341.pdf`, Accessed November, 2013.

[159] H.E. Tseng, C.C. Chang, and C.J. Cheng. Disassembly-oriented assessment methodology for product modularity. *International Journal of Production Research*, 48(14):4297–4320, 2010.

[160] T.E. Graedel and J.A. Howard-Grenville. *Greening the industrial facility: perspectives, approaches, and tools*. Springer Verlag, 2005.

[161] L. Hui Mien, R. Gay, L. Wen Feng, and S. Bin. The framework of information sharing in end-of-life for sustainable product development. In *IEEE International Conference on Industrial Informatics*, pages 73–78. 2006.