Economics of End-of-Life Materials Recovery – A Study of Small Appliances and Computer Devices in Portugal

by
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B.S. Environmental Engineering, Worcester Polytechnic Institute (2013)

Submitted to the Institute for Data, Systems, and Society in partial fulfillment of
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ABSTRACT

The challenges brought on by the increasing complexity of electronic products, and the criticality of the materials these devices contain, present an opportunity for maximizing the economic and societal benefits derived from recovery and recycling. Small appliances and computer devices (SACD), including mobile phones, contain significant amounts of precious metals including gold and platinum, the present value of which should serve as a key economic driver for many recycling decisions. However, a detailed analysis is required to estimate the economic value that is unrealized by incomplete recovery of these and other materials, and to ascertain how such value could be reinvested to improve recovery processes. I present a dynamic product flow analysis (dPFA) for SACD throughout Portugal, a European Union member, including annual data detailing product sales and industrial-scale preprocessing data for recovery of specific materials from devices. I employ preprocessing facility and metals pricing data to identify losses, and develop an economic framework around the value of recycling including uncertainty. I show that significant economic losses occur during preprocessing (over $70M USD unrecovered in computers and mobile phones, 2006-2014) due to operations that fail to target high value materials, and characterize preprocessing operations according to material recovery and total costs. Finally, I present market level, operational, and policy recommendations aimed at capturing the unrecovered economic value identified in the Portuguese WEEE recycling system.

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I would also like to thank several individuals who assisted with various portions of this project over the past two years. T. Reed Miller, a Research Specialist at MIT, was central to the development of the dynamic product flow analysis. Jae Hyun Kim, an undergraduate at MIT in Course 3, performed the SEM/EDS work for the materials characterization portion of this project. Several employees at ALS Environmental in Tucson, AZ performed the ICP-OES analysis and were responsive and helpful throughout the project.

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Lastly, but certainly not least, I would like to say thank you to all of my friends and family who have supported me throughout my time at MIT, especially my brother, my parents, and my wife, who has been my rock throughout this process.

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Chapter 1: Introduction

Portions of this chapter are based on a 2016 publication by Ford et al. in Environmental Science & Technology, titled Economics of End-of-Life Materials Recovery – A Study of Small Appliances and Computer Devices in Portugal.[1]

1.1. Motivation

The consumer electronics industry has seen increased adoption rates, device diversification and decreased product lifetimes all resulting in significant product proliferation. Effective disposal of these devices, or management of Waste Electrical and Electronic Equipment (WEEE), has long been a focus of environmental management policy, due primarily to concerns around human health and ecosystem impact.[2-5] More recently, high demand for, and fluctuating supplies of, metals within such devices, the mining and primary processing of which includes additional environmental and geopolitical impact,[6] has renewed interest in the overall flow of these devices at end-of-life. These ongoing efforts aim to discover where materials come to rest within the so-called "urban mine", and to quantify how the embedded value in particular electronic products might drive material recovery.[7-9]

Despite the potential value present within these devices, collection rates for products and materials recovery remains low. Limited materials recovery stems primarily from the lack of actionable information within the recovery network. Simply put, it is often not clear *a priori* whether the recovery of existing materials from used electronic devices is economically competitive with procurement of "new" materials. The composition of the generated waste stream is dynamic and offset in time and geographic location from the sale of the device, such that the available materials for recovery are not considered at the point of recycling system design. More specifically, there are several processes upstream of the actual metal recovery and refinement processes (generally termed preprocessing), which dictate final process yields and resulting value.[10, 11] These combined factors can result in scenarios that are intended to promote effective recycling – e.g., legislated recovery targets, grouping of printed circuit board (PCB) levels upon collection, and recovery facility design – that do not align well with maximizing the value recovered. Even when the amounts and locations of materials within devices are known, it may not be clear whether and to whom the recycling of such materials at end-of-life presents value.[12]

In the European Union (EU), an extended producer responsibility scheme has been implemented for WEEE in an attempt to meet the previously mentioned legal recovery targets. However, a lack of granularity with regard to the evolving composition of devices over time, the increase in the supply of secondary materials generated by recovery targets without a clear understanding of the downstream demand, and the inefficient recovery of potentially valuable and/or critical materials has led to a misaligned optimization of the recycling system around mass based, rather than value based metrics.

1.2. Research Questions

The economic and material losses incurred in recycling as a result of inefficient operational schemes and a lack of granular materials characterization data at the preprocessing level has led to the following research questions:

- **Can the economics of the recycling of small appliances and computer devices drive increased materials recovery?**
- **What market level and operational dynamics must be leveraged to capture the value of small appliances and computer devices at the end-of-life given material composition information?**

Through dynamic product and material flow analysis, coupled with detailed case data for preprocessing facility performance, this work establishes an economic framework for the value of recycling. Here I focus on the country of Portugal as a data-rich and well-defined recovery network that employs advanced technologies within its facilities, and consider the system from the point of sale to the preprocessing step for a subset of products termed small appliances and computer devices (SACD). This categorization is my own term. It is consistent with the classification of recovery data collected in Portugal that includes small consumer products and industrial equipment that share electronic components including PCBs, and to exclude large products (including large household appliances and photovoltaic panels). By considering the perspective of the preprocessor facilities within a particular country, I identify losses in material recovery that could be reinvested in the system in that region. Even though a preprocessor does not typically have visibility into the materials-level recovery potential, the decisions at this stage limit maximum efficiency of downstream recovery and refinement steps that define the secondary materials market.

1.3. Overview

This thesis will be organized into the following sections:

- Background information on product and material flows, including the Portuguese framework within which this work will focus
- A characterization of the Portuguese WEEE recycling system through the use of a dynamic product flow analysis (dPFA)
- An analysis of potential methodologies and frameworks that could be utilized to leverage the operational inefficiencies characterized in the dPFA to bring about system wide improvements

Chapter 2: Background

Portions of this chapter are based on a 2016 publication by Ford et al. in Environmental Science & Technology, titled Economics of End-of-Life Materials Recovery – A Study of Small Appliances and Computer Devices in Portugal.[1]

2.1. Urban Mine Characterization

Understanding overall material and product flows within the current recycling infrastructure informs criticality assessments, access to the urban mine, legislative compliance, and design for materials or product targeting. The foci of these studies have been twofold, to understand the composition and flow of products and materials in the urban mine, and to analyze the losses during the preprocessing and recovery stages of recycling. This section will focus on the urban mine, and the following two on the flows of materials and losses during preprocessing.

According to Georgiadis and Besiou, the total amount of WEEE to enter the urban mine was projected to rise by 16-28% annually.[13] Several studies have quantified the materials contained in a variety of electronic devices that make up the urban mine, including but not limited to computers,[8, 14] phones,[15-20] and printers.[8] These studies formed the foundation of the material composition data used in the dPFA, however, there is still a need for a more detailed accounting of not only what is contained in the devices, but where the key materials are found within the devices. Detailed insights into which materials are found in which portion of the device, such as the speaker assembly in a mobile phone versus a PCB in a mobile phone, would allow preprocessors to more readily determine how to treat that product at the end-of-life, thereby increasing the potential for decreased environmental impacts and increased economic recovery.

In 2015, Chancerel et al. examined the quantities of critical metals in consumer equipment, potential pathways for the removal of those metals, and the potential economic impacts of recovery processes.[21] The authors were consistent with other studies in identifying gold as the economic driver of WEEE recycling. Additionally, a comparison between the mass and economic value contained in mobile phones was carried out, showing that, for the materials analyzed, cobalt had the greatest mass. Other materials analyzed included indium, gallium, light rare earth elements (REE), heavy REE, tantalum, tin, palladium, and silver. Figure 1 shows the results of that analysis. This work was an important contribution in that the authors performed a detailed accounting of the mass of a material versus its economic value, as seen in Figure 1. Additionally, the types of materials analyzed include those that are known to be economically advantageous to recover, such as gold, as well as those that are typically lost within the current recycling system in the EU, such as light and heavy rare earth elements (REE). The analysis that I performed, and will be expanded upon below, will take this a step further, defining the mass and economic losses within a specific recycling system, and arguing for an optimization of the system around economic recoveries rather than mass alone.

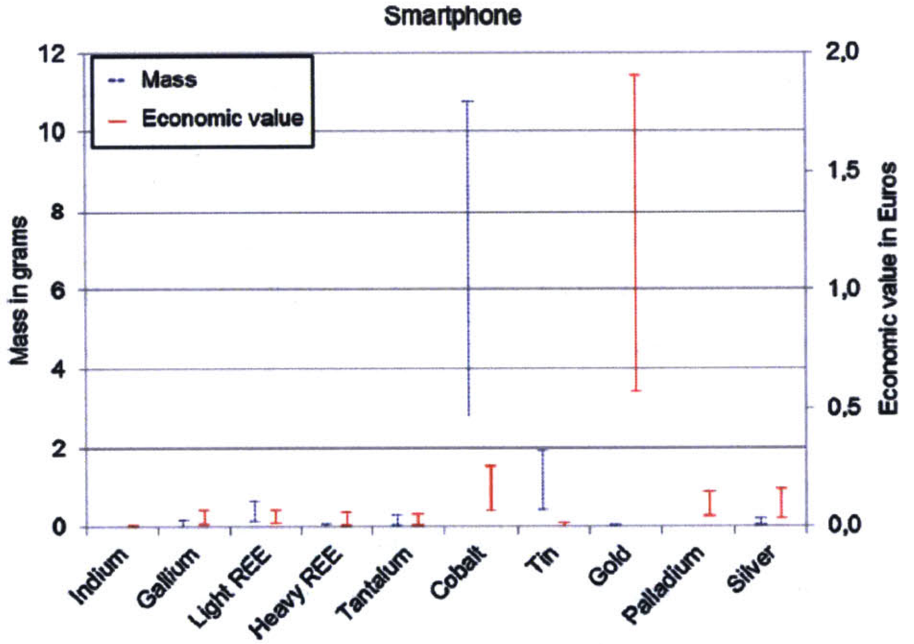


Figure 1. Average ranges of the mass and economic value of the target metals embedded in a smartphone sold in Germany in 2012 (Figure reproduced from Chancerel et al. 2015).[21]

2.2. Product and Material Flows

Material flow analysis (MFA) has been applied as a methodology for understanding a plethora of complex material systems in the past. For the purposes of this work, I will refer to the analysis completed as a product flow analysis (PFA) because the flow of materials throughout the recycling supply chain is dependent on the flow of the products they are found in. Muller et al. compiled a review of dynamic MFA methodologies in 2014, and used several terms to characterize their overarching processes. The terms that are central to this work are: static versus dynamic, top-down versus bottom-up, and prospective versus retrospective. This PFA is dynamic because it captures an analysis over time, allowing me to observe trends in the data rather than a single snapshot. This PFA represents a top-down approach because the stocks of materials found within the system boundary at any given time are defined by the difference between the inflows (i.e., product sales) and outflows (i.e., collection) from the system. Finally, this PFA is retrospective because it involved the analysis of historical data in order to define the stocks and flows within the system.[22]

More specifically, this analysis is modeled after work completed by several researchers in the areas of substance and material flows. Navazo et al. used a material flow analysis to study the material and energy impacts of the recovery process for mobile phone materials.[23] This research provided insights into the composition of mobile phones, the use of manual dismantling and mechanical shredding during preprocessing, and the importance of gold as the economic driver of mobile phone recycling. Chancerel et al. used a substance flow analysis (SFA) to explore the flow of precious metals through the preprocessing stage of recycling.[24, 25] A SFA is a specific type of MFA, where elements are tracked within a given set of system boundaries. This research provided insights into the importance of analyzing the preprocessing stage of recycling from a granular materials level.[24]

Several other researchers have employed varying sets of tools, including system dynamics, agent-based modeling, environmental impact assessments, and life cycle assessments to explore the recycling system and its impacts.[3, 13, 26-30] Each of these studies was used to inform the analysis carried out in this work, either through the types of devices and/or recycling processes studied, or the methodology employed. The methodology that I followed in developing the dPFA used in this work follows a similar overall structure to those found in the literature, but expands upon what is available by using a robust data set focused on preprocessing to couple material mass and economic flows, as explained in Chapter 3.

2.3. Recycling System Architecture and Performance

Researchers have investigated system architecture and performance to assess key material losses, legislative costs, and the environmental and economic health of the system. Meskers et al. provided an overview of the recycling and recovery process for WEEE and batteries, which included an analysis of which materials drive the economic argument for recycling, and the barriers to improved best practices.[19] Hageluken discussed the economic, environmental, and resource recovery opportunities surrounding the processing of electronic waste, finding that value-based metrics are needed to supplement the weight-based metrics specified in the WEEE Directive. The author also addressed tradeoffs between manual and mechanical preprocessing, and challenges such as material comingling and process capital costs.[31]

Two studies described earlier by Navazo and Chancerel were also instrumental in characterizing the performance of recycling systems. In 2014, Navazo et al. detailed the material losses experienced during the processing and recovery stages of electronic waste recycling.[23] Although the MFA was applied to the recycling process downstream of preprocessing, it was useful in understanding the treatment steps that occur outside of the system boundary in Portugal. In 2009, Chancerel et al. analyzed the flow of one tonne of information technology and telecommunications equipment (WEEE category 3) through the preprocessing stages of recycling, focusing on gold, silver, palladium and platinum. The authors provided examples for the losses of precious metals at the pre-sorting, manual sorting and depollution, pre-shredding and manual sorting, and shredding and automated sorting stages of preprocessing and recommendations for system improvements.[24]

In the 2015 Chancerel et al. study researchers also recommended recycling options for various types of products, as shown in Figure 2. In Figure 2, the left most set of boxes includes the types of devices analyzed, which are similar to the categories used in my analysis. The main exceptions are that they separate smartphones and other mobile phones, group mobile phones with other small high-grade equipment, and include a category for LCD televisions with CCFL and LED backlighting. The set of operations in the middle, labeled as "Pre-processing," include the steps required to remove the components that the authors deem to be the most important. Finally, the operations listed on the right, labeled "Recovery," include the downstream operations that depend on the preprocessing step.

The analysis that I present here will focus on the preprocessing stage, and specifically the removal of the PCBs. Therefore, I feel as though the authors should have included a "further research required for this route" arrow going from the smartphones and mobile phones categories to the "Removal of the PCB" step of preprocessing. Due to the need to remove the PCB and the battery during the de-pollution stage of preprocessing, it may not be possible to send the entire device to downstream recovery operators without this step. Overall, the authors found that, using current technologies, the removal of certain materials, such as indium, gallium, rare earth elements (REE), and tantalum, was not yet economically favorable. However, they also identify the need for additional research to quantify the total potential mass of these materials that reaches the end-of-life in WEEE in order to lay the groundwork for increased materials recovery.[21]

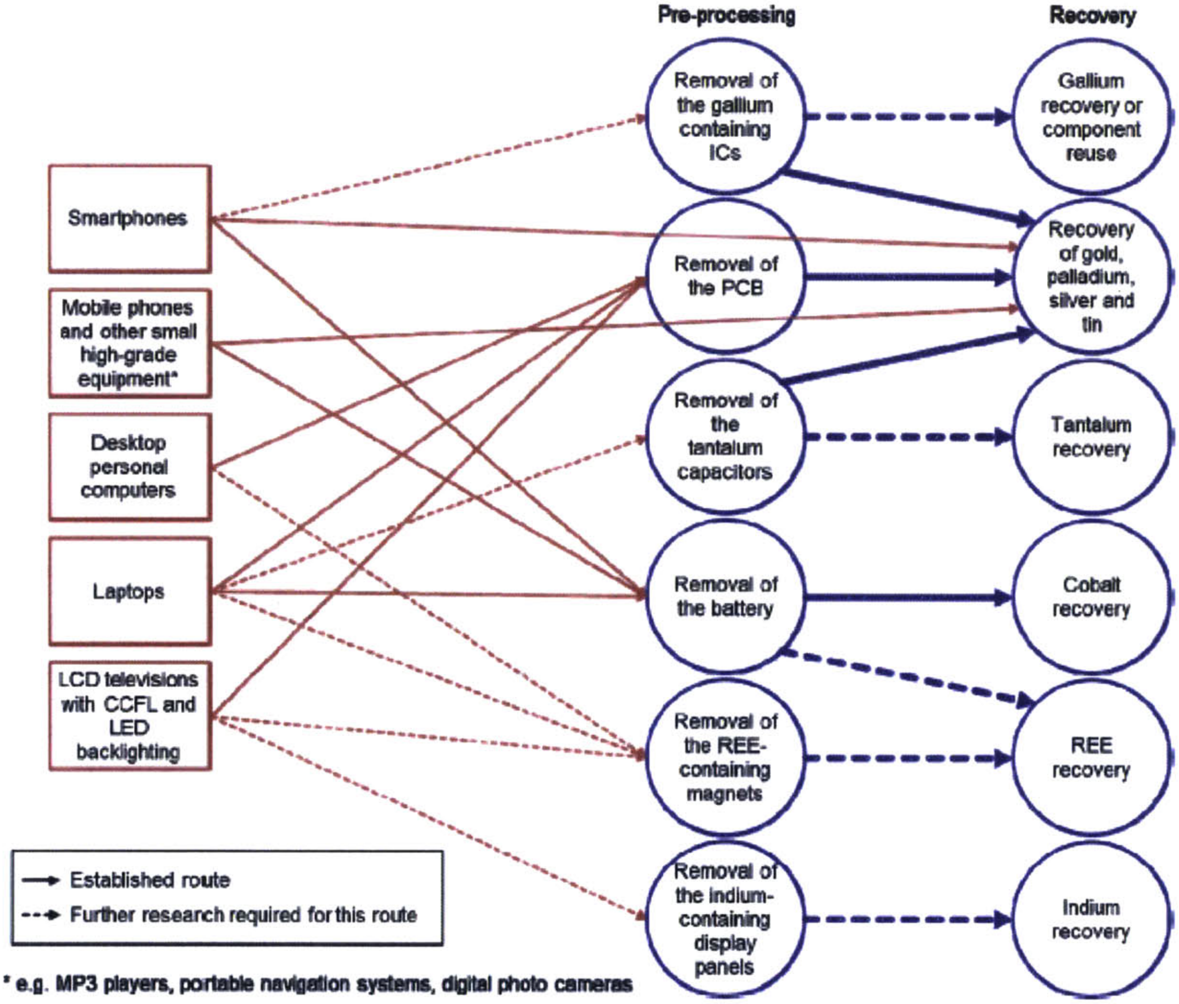


Figure 2. Recommended recycling routes for information and communications technology (ICT) and consumer equipment (CE) (Figure reproduced from Chancerel et al. 2015).[21]

Several other studies have analyzed the preprocessing stage of recycling and quantified key material and economic losses.[20, 32, 33] Further, impact assessments carried out by the United Kingdom's Department for Business, Innovation, and Skills (BIS), in conjunction with others, studied the economic costs and benefits of the most recent WEEE Directive, listing impacts for businesses, government, and recyclers.[34]

2.4. WEEE Directive

The WEEE Directive was first established in 2003 (2002/96/EC), but was recast in 2012 as 2012/19/EU. This most recent version went into full effect in 2014 and was transposed in Portugal through Decree-Law No. 67/2014.[35] The overall goals of this directive are to minimize the mass of WEEE entering landfills each year, to protect environmental and human health, to increase the mass of commodity materials reused each year, and to hold producers responsible for the devices that they put on the market.[34, 36] More specifically, the target collection rate of end-of-life WEEE is 45% from 2016 – 2019 and 65% from 2019 going forward. The collection rates are measured by mass, and not by numbers of devices or the economic value of a given device.[36] Downstream of collection, targets are also established for the recovery and recycling of the waste materials. Recovery is defined as any operation in which waste serves "a useful purpose by replacing other materials which would otherwise have been used to fulfill a particular function." Recycling is defined as "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes."[37] Starting in August 2015, recovery targets range from 75% to 85% and recycling targets range from 55% to 80% depending on the category of waste in question.[36] The recycling process can vary by device and facility, but the directive mandates that printed circuit boards with surface areas greater than 10 square centimeters must be removed. However, this is only the case for "separately collected WEEE," which is defined as "collection where a waste stream is kept separately by type and nature so as to facilitate a specific treatment."[37] Although it was reported in 2008 that 65% of WEEE put on the market was collected separately, it is widely believed that much of this is still improperly handled downstream of the collection process.[36] This can lead to large losses of the valuable materials detailed above, attributing to losses of capital and secondary resources, and negative environmental impacts.

2.5. Battery Directive

The Battery Directive (2006/66/EC) went into effect in 2008, and mandates that all batteries be removed from devices prior to being recycled. It also requires that all member states achieve a collection rate of at least 45% by 26 September 2016. Further downstream of collection, this directive requires that recycling processes for lead-acid, nickel-cadmium, and other batteries and accumulators recover 65%, 75%, and 50% by weight, respectively.[38] These requirements have been put in place to reduce the negative environmental impacts of materials within batteries, both in use and at end-of-life.[38] Batteries were not included in the PFA that I present in the sections that follow because of the additional steps required for their removal and safe treatment downstream. As downstream operators (beyond preprocessing) develop more effective and economical methods for recovering the key materials in batteries, it may be important for future work to include the incorporation of the flow of batteries within the PFA.

2.6. Producer Responsibility Organizations

The waste directives that have been established in the EU, including the WEEE and Battery Directives, laid the groundwork for the implementation of widespread extended producer responsibility (EPR) schemes. An overview of the EPR scheme for WEEE in Portugal can be found in Figure 3. In Figure 3, there are three major types of flows, mass flows, monetary flows, and information flows, as denoted by the arrows. The work presented in the sections that follow focused on the inefficiencies of the preprocessing plants and the opportunities for improvement that are inherent in the monetary and information flows between the preprocessing plants and the Producer Responsibility Organizations (PROs). Due to this, the mass flows to downstream operators that perform recycling, mass recovery, energy recovery, landfilling, or incineration were not included in the scope of this work. The paragraphs that follow will detail each of the key organizations that participate in the WEEE EPR scheme in Portugal.

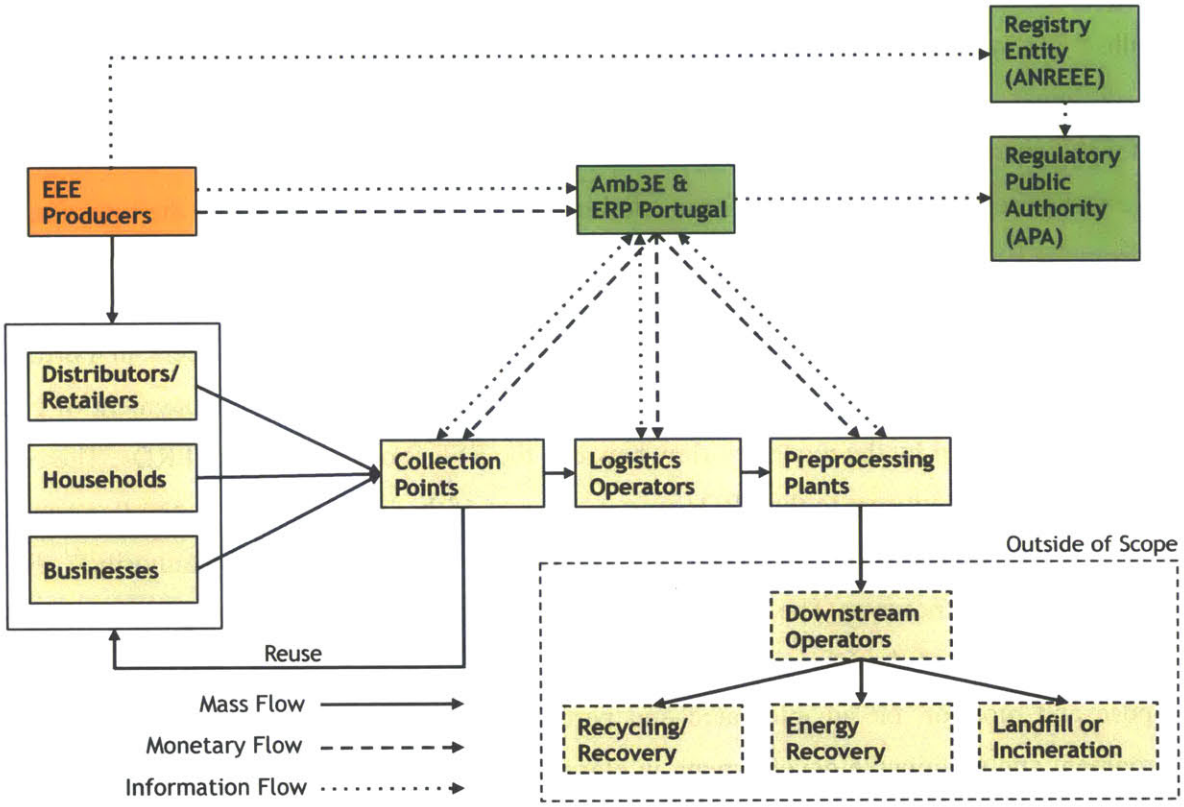


Figure 3. Overview of Portuguese WEEE recycling network (Adapted and reproduced from Santos 2013)[39]

In Portugal and other EU nations, the companies that put the devices on the market are responsible for ensuring that they are collected and recycled in accordance with the applicable regulations, which in this case are the WEEE and Battery Directives. When a device is placed on the market, it will typically be purchased by a retailer, business, or household. At the end of its first life, the product can either be stored, discarded (not shown in Figure 3), or collected. If it is collected, it can be reused if it is still in working condition, or it can be transported to a preprocessing plant via a series of logistics operators. It is important to note that there is a potential for material losses at each of these steps, but this is not shown in Figure 3.

In order to track the mass flows throughout the country, there are a series of information flows between each of the key players. First, producers of electrical and electronic equipment are required to register with the Associação Nacional Para O Registo De Equipamentos Eléctricos E Electrónicos (ANREEE), which was licensed in March 2006. ANREEE's mission is "to assure, organize, and keep the mandatory register of EEE (DL 230/2004, altered by DL 132/2010 of 17th

December) and B&A (Batteries and Accumulators, DL 6/2009 of 6th January) producers. This will allow the monitoring and financial control of their obligations and objectives laid down in these diplomas and in other relevant legislation." Therefore, ANREEE's major focus is to monitor the quantities of products placed on the market by producers and the product life cycles in an effort to reduce the overall environmental impact.[40] This is represented by the information flow from the EEE Producers to ANREEE.

Due to the complex nature of WEEE recycling schemes, many of the producers in Portugal delegate the responsibility for the management of WEEE to PROs through the payment of eco-values, as represented by the monetary flow between the EEE Producers and the PROs. The eco-values paid by the producers to the PROs are set as a part of the license issued by the Portuguese Environment Agency, which is shown in Figure 3 as the Regulatory Public Authority.[41] This authority, which is known as The Portuguese Environment Agency (APA), and falls within the Portuguese Ministry of the Environment, Territory Management and Energy, has the mission to "propose and monitor, on an integrated and participated manner, the public policies for the environment and sustainable development, in close cooperation with other sectorial policies and public and private entities."[42] As seen in Figure 3, information is shared between the PROs, ANREEE, and the APA.

Once the eco-values are set by the APA in the PROs' licenses, The PROs assume the responsibility for ensuring the collection, recycling, and recovery targets of the WEEE Directive are met.[41] This includes the allocation of the eco-values to collection points, logistical operators, and preprocessing plants based on the mass of WEEE handled at each stage and the difference between the cost to process the WEEE in accordance with the WEEE and Battery Directives, and any revenue derived from its treatment. The PROs also work with the various treatment operators within Portugal in an attempt to ensure that they are following industry best practices and having the smallest environmental impact possible.

It is important to note to note that, while this diagram shows the EPR scheme as a snapshot in time, the mass flows are constantly changing based on the type and quality of products being put on the market. The evolving composition of the waste stream, caused by changes in device composition and the types of devices being bought and sold, can have downstream impacts on the revenues that can be derived from preprocessed devices. The dPFA presented in the sections that follow accounts for the changing composition of devices over time as allowed by the available data.

Portugal has two PROs for WEEE, Associação Portuguesa de Gestão de Resíduos (Amb3E) and European Recycling Platform Portugal (ERP Portugal), that organize the collection and treatment of WEEE, and have been licensed by the government since 2006.[39, 43] Since 2006, operators in Portugal have complied with the recycling and recovery targets set in the WEEE Directive, which was updated in 2012 as 2012/19/EU and legislates the treatment of electronic waste.[44, 45] The following two sections will describe each of the PROs in greater detail.

2.6.1. Amb3E

Amb3E is the larger of the two PROs in Portugal. The Ministry for Environment, Spatial Planning, and Regional Development and The Ministry of Economy and Innovation granted Amb3E its first license by Joint Dispatch No. 354/2006 in 2006. Since that time, its license has been renewed through Dispatch No. 1516/2012.[46-48] According to its most recent report, Amb3E manages the WEEE of approximately 1,200 producers, which put roughly 83,000 tonnes of WEEE on the market in 2013.[44, 46]

Figure 4 shows the number of producers reporting to Amb3E in 2012, 2013, and 2014. It is evident from the graph that the number of producers reporting to Amb3E has increased by approximately 10% from 2012 to 2014. This graph does not say anything about the quantity of products put on the market each year by these producers (which is shown in Figures 5 and 6), but rather, that there may be an increase in the diversity of products and brands being purchased in Portugal.

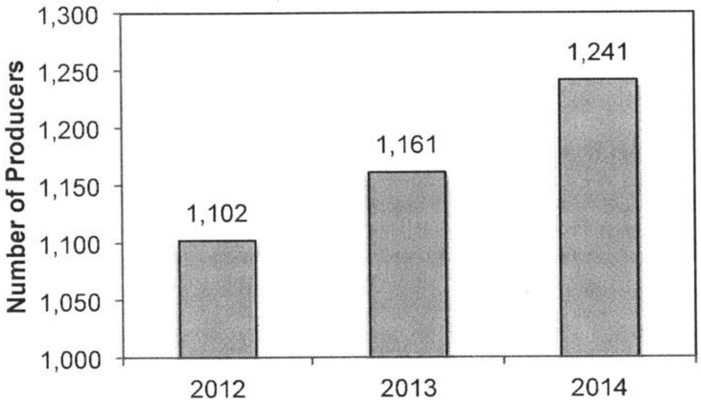


Figure 4. Number of producers reporting EEE put on the market to Amb3E (Adapted from Amb3E Relatorio de Actividades 2014[44])

Figures 5 and 6 show the progression of electrical and electronic equipment (EEE) declared to Amb3E by producers from 2006 – 2014 in tonnes and thousands of units.[44, 49, 50] Interestingly, the mass of EEE declared to Amb3E in 2014 was close to the mass declared eight years earlier in 2006. However, the number of units put on the market increased by approximately 50%. This points to the fact that many devices, including laptops and mobile phones, are more compact now than they were 10 years ago. The decreased size and weight of many products, coupled with an increase in complexity, makes it more difficult for recyclers to identify and remove key materials from WEEE during preprocessing.

Looking at the values within each of the graphs, it is interesting to note the similar trends found in each. The drop seen between 2008 and 2009 was likely due to the global financial crisis. There is an increase in both the tonnes and units declared to Amb3E in 2010, perhaps pointing to a small recovery, but another large decrease between 2010 and 2012. This decrease was most likely due in part to the economic downturn in Portugal that began in 2010.[51] Since 2012, both values have increased steadily, potentially pointing to a period of recovery for the sale of EEE.

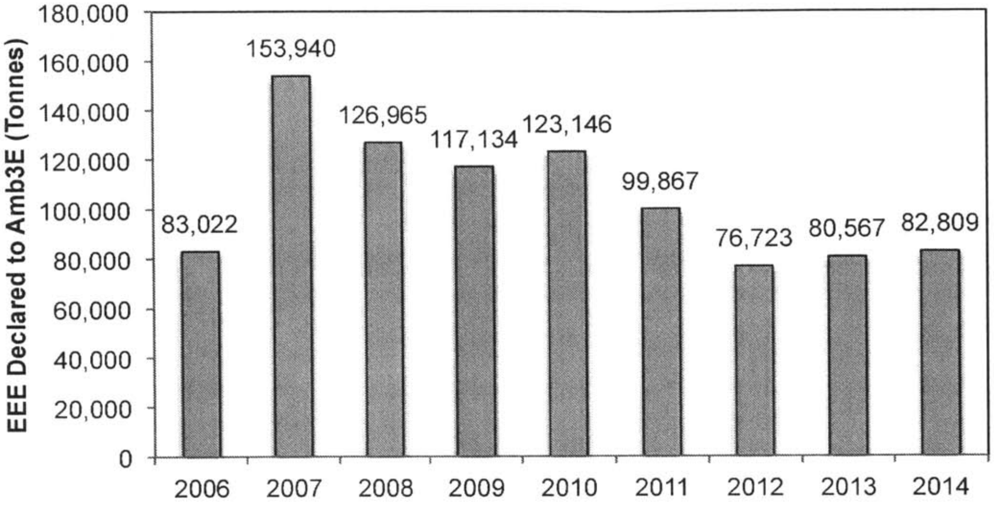


Figure 5. Tonnes of EEE declared to Amb3E by producers (Adapted from Amb3E Relatorio de Actividades 2014[44])

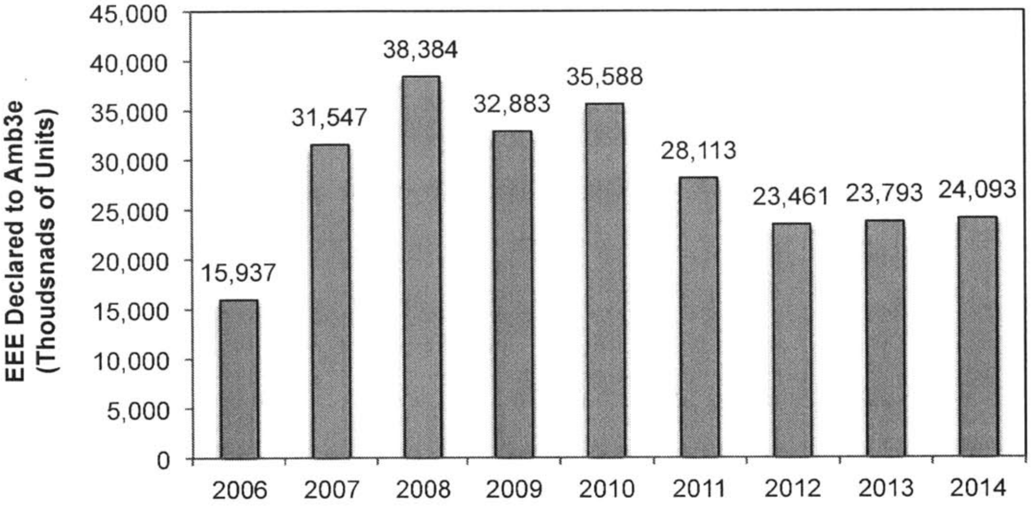


Figure 6. Thousands of Units declared to Amb3E by producers (Adapted from Amb3E Relatorio de Actividades 2014[44])

As described in the previous section, each producer pays an eco-value to Amb3E based on the type and quantity of waste put on the market in a given year. The fee structure is established by Dispatch No. 2103/2015, and is distributed by Amb3E for the collection, transportation, and processing of end-of-life products.[39, 52]

Amb3E participates in the European Association of Electrical and Electronic Waste Take Back Systems (WEEE Forum), a not-for-profit, EU wide sector association that conducts benchmarking analysis of the country-level performance of its members. In addition, the WEEE Forum makes it possible for PROs to work together towards the optimization of WEEE treatment processes and the reduction of environmental impact. In 2012, its 32 members reported the collection of approximately two million tonnes of WEEE.[53] The WEEE Forum is not included in Figure 3 because it is not a part of the legal framework that makes up the WEEE EPR scheme.

2.6.2. ERP Portugal

The Ministry for Environment, Spatial Planning, and Regional Development and The Ministry of Economy and Innovation granted ERP Portugal its first license by Joint Dispatch No. 353/2006 in 2006.[54, 55] According to its most recent reports, ERP Portugal manages the WEEE and B&A of approximately 530 producers, and has a network of roughly 1,650 collection points.[45, 54, 56] In 2013, its producers put approximately 45,000 tonnes of WEEE on the market.[45]

Figures 7 and 8 show the progression of producers that report to ERP Portugal and the increase in collection points from 2006-2014.[56] Overall, since 2006, the total number of producers reporting to ERP Portugal has more than doubled, and the number of collection points has increased thirtyfold. The added collection infrastructure has helped to facilitate an increase in the overall collection of WEEE, at the same time as the number of producers, and thereby the number of products reaching the end-of-life has also increased. Across these collection points, approximately 100,000 tonnes of WEEE was collected between 2006 and 2014.[56]

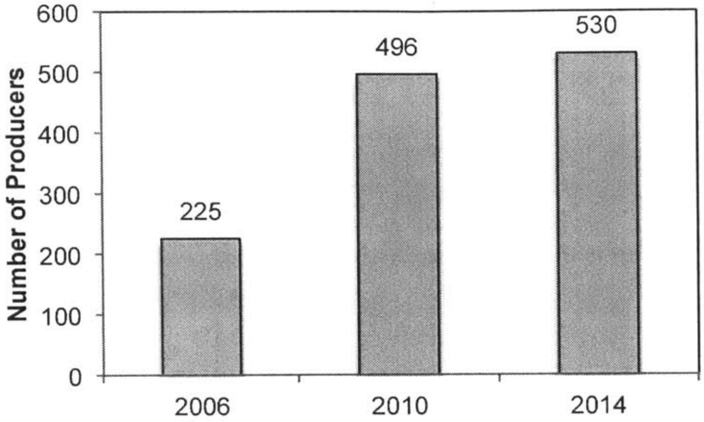


Figure 7. Number of producers reporting EEE (2006) and EEE and batteries and accumulators (2010 and 2014) put on the market to ERP Portugal (Adapted from *10 Years Promoting Competition in the Waste's Sector*[56])

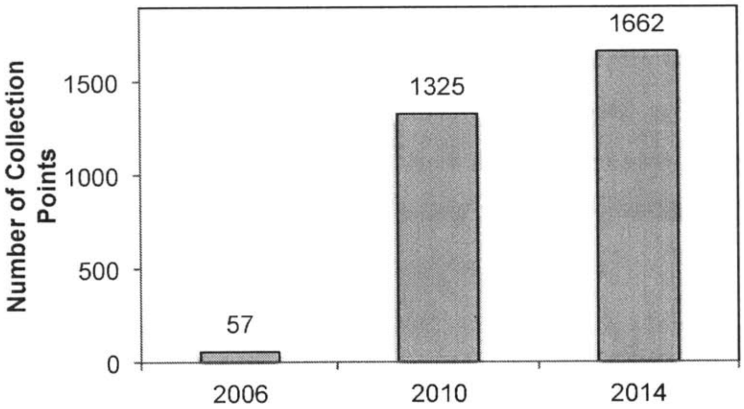


Figure 8. Number of ERP Portugal collection points (Note: Value for 2010 is approximate) (Adapted from *10 Years Promoting Competition in the Waste's Sector*[56])

Just as with Amb3E, each producer pays a fee to ERP Portugal based on the type and quantity of waste put on the market in a given year. The fee structure is established by Dispatch No. 2104/2015, and as seen above, is distributed by ERP Portugal for the collection, transportation, and preprocessing of end-of-life products.[39, 57] Figure 9 shows the breakdown of the payments made by ERP Portugal to operators at each of these stages of the recycling chain.[45] Due to the large number of collection points managed by ERP Portugal, the total cost for collection is approximately 3.5 times the cost of transportation and 26.5 times the cost of valorization, recycling, and treatment.

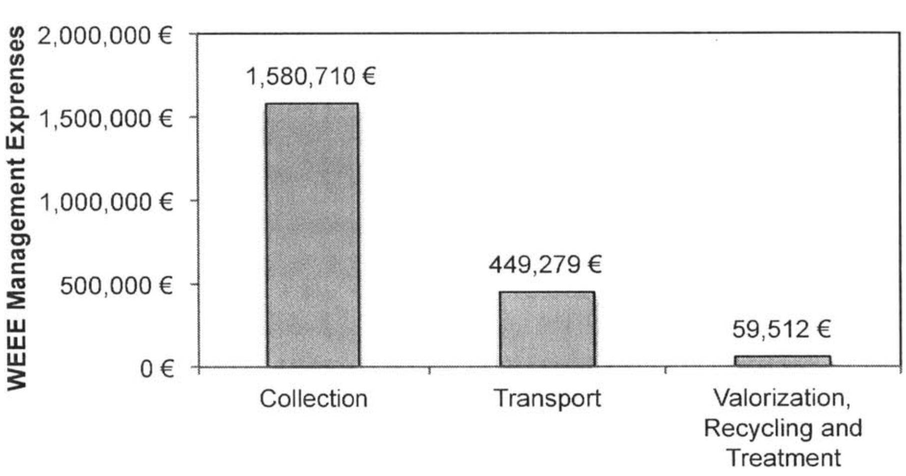


Figure 9. Breakdown of WEEE management expenses for ERP Portugal (Adapted from Relatório Anual de Actividades 2013[45])

Lastly, in contrast to Amb3E, which operates only in Portugal, ERP operates in 16 additional countries, including Austria, Denmark, Finland, France, Germany, Ireland, Israel, Italy, Norway, Poland, Slovakia, Spain, Sweden, The Netherlands, Turkey, and The United Kingdom. Across all of these territories, ERP manages the WEEE and B&A put on the market by approximately 2,600 producers.[54]

2.7. Summary and Outlook

In Chapter 2, I detailed how researchers have characterized the material composition of EEE and modeled the flow of devices through complex recycling systems. I also described the WEEE and Battery Directives, which form the regulatory imperative for the proper collection, handling, and treatment of WEEE. Lastly, I presented the Portuguese WEEE EPR scheme, and the two PROs, Amb3E and ERP Portugal, that are primarily responsible for ensuring that all legal requirements are met. Although this system has proven to be effective at ensuring that the minimum requirements of the WEEE and Battery Directives are met, I don't believe that it allows for the optimization of the system as a whole around the recovery of certain key materials. This means that, while the mass based metrics of the Directives are met, valuable materials, such as gold, can be lost.

In Chapter 3, I will apply the background information detailed above to the case of Portugal, using a dPFA to model the sales, generation, collection, and preprocessing stages of the recycling system. I will also use the data gathered on the material composition of devices and the value of the materials within them to characterize the material and economic losses within the recycling system, accounting for uncertainties throughout the dPFA. I will conclude the chapter by exploring ways in which this data can be used to inform future invests aimed at optimizing the recycling system around the recovery of key materials.

Chapter 3: Characterizing Portuguese Recycling System Losses

Portions of this chapter are based on a 2016 publication by Ford et al. in Environmental Science & Technology, titled Economics of End-of-Life Materials Recovery – A Study of Small Appliances and Computer Devices in Portugal.[1]

3.1. Dynamic Product Flow Analysis Methods

The framework presented here identified the material and economic losses experienced throughout the defined electronic waste supply chain, and identified which opportunities existed to maximize the total recovered value for the system.

A dynamic product flow analysis (dPFA) was developed to determine the amount of materials available for recovery using a methodology derived from work of Navazo and Chancerel et al. and combined with a detailed assessment of preprocessing facilities.[23, 24] I used dPFA to track sales of SACD (S_p) through their projected lifetimes ($G_p(t)$), collection ($C_p(t)$), and preprocessing ($R_p(t)$). At the point of preprocessing I applied detailed accounting for materials composition by product and over time, preprocessing yields, and economic performance within preprocessing facilities. It was also necessary to calculate the costs associated with each operation within the preprocessing plants in an effort to guide potential investments aimed at reducing widespread losses. An overall schematic of the methodology is provided in Figure 10 and an overview of the logistics of the dPFA can be found in Appendix A.

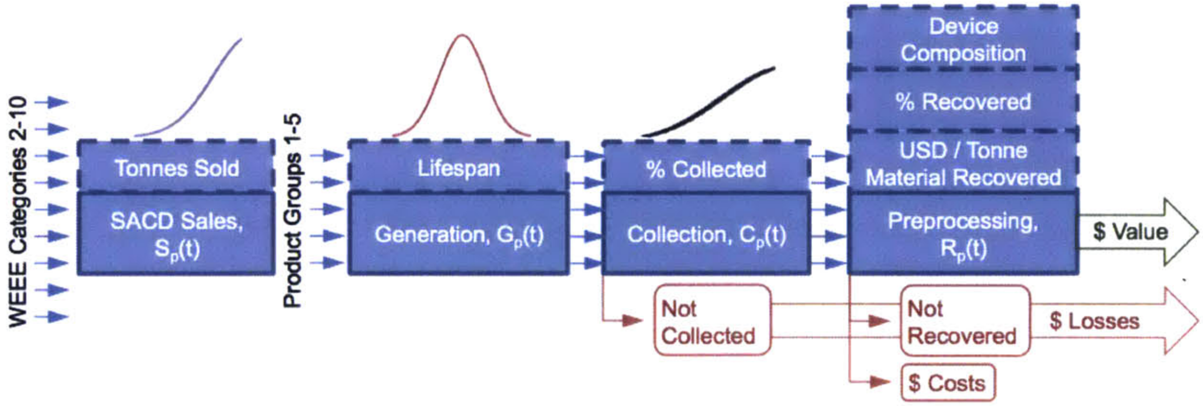


Figure 10. Schematic of overall model methodology

WEEE entering preprocessing stock R in each year t was tracked by product group p, as detailed below. Therefore, the mass (or units) of WEEE into preprocessing year t, $R_p(t)$, was the amount of WEEE generated $G_p(t)$ multiplied by the fraction of products collected in that year $C_p(t)$. Thus, $G_p(t)$ equaled the mass (or units) of products sold in the previous year S_p (indexed on s), multiplied by the probability of reaching end-of-life in year t, λ_p, summed over all production years prior to t. Therefore, the amount of product in preprocessing was calculated using the following relationship.

$$R_p(t) = \left(\sum_{s=t^0}^{t} S_P\,(s,t) * \lambda_p(s,t) \right) * \; C_p(t)$$

R_p in each year may be manually dismantled or shredded (or a combination of both), and are then sorted into a range of categories based on material composition. Prior to being shredded, the battery is removed from the device in accordance with de-pollution regulations.[38] The non-battery fractions, including components such as the PCB, speaker(s), camera(s), and outside casings are then sent to the appropriate downstream processes within the preprocessing facility. At the preprocessing stage, the total mass of each material subcategory not recovered was multiplied by the approximate value for which the material fraction could have been sold on the secondary materials market.

3.1.1. Sales

The starting point for this analysis was the use of detailed SACD sales data and projections for the years 2000 – 2014. These years were chosen due to the specificity of data available. A large portion of the sales information was gathered by ANREEE in its annual market data reports.[58-65]

SACD includes WEEE categories two through ten, as defined in the WEEE Directive: small household appliances; IT and telecommunications equipment; consumer equipment; lighting equipment; electrical and electronic tools; toys, leisure, and sports equipment; medical devices; monitoring and control instruments; and automatic dispensers.[66] The heterogeneity of these device categories complicates characterization and definitions focused on materials recovery processes. For this reason, I combined these WEEE categories within five product groups that are based on the type of product, the quality of its PCB and the materials contained within, and the projected lifespan of the device. Please refer to Appendix B for a detailed breakdown of the devices within each WEEE category into the five product groups below. The five product groups used are as follows:

1) Computing Devices
2) Telecommunications Devices
3) Printers
4) Other with 20+ year mean lifespan
5) Other with 0-19 year mean lifespan

3.1.2. Generation

In the context of this model, a waste generation event was defined as the point in which a device enters the waste stream, after being used and/or reused for an amount of time determined by the assumed mean and standard deviation (SD) of its lifespan. The distribution was assumed to be log-normal. According to the methodology developed in this work and modeled after the work of Duan et al., the lifespan of each device included initial use, initial storage, informal reuse, and reuse storage.[7] T. Reed Miller, a Research Specialist at MIT and co-author on the Duan et al. paper, worked with me to fit the lifespan modeling to my work. Product lifespan data were collected from various sources, including that of Duan et al., Geyer and Blass, and Navazo et al., in conjunction with the Lifespan Database for Vehicles, Equipment, and Structures.[7, 23, 67, 68] Table 1 shows the mean and standard deviations used for the lifespans of the five product groups.

Table 1. Assumed mean lifespans of devices within the five product groups[7, 23, 67, 68]

Product Group	Mean	SD
1 - Computing Devices	6.50	1.50
2 – Telecommunications Devices	4.50	1.56
3 – Printers	6.00	1.50
4 - Other with Extended Lifespan	20.00	2.00
5 – Other	10.00	2.00

Figure 11 shows the mass generated (i.e., that entered the waste stream) by year for an example set of computers sold in 2005 on the primary vertical axis (dashed line). The peak between 2010 and 2011 reflects the average lifespan of computing devices, as noted in Table 1. The secondary vertical axis portrays the cumulative mass generated over that time period (dotted line). The data shown in Figure 11 are for computers (product group 1) only and the shading qualitatively represents the uncertainty in the data, which is propagated throughout the analysis and shown quantitatively in Figure 14.

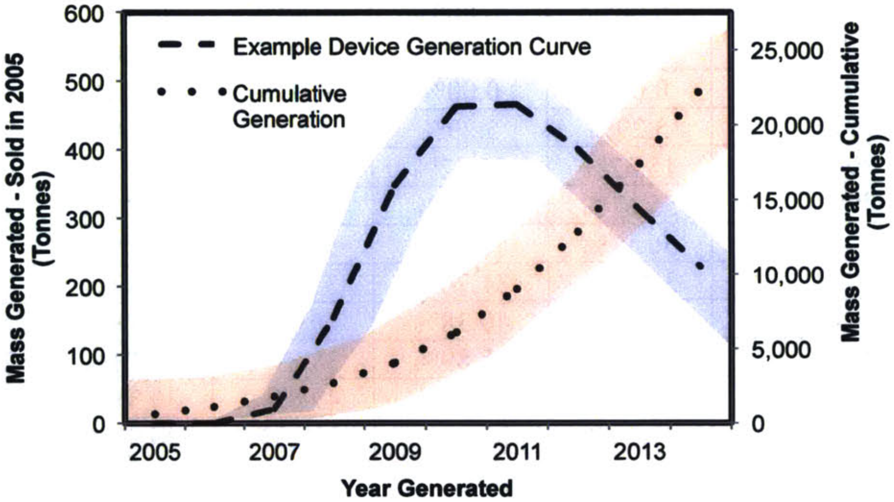


Figure 11. Mass of computers sold in 2005 that is generated until 2014 (primary axis) and the cumulative mass of computers generated over the same time period (secondary axis)

3.1.3. Collection

The collection rate varied by the product group and over time. It was assumed that the collection rate for all devices prior to 2006 was 0% because there was a limited formal collection system established prior to when Portugal transposed the WEEE Directive. Data made available by Eurostat were used for all product groups for 2006 to 2013, and data calculated by my collaborators were used for 2014.[39, 69] For 2006 to 2013, the collection rates were calculated by dividing the mass of WEEE collected in a given year by the mass put on the market in the preceding three years. For 2014, collection rates were calculated by dividing the mass of WEEE generated in a given year by the mass of WEEE collected in that year within the Portuguese recycling infrastructure.[39] As of 2014, the average collection rate for all SACD fell between 37.0% and 40.0%.[39, 69-71] See Table 2 for detailed collection data by year and by product group including uncertainty.

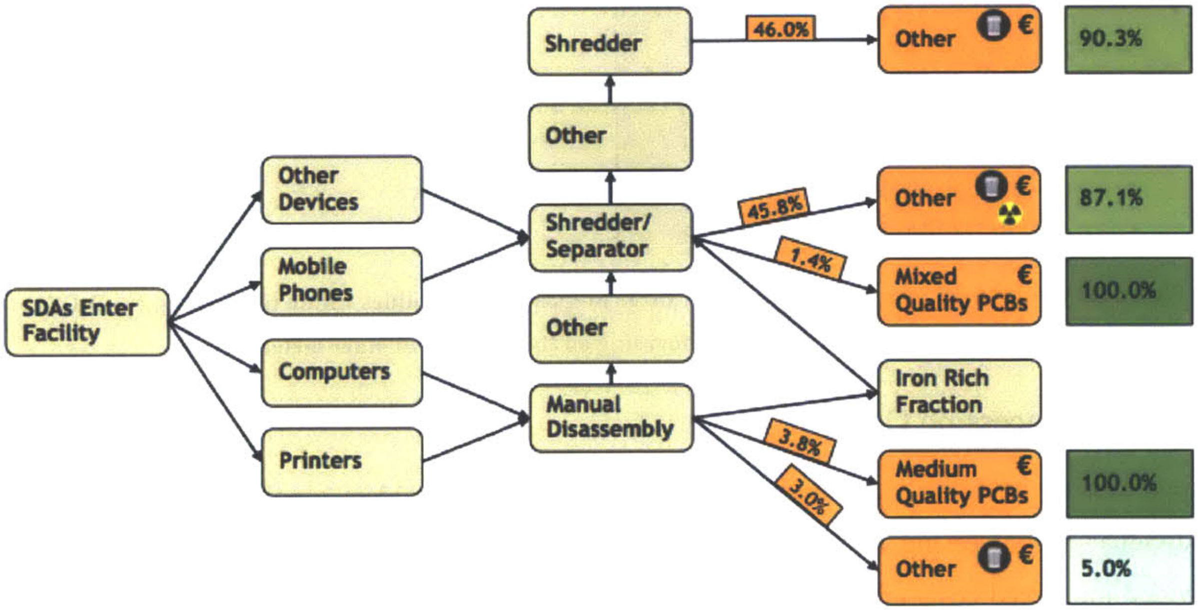
Table 2. Collection rates over time (Coefficient of variation: CV = 0.10 for 2006 - 2013 and CV = 0.20 for 2014)

Collection Rate	Product Group Collection Rate				
	1	2	3	4	5
2000	0.00%	0.00%	0.00%	0.00%	0.00%
2001	0.00%	0.00%	0.00%	0.00%	0.00%
2002	0.00%	0.00%	0.00%	0.00%	0.00%
2003	0.00%	0.00%	0.00%	0.00%	0.00%
2004	0.00%	0.00%	0.00%	0.00%	0.00%
2005	0.00%	0.00%	0.00%	0.00%	0.00%
2006[69]	5.29%	5.29%	5.29%	1.19%	1.19%
2007[69]	15.52%	15.52%	15.52%	6.04%	6.04%
2008[69]	55.61%	55.61%	55.61%	15.01%	15.01%
2009[69]	56.11%	56.11%	56.11%	20.85%	20.85%
2010[69]	31.70%	31.70%	31.70%	19.49%	19.49%
2011[69]	40.38%	40.38%	40.38%	26.78%	26.78%
2012[69]	38.89%	38.89%	38.89%	24.73%	24.73%
2013[69]	49.82%	49.82%	49.82%	30.31%	30.31%
2014[39]	39.19%	39.19%	39.19%	36.97%	36.97%

3.1.4. Preprocessing Operations

To calculate material recovery and loss during preprocessing, I used data from sixteen preprocessing facilities within the recycling infrastructure of Portugal collected by one of my collaborators, Dr. Eduardo Santos, as a part of his PhD.[39] Dr. Santos played an instrumental role in the analysis of the preprocessing facility data and ensuring that the dPFA reflected the current operations at the facilities to the greatest extent possible. Among the 16 facilities, which comprise the outstanding majority of plants in the country, there was a wide range of material recovery percentages due to variances in their size and use of manual and mechanical separation operations. Smaller plants (twelve in total) relied mostly on manual operations to dismantle fractions for the purpose of recovering the PCB and any other valuable materials (i.e., copper). Medium sized plants (three in total) relied less on manual dismantling, and were equipped with medium sized shredders and separators for the processing, identification, and sorting of metals and plastics. For the sole large plant, a majority of WEEE processing was done in large shredders and separators (i.e., car shredders) along with other waste materials, such as end-of-life vehicles (WEEE generally represented only a small percentage of the feedstock).

As a part of the aforementioned thesis, full-scale batch tests were performed by my collaborators at the main operators in Portugal, representing more than 70% of the total installed capacity, to evaluate the industrial technologies used to preprocess the WEEE.[39] These tests yielded detailed information about the intermediate and final operations at each of the plant, as well as the fractions that were sent downstream. Figure 12 provides a generalized schematic of three of the preprocessing facilities, showing only those fractions that contain *other metals*. For the dPFA, the category labeled *other metals* was assumed to contain the following elements: Ag, Au, Pd, Pt, Co, Ni, Sn, Ta, W, and other nonferrous metals except aluminum. The final fractions labeled "other" include iron and aluminum rich fractions, as well as others. It is evident from the figure that other metals are recovered most effectively in PCB containing fractions. In others, where the focus may be more prevalent base metals, other metals are often lost to the waste stream. It should be noted that the three plants shown in this figure are the highest performing from the standpoint of other metals recovery, with approximate average recoveries of 85%, 70%, and 80% respectively. Amongst the other thirteen facilities, the highest average recovery is approximately 15%.



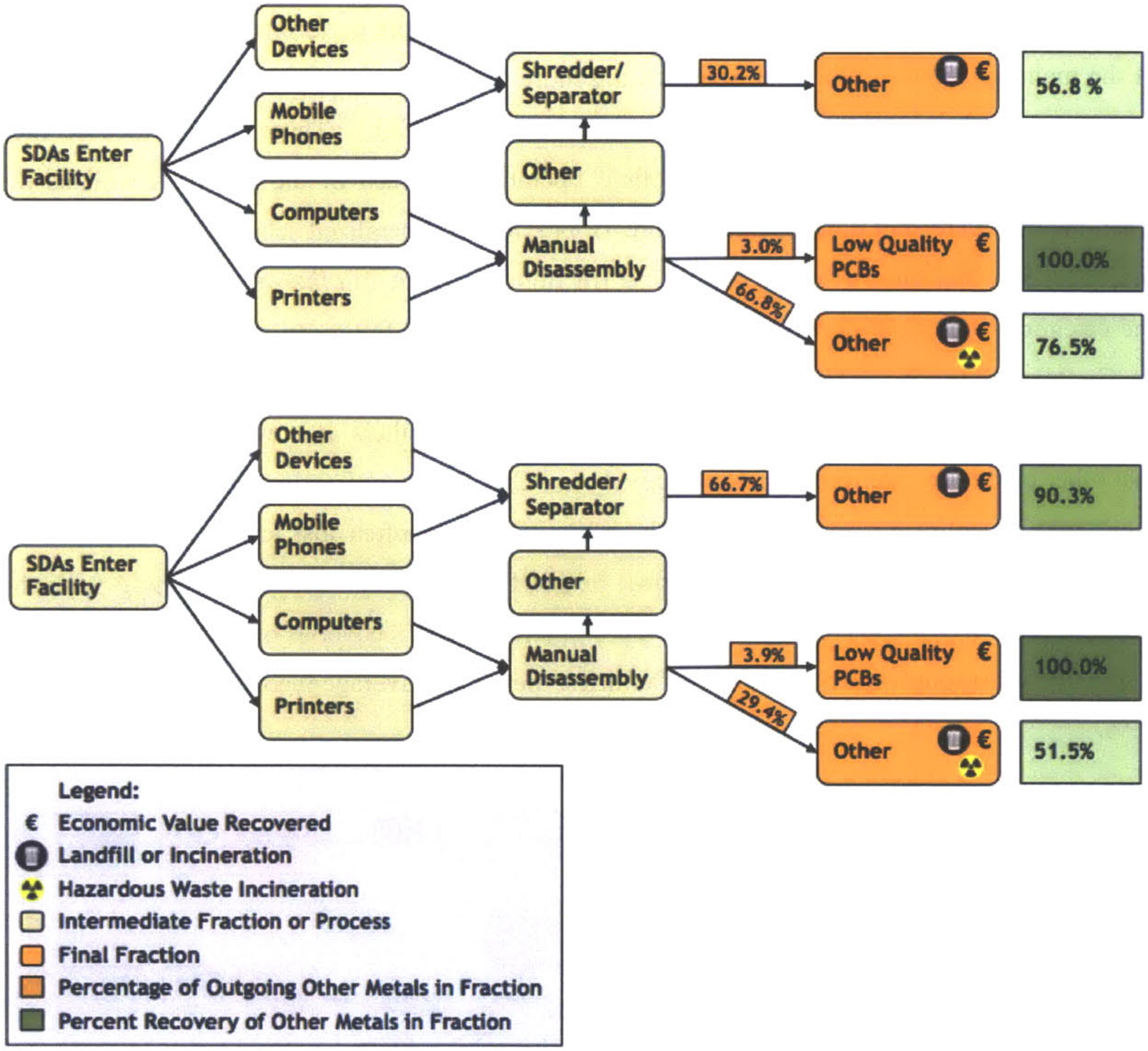


Figure 12. Generalized process schematics for three preprocessing facilities within the Portuguese WEEE recycling infrastructure, focusing on the recovery of other metals

3.1.5. Preprocessing Costs

Preprocessing operators, facility providers, and equipment providers supplied the cost data on individual preprocessing operations within the Portuguese recycling system. The data were divided into fixed costs and variable costs by operation (manual and mechanical treatment) for each plant and varied based on the types of materials being targeted and processed.[39] The average fixed cost and variable cost to preprocess SACD (using a combination of manual and mechanical dismantling) was 10 to 80 USD/tonne and 125 to 175 USD/tonne, respectively.

These cost data were compared to studies completed by WRAP[72], the WEEE Forum[70], Ramboll and Fichtner,[73] and the Department for Business, Innovation, and Skills (BIS) in the United Kingdom.[34] The purpose of this comparison was to analyze the relative costs of preprocessing throughout the EU, in order to verify the data collected from processors within the Portuguese system.

3.1.6. Characterizing the Composition of the Waste Stream

The shredded and dismantled pieces produced by these technologies were divided into the following material-level categories: ferrous, aluminum, copper, other metals, plastic, rubber, textiles, cement, glass, wood, and other. Using this dataset in conjunction with available literature, I determined the approximate material composition of all waste streams and the recovery percentages for all metals and non-metals. Material composition data for a device was broken down by product category and year manufactured. The two time periods used for mobile phones were 2001 – 2005[16, 23] and 2006 – 2014.[18-20] For the remainder of the devices, a single time period of 2001 – 2014 was used.[8, 14] See Appendix C for a breakdown of the material composition data used in the analysis, including uncertainty.

3.1.7. Calculating the Economic Value of Preprocessing

To calculate the potential profit lost during preprocessing I evaluated the economic value of the recovered and lost materials as a source of potential revenue. Values were assigned to each metal for each year based on annual data presented by the United States Geological Survey (USGS) and the United States Department of the Interior.[74, 75] All values were adjusted to 2010 USD to account for inflation. See Table 3 for a detailed breakdown of the material values used in the analysis.

Table 3. Inflation adjusted prices for materials included in analysis

Material	Inflation Adjusted Price to 2010 (USD per Troy Ounce)[74, 75]								
	2006	2007	2008	2009	2010	2011	2012	2013	2014
Silver (Ag)	$13	$14	$15	$15	$20	$34	$30	$22	$18
Gold (Au)*	$656	$735	$885	$990	$1,228	$1,523	$1,589	$1,324	$1,170
Palladium (Pd)	$349	$376	$360	$270	$531	$716	$617	$683	$764
Platinum (Pt)	$1,238	$1,376	$1,599	$1,227	$1,616	$1,671	$1,478	$1,394	$1,326
Copper (Cu)	$0.23	$0.24	$0.22	$0.17	$0.24	$0.27	$0.24	$0.22	$0.20
Cobalt (Co)	$1.28	$2.20	$2.71	$1.24	$1.43	$1.20	$0.92	$0.83	$0.91
Nickel (Ni)	$0.82	$1.22	$0.66	$0.46	$0.68	$0.69	$0.52	$0.44	$0.48
Tin (Sn)	$0.42	$0.65	$0.78	$0.58	$0.85	$1.05	$0.84	$0.87	$0.64
Tantalum (Ta)	$2.45	$2.67	$3.06	$2.79	$3.70	$8.31	$7.04	$7.57	$6.95
Tungsten (W)	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01
Other Non-Ferrous Metals	$0.09	$0.09	$0.08	$0.06	$0.07	$0.08	$0.07	$0.06	$0.07
Ferrous Metals	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01

3.2. Calculation of Uncertainty

Because the data are from a variety of sources and of varying degrees of quality I included a treatment of data uncertainty. I assumed that there was uncertainty associated with the sales, device composition, collection, and pre-processing data.

For the device composition data, where sufficient quantitative data were available I used a uniform or triangular distribution depending on the number of data points available for each device.[76, 77] I used a data quality indicator approach based on the pedigree matrix for the values derived from a single data point to characterize the uncertainty associated with my results.[21, 78, 79] I used a lognormal distribution to define the uncertainty associated with those parameters for which I determined the arithmetic mean and standard deviation using the pedigree matrix assessment of data quality.

The sales data, which was published by ANREEE, was assumed to have a coefficient of variation (CV) of 0.10 for all years reported, except for 2009, where the CV was assumed to be 0.15. The CV of 0.10 was chosen due to the high accuracy of the ANREEE reports and the automated audits performed on the data. The higher CV of 0.15 was chosen because no values were reported for 2009, so the inputs for the product flow analysis were interpolated. The collection data, which was published by Eurostat and in a thesis completed by my collaborator, was assumed to have a CV of between 0.10 and 0.20. The CV of 0.10 was used for the years 2006 – 2013, and was determined by analyzing the Eurostat Quality Grading System with respect to the statistical metadata.[80, 81] For 2014, The values reported in Tables 4.9 and 4.10 of the previously mentioned thesis were utilized, and a CV of 0.20 was assumed due to the multiple sources and the analyses used in order to calculate the final results.[39] I used the CV to calculate the standard deviation of each value and assumed a normal distribution for calculating the error. The preprocessing data was collected as described in the methods section and the aforementioned thesis.[39] A CV of 0.10 was assumed due to the robust nature of the batch tests completed as a part of that work. A beta distribution was used in order to model the uncertainty. The uncertainty associated with each of these parameters was propagated throughout the model and can be seen in Figure 14.

3.3. Dynamic Product Flow Analysis Results

The growth of the electronics industry, and in particular the increasing diversity of materials contained within SACD, provided a new opportunity to investigate economic potential for materials recovery at the device end-of-life. I focused on the perspective of the preprocessor, as facility infrastructure decisions at this stage of recycling hold significant impact for downstream materials recovery that results in secondary material markets. The results detailed below, with explicit consideration of the uncertainty within the data, support the assertion that present day WEEE preprocessing is limited by inefficiencies that reduce potential revenues for operators. This value may be sufficient for reinvestment in preprocessing operations for the increased recovery of specific SACD subsets, device components, and key materials.

The case presented involves materials recovery data specific to Portugal and accompanying legislation within the European Union (EU). However, I provide conclusions as a function of the characteristics in the system, which may be applicable to other EU nations because of Portugal's state-of-the-art technologies and participation in EU wide recycling initiatives.

3.3.1. Material Mass Losses

Figure 13 shows the result of the product and material flow analysis by mass, depicting the quantity collected and then preprocessed over the years modeled. Here I provide an example for the mass of gold in computers spanning 2001 – 2014 where the vertical axis indicates the mass in tonnes in each year available upon generation (dashed line), after collection (dotted line) and after preprocessing (solid line). The line corresponding to the mass generated at end-of-life is a direct result of the dynamic PFA, and is derived from the assumed sales and lifetime distribution of the products. The model assumed collection began in 2006 as shown by the red arrow in Figure 13. Finally, the mass of gold recovered during preprocessing was based on the data for the 16 preprocessors in Portugal. The arrow labeled "loss during collection" reflects losses due to ineffective collection schemes and incomplete public awareness of and compliance with collection streams for end-of-life electronic goods. The arrow labeled "loss during preprocessing" represents operational inefficiencies that fail to target the high value materials locked in the devices' PCBs. These losses can occur during both manual dismantling and shredding. Based on my analysis, the largest loss of gold in 2014 was due to inefficient collection (over 3 tonnes of gold left unrecovered), however, the mass lost during preprocessing also represents significant economic potential (over 1 tonne of gold lost). The qualitative uncertainty represented by the shading in Figure 13 was calculated for the material composition, sales, collection, and preprocessing efficiency data, and carried throughout the analysis.

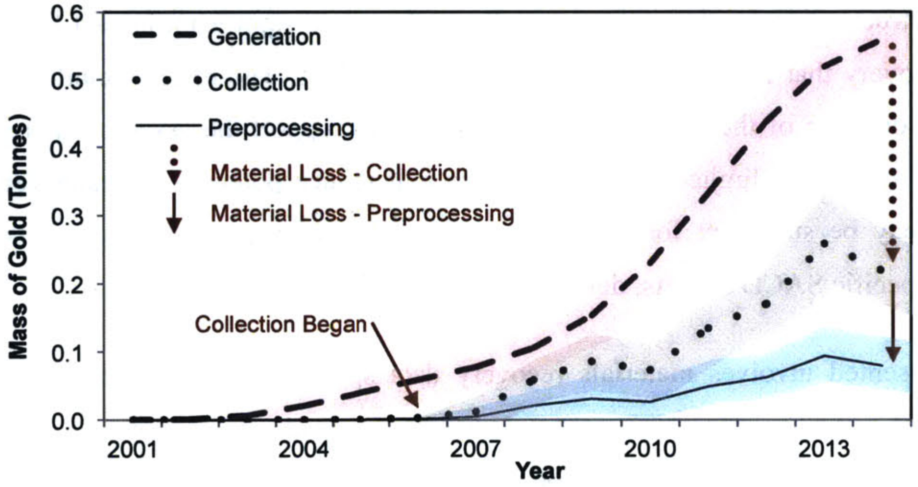


Figure 13. Mass of gold from computers at the generation, collection, and preprocessing stages of recycling in Portugal over time. Arrows represent the materials losses incurred from inefficiencies during collection and preprocessing. All values for mass are derived from the material composition data in the dPFA, and shading represents qualitative uncertainty.

3.3.2. Material Value Losses

Figure 14a shows the individual market value by product group of materials recovered during preprocessing (silver, gold, palladium, copper, and tin) for each year in the first three levels: computers, mobile phones and printers. These trends over the years appear similar to those in Figure 13, but represent the total market value of each material independently in millions of USD. This figure represents the total value that is contained in the silver, gold, palladium, copper, and tin found in the end-of-life electronics that are recovered at the preprocessing facilities. Due to inefficient operational schemes, this value is lower than the potential recovery, as represented in Figure 14b, although there is significant uncertainty in these figures.

We see from Figure 14 that the recovery of mobile phones and computers is driven by the potential recovery of gold. This result is consistent with previous work that has indicated that gold is the most important metal contributing to increasing the economic value of recycling.[21, 82] The economics of printer recycling, on the other hand, is shown to be driven by the potential for recovery of copper. This is because the mass of gold in the PCBs of printers is smaller than that found in computers and mobile phones. Due to its larger size, the copper can be targeted more easily and removed from printer PCBs.[8]

Figure 14b uses the same materials price data but quantifies the value of the lost material corresponding to the arrow labeled "loss during preprocessing" found in Figure 13. For computers and mobile phones, the majority of lost value again is in the gold not recovered based primarily on incomplete separation of PCBs. Palladium is also a potentially valuable material stream to target for increased recovery within the computer and phone product groups. For printers, the losses were much less significant due to the high recovery rates of copper, but this analysis also indicates that the increased recovery of gold, palladium, and tin would have the greatest impact on reducing economic losses during preprocessing. The heterogeneity of the devices within each product group and the operations used during preprocessing introduce uncertainty into these results, with the largest contribution coming from the device composition data (For clarity, uncertainty is only shown for Figure 14b). However, even at the lower bounds of my uncertainty analysis, I found that the potential economic value not recovered in Portugal during the specified time period exceeded $70M for the materials shown.

The quantification of the value of materials recovery within SACD over time and by material demonstrates that a few key materials drive the recycling economics for electronic waste and that there are significant losses for the case of Portugal. Studies have shown that this is also the case for recycling systems in many other EU nations. Similar to the situation in Portugal, low collection rates mean that only a fraction of the potential end-of-life devices arrive at facilities able to separate and sort their contents, and that gold and other precious metals are key targets for making system wide improvements.[83, 84]

Figures 13 and 14 include data only up to 2014 for two reasons. The first is that the goal of the study was to analyze the current conditions of the recovery system, and to use that information to inform future decision making, not to make predictions. The second is that fluctuations in material prices made it difficult to project the economic implications of material losses into the future.

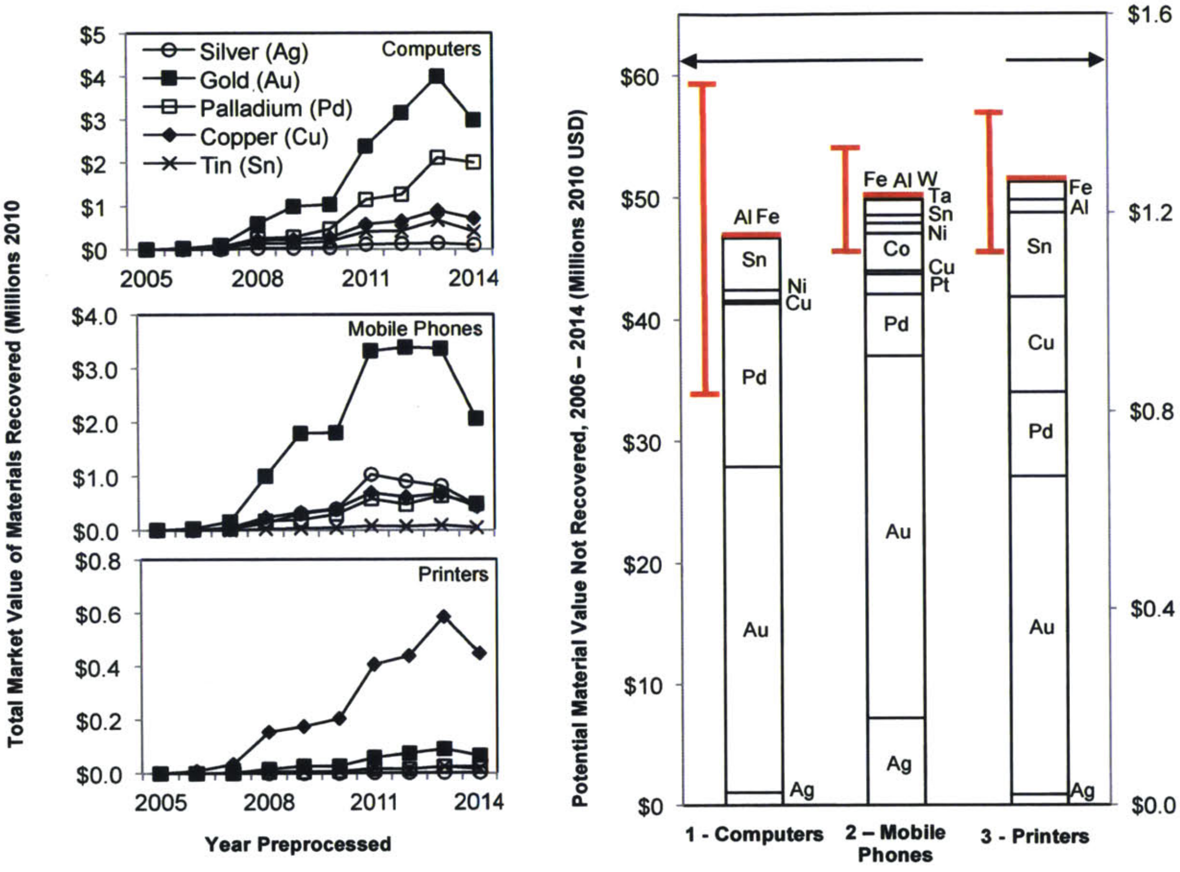


Figure 14. (a) Total market value of materials recovered during preprocessing by product group in 2010 USD across 16 preprocessing plants within Portugal (b) Total potential market value not recovered by product group from 2006 – 2014 and the metals impacting the economic losses (Error bars represent one standard deviation). The values for computers and mobile phones are plotted on the primary y-axis, and the values for printers are plotted on the secondary y-axis.

Figure 15 shows that by value the lost potential per tonne for mobile phones is larger than the other categories studied because of the high value of the materials in the device PCBs and the smaller mass of the individual devices and total flow of materials. These results should be viewed as a way to compare across product categories rather than as absolute values, due to the uncertainties inherent in the assumptions used in the dPFA and the heterogeneity of preprocessing operations.

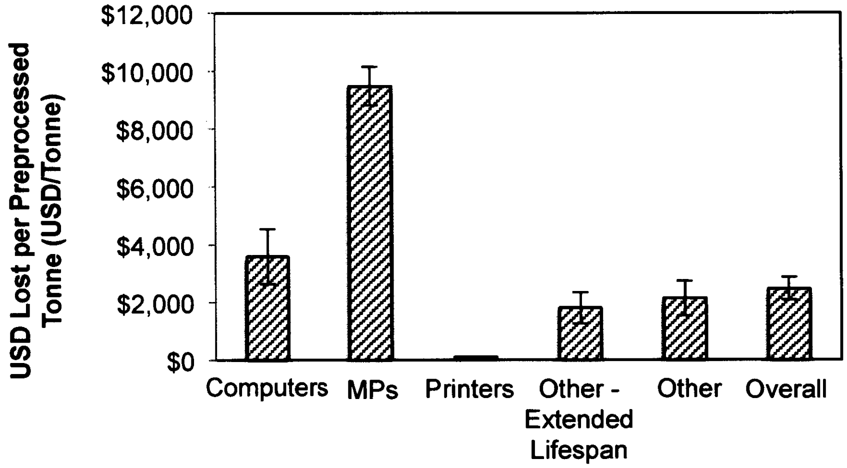


Figure 15. Total 2010 USD lost per tonne of each product group that was preprocessed from 2006 - 2014 (Error bars represent one standard deviation)

3.4. Informing Future Investments

The results so far have shown that there is significant potential economic value not recovered from electronic waste in Portugal. The model framework developed here can be used to inform operational and investment decisions from the perspective of the preprocessor. Increased recovery of materials will come at a cost to the facility in the form of additional equipment or personnel. My next analysis explores the impact of these potential investments.

The heterogeneity of the operations used by varying preprocessing plants presents challenges to optimizing recovery across recycling systems. However, the results presented in my analysis can provide useful insights into some of the tradeoffs between costs and recovery percentages for high value materials. Among the 16 plants studied, the major difference that I observed was the recovery of "other metals," which includes high value nonferrous metals such as gold, palladium, platinum, and silver. This is due in large part to the fact that several of these plants are not equipped to remove the PCBs from devices effectively, either through manual or mechanical dismantling. For this analysis, I studied two primary operations, manual dismantling and shredding. In manual dismantling, workers remove valuable materials from larger devices such as laptops and printers and hazardous materials, such as the battery, from all devices. In mechanical dismantling, or shredding, devices that have gone through the manual dismantling step are shredded into pieces of varying sizes, and sorted using density-based, sensor, and other technologies. The degree to which these machines can identify and remove valuable materials plays a large role in the final economic output of the plant.

In order to make recommendations for future investments, I adopted several assumptions about the data. First, for Figure 16 below, I considered in detail the data from three of the 16 plants. Second, due to the low recovery rates and high values associated with so-called "other metals," I focused potential changes on fractions or processes containing other metals. In addition, based on fieldwork and input from my collaborator Dr. Eduardo Santos, I assumed that these plants had made process updates since they were analyzed fully in 2012. It is for this reason that high recovery rates are observed for several residual waste streams. Lastly, I assumed that the recovery rate of gold was the same as that for all "other metals" due to the fact that many of them are found in the PCB.

Figure 16 presents data from these three plants that could be used to inform future investments. Due to the complexity of these systems, any investments made would need to consider downstream impacts on other systems at the plants, evolving process inputs, material market prices, and many other factors. The horizontal axis indicates the material value of the entire output fraction containing other metals, divided by the tonnes of that fraction preprocessed by a given plant in a year. The vertical axis indicates the recovery percentage of other metals for a given fraction, divided by the fixed and variable costs associated with the preprocessing of that fraction. All values used in Figure 16 were calculated as a part of the dPFA in accordance with the previously described methodology. The points highest on the graph, shown in blue, represent those processes for which the largest amount of material can be recovered at the lowest cost. In this case, each of these points represents a manual dismantling process, due in large part to the low capital costs of hiring more people as compared to installing shredders and separators. Also, the further to the right that a point is located (points shown in orange), the higher the value of the materials contained in that fraction relative to the tonnes preprocessed. The orange highlighted area includes process streams from both manual and mechanical dismantling. These are significant because they represent fractions containing high value materials that have been targeted, even though the mass of that fraction is small in comparison to others, such as the ferrous metals. Therefore, the red arrow in the figure points to the desired area of the graph in terms of framing future investments, where high recovery percentages of valuable materials at the lowest costs occur. Overall, the vertical axis is concerned with the process that a given fraction undergoes during preprocessing, and the horizontal axis conveys the make-up and quantity of that fraction.

Downstream processing and refining was not included as a part of the present analysis, but it is necessary to consider the costs associated with these processes in order to make investment decisions. The costs of refining and recovery of metals from preprocessed fractions ranges from approximately \$500 to \$2,500 USD per tonne. Within this range, the cost of recovering the metals in PCBs is approximately \$1,500 USD per tonne.[39] These values are only assumptions, and may vary greatly across companies and treatment technologies used.

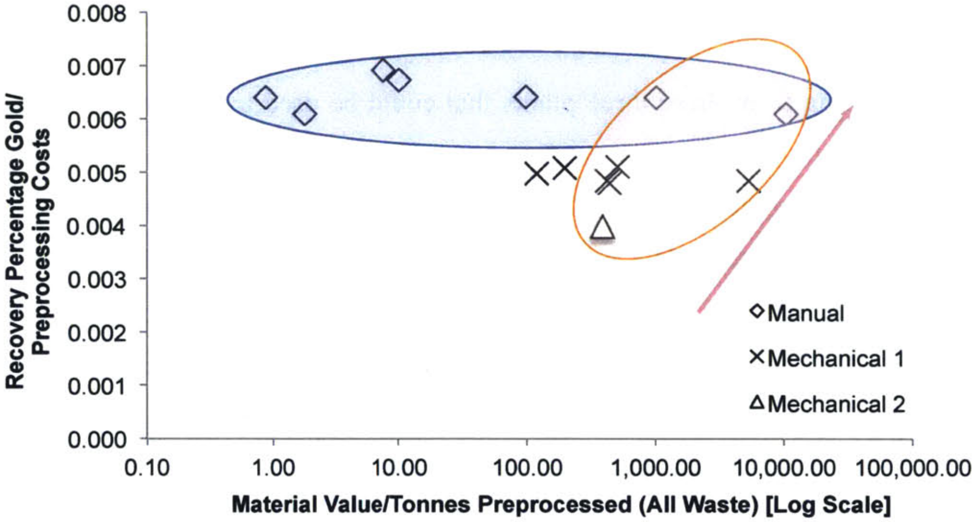


Figure 16. Normalized process and material data showing the tradeoffs between recovery percentages, costs, material values, and tonnes preprocessed

Through this data-driven analysis, I identified opportunities for investment that could increase recovery and realize increased economic value of materials at the preprocessing stage of recycling. These findings are consistent with several studies completed in the past, and are strengthened by the addition of granular material market value data.[20, 23, 24, 32, 33, 85, 86] For example, I have found that incrementally adding workers to dismantle devices is the most effective way to increase the recovery percentages of "other metals" at the lowest up front cost. Additionally, making investments in mechanical dismantling that prioritize sorting operations post-shredding will have the largest impact on recovery rates, especially for those metals that are found in the PCB. This can be seen in the orange region, where most of the losses of other metals are due to PCBs that end up in waste streams.

Based on recent discussions with practitioners in Portugal, I have found that the most significant increases in material recovery efficiencies seem to be arising from the adoption of sensor based sorting technologies. I recommend that these technologies be used as needed to identify and remove valuable materials, such as gold and other precious metals, from the recycling stream, but that a focus remains on recovering the PCB without shredding at the lowest possible costs. This may include sending entire devices, such as mobile phones, directly to downstream operators after the removal of the battery.[31] If facilities are able to minimize lost PCBs or recover other metals from material streams, then a higher economic value can be extracted.

Certainly, the exact magnitude of any investments would need to be determined on a case-by-case basis depending on the location of the plant, the costs, the materials preprocessed, and several other factors. However, these findings provide a methodology and framework to identify specific operational and systems-level modifications that can drive decisions on the economic viability of materials recovery. The major implication of these findings for the preprocessing industry is the potential for an optimization of plant operations based not only on total mass recovered, but also on the economic value contained in the WEEE. I have also provided evidence for the importance of utilizing granular materials characterization data in the operational decision making process.

3.5. Summary and Outlook

In Chapter 3, I utilized a dPFA to model the Portuguese WEEE recycling system, identify the major losses of material mass and economic value, and provide insights into potential investments that could lead to higher recovery rates in the future. In Chapters 4 and 5, I will build on these findings to explore various methods aimed at improving the WEEE recovery system and optimizing recycling for the recovery of materials based not only on mass, but also on value. Chapter 4 will focus on increasing the granularity of available data on the material composition of devices. I will use mobile phones as a case study to consider how the composition of devices has changed over time, and how improved knowledge of the composition of mobile phones outside of the PCB could change the "formula" that operators use to determine which portions of the devices to target during preprocessing. A summary of the work completed to date will be included, along with recommendations for future work.

In Chapter 5, I will provide details regarding a collaboration that has been established between MIT, Amb3E, IST, and 3DRIVERS, aimed at finding concrete ways to optimize the WEEE recovery system. In addition, I will present data from the dPFA to show the need for a consideration of value based metrics in addition to the mass based metrics used today. I will conclude with a brief discussion of the European Commission Circular Economy Strategy, and how it relates to the rest of the work presented here.

Chapter 4: Improved Mobile Phone Material Characterization

This chapter will focus on the impact of improved device characterization on the recycling system, based on an analysis of mobile phones. Characterizing the change in material composition over time and the composition of pieces outside of the PCB could help preprocessors to better optimize their operations, while also helping Producer Responsibility Organizations characterize the environmental impact of the products being put on the market.

Mobile phones were chosen for this analysis because they contain a complex set of valuable and often difficult to recover materials, and are often not recycled or are recycled ineffectively because of assumptions made about their contents and value. It has been assumed in the literature that a large percentage of the valuable materials within consumer electronics reside in the printed circuit board, meaning that analyses assume that if the PCB is recovered in a recycling process, then most/all of the valuable materials (such as precious metals) are also recovered. Work completed by Chancerel et al. in 2015 goes the furthest in examining where in the device materials may be located, but still states that the location of target materials introduces uncertainty into their analysis.[21] In addition, a study focusing on conflict minerals by Fitzpatrick et al. in 2015 stated that there is a lack of information regarding where materials such as gold are located in devices outside of the PCB.[15] While I will not disagree that a large percentage of the valuable materials are found in or attached to the PCB, I believe that it is possible that a small, but significant mass of recoverable materials may be located outside of it. More specifically, I feel as though certain assemblies, such as the speaker(s), camera(s), and screen, may contain materials that are currently, or one day will be, valuable from a materials recovery perspective.

The following sections will detail the mobile phones used in the analysis, the calculation of a PCB to total mass ratio, and the two primary methods used to qualitatively and quantitatively assess the material composition of the devices, Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) and Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES).

4.1. Dismantling

The first step in this analysis was to manually dismantle approximately 50 mobile phones. The phones selected ranged in date manufactured from 2002 to 2013 and the brands analyzed included Motorola, Nokia, LG, Samsung, UTStarcom, Apple, Sanyo, Blackberry, and Pantech. The dismantled devices were sorted into three batches, 2002-2006, 2007-2008, and 2009-2013. Each individual device was first characterized by total mass, mass of PCB, and type (flip phone, camera phone, etc.). A summary table including each of the dismantled phones can be found in Appendix D. A sample photograph of one dismantled phone from each batch can be found in Figure 17.

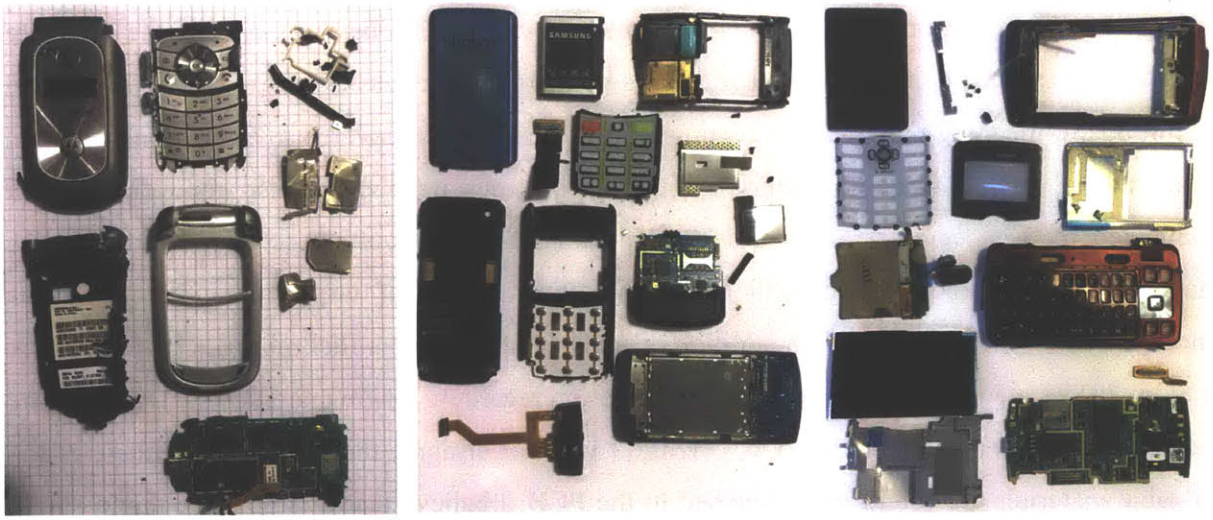


Figure 17. Dismantled mobile phones from batches 1, 2, and 3 (a. Motorola V325i H/W, 2005; b. Samsung SGH-A777, 2008; c. LG VX9200M, 2009)

4.2. PCB to Total Mass Ratio

The devices were categorized by the mass of their PCB relative to their total mass. A majority of the metals that drive the economic argument for increased recycling reside in the PCB, making it important to be able to predict their mass flow through the preprocessing stage, relative to incoming devices. Knowing these ratios can help preprocessing operators to make more informed decisions about how they treat SACD by providing insight into the approximate makeup of the incoming materials.

For mobile phones, I determined the ratio by manually dismantling and weighing 43 mobile phones that were manufactured between 2002 and 2013. Literature data were used for the other PCB categories[8, 14] The PCB to mass ratio for each of the five product levels can be found in Table 4, and range from approximately 3% for product groups 4 and 5 to approximately 15% for phones. It should be noted that there is significant uncertainty associated with each of these values due to the heterogeneity of these devices.

This data could be used within the Portuguese WEEE recycling system and elsewhere to estimate the total mass of printed circuit boards that should be generated by a given mass of end-of-life electronics fed into a preprocessing facility. If the mass of PCBs in the final outgoing fraction falls below one of these marks, it may signal an operational inefficiency or error that needs to be corrected.

Table 4. PCB mass to total device mass for each product category

Product groups	PCB:Mass Ratio
1 - Computing Devices[8]	10%
2 – Phones	15%
3 - Printing Devices[8]	7%
4 - Other with extended life spans[14]	3%
5 - Other[14]	3%

4.3. Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS)

As described above, there is a need to develop a better understanding of the types and quantities of materials located outside of the PCB. This will allow recyclers to make more informed decisions about which portions of devices to target at the end-of-life. As a part of this work, I managed an MIT undergraduate student, Jae Hyun Kim, who used SEM/EDS to characterize several mobile phone pieces that were located outside of the PCB. SEM/EDS is a commonly used technique for characterizing the materials present on the surface of a given sample.[87]

For this analysis, only the qualitative portion of the SEM/EDS output data was used. The machine used to carry out the analysis was a Philips XL30 FEG ESEM. The Philips machine is described as a "high performance, extremely flexible and well-equipped microscope for general-purpose microscopy, low-vacuum and environmental scanning microscopy (ESEM). It is also equipped with a Peltier Stage. Resolution at 30KV is 3.5 nm. The minimum magnification is about 20x." The phones analyzed using SEM/EDS were numbers 1, 23, 29, 30, 43, 45, and 51, and a total of 32 samples were tested from those devices. From this analysis, Jae Hyun Kim and I identified a number of elements in parts outside of the PCB, including Cu, Zn, Ni, Pd, Fe, Au, Cr, Ag, and Nd. The locations where these materials were found include: speaker assemblies, camera assemblies, charging ports, and attached to outer casings. See Appendix E to view the SEM/EDS results of the most relevant samples.

Knowing that these materials are being used outside of the PCB, the next step was to quantify exactly how much was present in order to identify whether or not it is economical to target these pieces within preprocessing operations. For that analysis, I sent my samples to be shredded by my collaborator, Professor Fernanda Margarido of IST in Lisbon, and then to a lab to be analyzed using inductively couple plasma – optical emission spectroscopy (ICP-OES) as described below.

4.4. Inductively Coupled Plasma – Optical Emission Spectroscopy

ICP-OES was used to analyze the material composition of mobile phone PCBs and parts outside of the PCB. Although this method has been used by researchers in the past to analyze the composition of mobile phone PCBs and entire devices, these studies have not focused on quantifying the composition of materials outside of the PCB from a recycling economics perspective.[88, 89] The testing was carried out by ALS Environmental, who reported that "approximately 50mg of sample was digested with HNO_3, HF, and HCL, brought to 50.0 mL with DI water, and analyzed by ICP-OES." The elements tested for were: aluminum, antimony, arsenic, barium, beryllium, cadmium, calcium, chromium, cobalt, copper, dysprosium, gallium, gold, iron, lead, lithium, magnesium, manganese, molybdenum, nickel, palladium, phosphorous, platinum, potassium, selenium, silicon, silver, sodium, strontium, tantalum, tin, titanium, tungsten, vanadium, zinc, and zirconium. In the first set of experiments, the PCBs of phones 3, 4, 5, 10, 11, 17, 19, 21, 32, 36, 37, 38, and 39 were used. Figure 18 shows the PCBs used in the analysis.

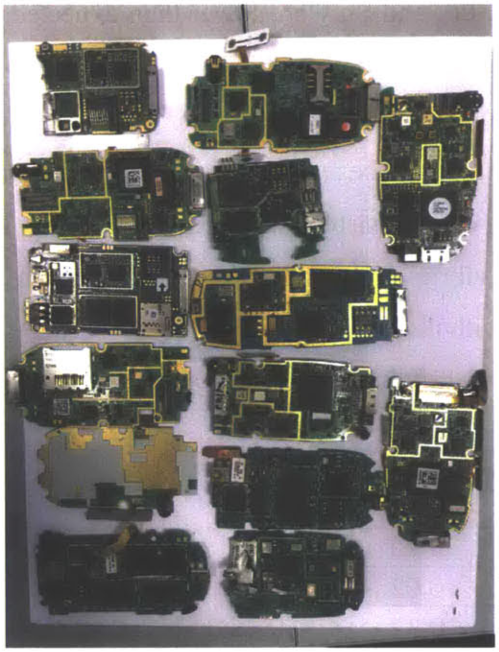


Figure 18. PCBs shredded and analyzed utilizing ICP-OES

The PCBs were shredded by my collaborators in Portugal using a Retsch SM 2000 shredder with tungsten carbide blades. They were first shredded using a 6mm sieve, followed by a 1mm sieve. This sample was homogenized and split into three batches using a Retsch sample divider. The results of the ICP-OES analysis carried out with the 1mm samples can be found in Appendix F. A review of the results showed that the three batches were insufficiently homogeneous, and that the variances for key materials across the batches was too high.

The same sample of PCBs was shredded down to an average size of 0.25 mm and was re-homogenized using the Retsch sample divider. The three batches were analyzed using ICP-OES. A summary of the results can be found in Table 5 and the full results of the analysis can be found in Appendix F. The results were reported in weight percent, and the mass/PCB was calculated using an estimated PCB mass of 14g, as determined by the PCB to total mass ratio. The results of this sample were more consistent than the first, with values across the three batches falling within the analytical error of approximately 3%. In total, the elements tested for in the analysis accounted for approximately 60%-65% of the total mass of each sample. This aligns with the literature, in that approximately 34%-40% of the PCB is composed of composite materials and non-metals such as plastic.[8, 88] The values for several of the precious metals and welding elements, namely Ag, Au, Pt, Pd, and Sn were lower than expected. This may be due to the fact that these elements can escape as dust during the shredding operation. There was no filter on the shredder at the time of the operation. The values for Cu, Fe, Al, and Ni, combined with the results of the SEM work, signify that these materials are present in measurable quantities outside of the PCB. The value for W was consistent with expected values, knowing that its primary use in mobile phones is in the vibration motor.[15] The value for Ta, which is typically used in capacitors, was also aligned with that found in literature.[15]

Table 5. Summary of the Results of the ICP-OES Analysis of Mobile Phone PCBs

Sample 2 - PCBs 0.25mm Shred Size	MP1b Mass/PCB	MP2b Mass/PCB	MP3b Mass/PCB	Average Mass/ PCB
Aluminum	0.26	0.28	0.26	0.269
Copper	5.23	5.26	5.38	5.290
Gold	0.02	0.02	0.02	0.020
Iron	0.32	0.46	0.53	0.433
Nickel	0.23	0.27	0.25	0.250
Palladium	0.0028	0.0028	0.0028	0.003
Platinum	0.0014	0.0028	0.0028	0.002
Silver	0.01	0.02	0.02	0.015
Tantalum	0.03	0.02	0.04	0.028
Tin	0.08	0.07	0.07	0.072
Tungsten	0.15	0.05	0.07	0.088

Due to the success of the ICP-OES analysis of PCBs, the next step in this work will be to shred and analyze pieces from outside of the PCBs according to the same methodology. The phones that will be shredded and analyzed are 3, 4, 5, 10, 11, 17, 19, 21, 32, 36, 37, 38, and 39 from batch 1 (2002 – 2006) and 2, 8, 12, 14, 18, 20, 25, 27, 28, 34, and 40 from batch 3 (2009 – 2013). I recommend that tests be done on both sets of samples in order to study not only the material compositions and presence of potentially valuable materials, but also to assess any changes in composition over time based on the year manufactured.

4.5. Summary and Outlook

In Chapter 4, I detailed the materials characterization that I have carried out, in collaboration with others, with the goal of identifying the types and quantities of materials located outside of the PCB, and the change in the composition of devices over time. This added granularity in materials characterization is important because of the potential impact that it could have on the ability of researchers and practitioners to optimize the system as a whole now and in the future. In Chapter 5, I will explore various methods and partnerships aimed at improving the WEEE recovery system, particularly around the recovery of materials with the highest economic value. This will include an analysis of economic levers such as the eco-value, operational levers such as product recyclability, and policy levers such as value based metrics for evaluating end-of-life product treatment.

Chapter 5: Improving the WEEE Recovery System

In this chapter, I will focus on methods that could be employed within Portugal in order to capture the potential economic value not recovered during preprocessing, as identified in Figure 14. I will explain the framework for a collaboration that has been formed between MIT, IST, 3Drivers, and Amb3E, aimed at increasing the total economic value derived from preprocessing in Portugal, reducing the costs of recovering key fractions, and reducing the overall environmental impact (See Appendix G for the proposal letter for the collaboration).

5.1. Amb3E Collaboration Framework

Researchers in the past have identified that there is an optimal technical solution to WEEE recycling and preprocessing specifically, but this work will explore how system level changes can be driven by leveraging the economic results detailed above and the appropriate policy instruments within Portugal. This collaboration is still in its early stages, and the sections below will detail the framework of the potential next steps, rather than the results. Overall, the three key focus areas of the collaboration will be:

1. An evaluation of the supply of and demand for specific secondary materials, the factors that impact supply and demand, and how evolutions in the supply and demand dynamic impact the effectiveness of the recycling system
2. The consideration of the environmental impacts of products when formulating WEEE eco-values
3. The development of technological and operational best practices and benchmarks for de-pollution and PCB removal in the context of the Portuguese WEEE recycling system

5.1.1. Secondary Materials Supply and Demand

As noted in Chapter 4, the composition of SACD and the quantity of valuable materials available for recovery at the end-of-life can have significant impacts on the final outcomes of recycling. In order to properly account for these impacts, it is important to analyze the recycling infrastructure as a dynamic system that changes over time in response to internal and external pressures, such as operational changes and new regulatory schemes.

I believe that two of the key factors impacting the supply of secondary materials to refiners downstream of preprocessors are technology advances and more stringent regulations. On the other side, I believe that demand for secondary materials by refiners is driven most significantly by the market value of a given material at that time. As an example, if a proposed policy mandated the recycling of greater percentage of the plastics found in devices at the preprocessing stage, is there a downstream market that will purchase those materials, or will preprocessors have to pay to dispose of them or store them on site? A second example would be if a specific rare earth element known to be found in SACD experienced a sudden supply shock. Could preprocessors use existing technologies and knowledge of the location of those materials in the devices to recover them at a higher rate?

The work detailed in the preceding chapters begins to answer these questions by quantifying the supply of a given set of materials within SACD, but it will need to be extended to include rare earth elements, critical materials, and a stronger consideration of demand as well. Gaining a better understanding of the complex supply and demand dynamics of the system may allow stakeholders such as preprocessors to more effectively target investments in system upgrades. Finally, insights into supply and demand may help policymakers to better understand the upstream and downstream impacts of the regulations that are promulgated on a countrywide or even an EU scale.

5.1.2. Incorporating Environmental Footprint into Eco-Value

As stated previously, the eco-value is a fee paid by producers to PROs based on the number of products they put on the market each year. These fees are set by the APA as a part of the PROs' license. Under current regulations, these values are set based on the cost to collect, transport, and treat WEEE at its end-of-life. Although the eco-values do vary by WEEE category, they do not account for the impacts of individual products or efforts by certain manufacturers to lessen the environmental impact of the products it puts on the market. Table 6 shows a sample of the eco-values set by Amb3E's license in Dispatch No. 2103/2015.

Table 6. Summary of Eco-Values in Dispatch No. 2103/2015[52]

Category	Device	Euro/Unit
1.1	Air Conditioners and Dehumidifiers <= 40kg	1.37
1.2.2	Large Household Appliances > 150kg	13.55
2.1	Cleaning Devices <= 5kg	0.17
3.2	Laptops	0.28
3.5.1	Photocopiers and Printers <= 20kg	0.34
3.13	Wireless Phones	0.06
4.4.1	Video Projectors <= 5kg	0.25

In Portugal, PROs do not have much direct leverage in influencing product design due to the fact that most products are imported into the country and not manufactured there.[41] Therefore, it can be difficult to promote end-of-life thinking at the design stage. This is a common issue for recyclers not only in Portugal, but throughout the EU, making many products, including computers, mobile phones, and printers difficult to dismantle. This causes greater portions to be lost during processing rather than recovered for value.

Researchers have analyzed recycling schemes in the context of product design, finding that manual dismantling leads to the least amount of material loss, as compared to shredding, under current technologies. However, in order for manual dismantling to be economically viable, product design must change in order to lessen the amount of time required to dismantle products and remove key portions, such as the PCB.[90, 91] Figure 19 shows example thresholds that were determined by Ardente et al. as a part of a study on the time required to dismantle electronic displays.[90] Using information such as this, dismantling time could be one metric used by policymakers to assess a given product's recyclability. Future work could include an analysis of the structure of eco-values to assess the viability of giving producers who design for the end-of-life a "discount" on the price per device that it puts on the market.

One key challenge that often arises around recyclability is the perceived tradeoff between designing for the end-of-life and designing for performance and consumer demands. Several studies have directly or indirectly analyzed the connections between designing for products' end-of-life and the durability and lifetime of those products.[92-94] However, there has been limited research completed to date on the impact of design for recyclability on product performance.

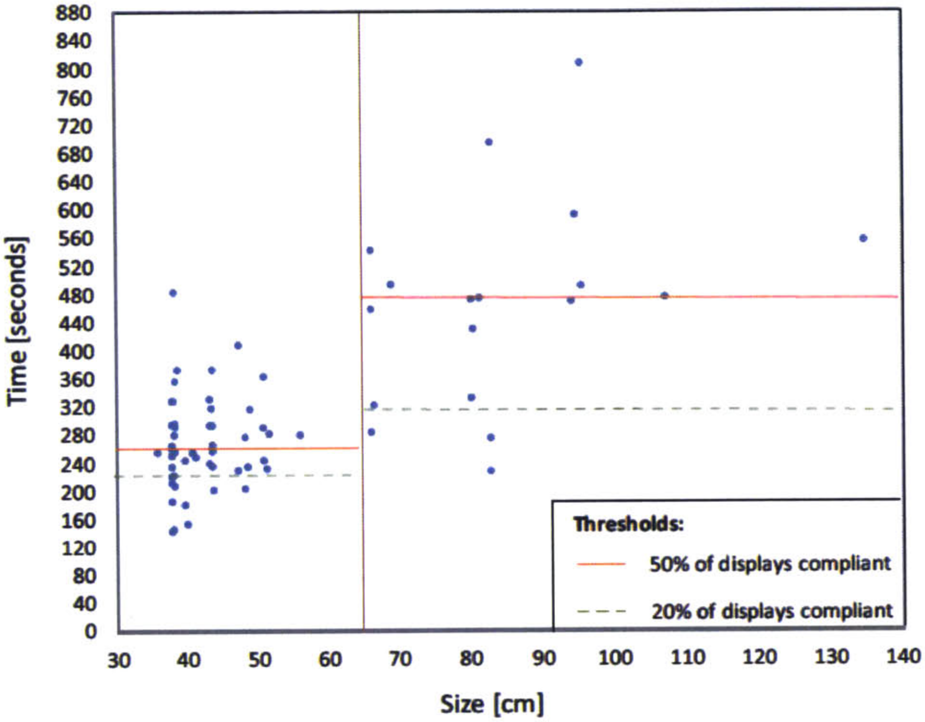


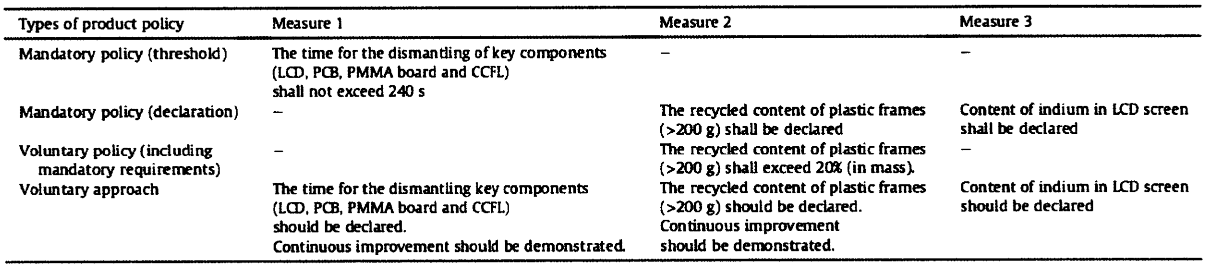
Figure 19. Example thresholds for determining an acceptable dismantling time for electronic displays (Figure Reproduced from Ardente et al.[90])

Ardente et al. also go on to state that a mix of voluntary and mandatory product policies could be used to encourage improved design for the end-of-life.[90] Through a case study on a liquid crystal display (LCD) televisions, Ardente and Mathieux identified specific examples of policies that could be implemented in order to increase recycling, as seen in Figure 20. In their estimation, mandatory policies would exist to remove underperforming products from the market, while voluntary policies would act as an aid to high performing companies.[95] These mandatory and voluntary product policies could then be analyzed using various "life cycle-based environmental assessment methods," as explored by Allacker et al.[96] These methods include the following:

- Publically Available Specification (PAS) 2050, which is "a method for assessing life cycle greenhouse gas emissions of goods and services"
- ISO/TS 14067, which specifies "principles, requirements, and guidelines for the quantification and communication of the carbon footprint of a product"
- BP X 30-323-0, which is "a repository of good practices that establishes principles and provides guidelines for environmental communications for products"

- Product Environmental Footprint (PEF), which is “a multi-criteria measure of the environmental performance of virtually any type of product throughout its life cycle”
- Resource Efficiency Assessment of Products (REAPro), which “supports transparent identification of potential resource efficiency measures for products and assessment of their improvements potentials based on a life cycle perspective”

The authors note that the PEF and REAPro methods are the best suited for analyzing product policies.[96]



Types of product policy	Measure 1	Measure 2	Measure 3
Mandatory policy (threshold)	The time for the dismantling of key components (LCD, PCB, PMMA board and CCFL) shall not exceed 240 s	–	–
Mandatory policy (declaration)	–	The recycled content of plastic frames (>200 g) shall be declared	Content of indium in LCD screen shall be declared
Voluntary policy (including mandatory requirements)	–	The recycled content of plastic frames (>200 g) shall exceed 20% (in mass).	–
Voluntary approach	The time for the dismantling key components (LCD, PCB, PMMA board and CCFL) should be declared. Continuous improvement should be demonstrated.	The recycled content of plastic frames (>200 g) should be declared. Continuous improvement should be demonstrated.	Content of indium in LCD screen should be declared

Figure 20. Examples of product measures related to various product policies (Figure Reproduced from Ardente and Mathieux, 2014)[95]

An example of a voluntary product policy that could be leveraged by Amb3E in a potential effort to incorporate environmental considerations into eco-values is the EU Ecolabel. The purpose of the EU Ecolabel is to signal to consumers which products have met a set of environmental criteria applied to the complete life cycle of that product, from material extraction to end-of-life treatment.[97] With regard to electronics, criteria have been established for imaging equipment, personal computers, notebook computers, and televisions. The criteria vary for each, and can be found in Table 7, along with the total number of devices that are certified. To date, criteria have only been established for a small number of electronic devices and a limited number of electronic products that have met the criteria.[98]

Table 7. Summary of EU Ecolabel Criteria for Electronics

Device	Criteria[99-102]	Number of Products[98, 103]
Imaging Equipment[104]	Availability of N-up printing; duplex printing; use of recycled paper; energy efficiency; restriction on indoor emissions; noise emissions; excluded or limited substances and mixtures; mercury in light sources; design for disassembly; design for recycling and/or reuse of toner and/or ink cartridges; toner and/or ink cartridge take-back requirement; substances in ink and toners; packaging; warranty, guarantee of repairs and supply of spare parts; user information; information appearing on the EU Ecolabel	0
Personal Computers	Energy savings: computer; energy savings: display; power management requirements; power supplies: internal; no mercury or display backlights; hazardous substances, mixtures, plastic parts; noise; recycled content; user instructions; design for disassembly; reparability; lifetime extension; packaging	0
Notebook Computers	Energy savings; power management; mercury in fluorescent lamps; hazardous substances and mixtures; substances listed in accordance with Article 59(1) of Regulation (EC) No 1907/2006 of the European Parliament and of the Council; plastic parts; noise; recycled content; user instructions; reparability; design for disassembly; lifetime extension; packaging; information appearing on the Ecolabel	0
Televisions	Energy savings; mercury content of fluorescent lamps; life-time extension; design for disassembly; heavy metals and flame retardants; user instructions; information appearing on the Ecolabel	1,781

Additional product policies also exist in the EU, including the Ecodesign Directive,[105] the Energy Labeling Directive,[106] and EU Green Public Procurement.[107, 108] The first two are mandatory, but EU Green Public Procurement is not. A short description of each follows:

- Ecodesign Directive – Goal is to remove the most underperforming "energy-related" products, from a sustainability perspective, from the market by setting design requirements[107]

- Energy Labeling Directive – Mandates the labeling of energy-related products with information about consumption of energy in the use phase[107]
- EU Green Public Procurement – "a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured"[107, 108]

Pastor et al. argue that these policies, along with the EU Ecolabel, often act as complementary forces in product design, but that more could be done to expand their scope. An example of this would be looking at product phases outside of energy use, including water consumption, the use of recycled materials in design, and ease of disassembly at the end-of-life stage. Additionally, they present the idea that the same methodologies used to develop the voluntary policies could be extended to mandatory policies within the EU.[107] If these product policies did shift to include a focus on a product's end-of-life, then it may be possible for policymakers in the WEEE system to consider this information in the calculation of the eco-values paid by producers.

The incorporation of environmental considerations into eco-values comes with it several challenges. The first would be the widespread adoption and adherence to voluntary and non-voluntary product policies, as described above. It would require innovations that lead to a breaking of tradeoffs between product recyclability and overall performance. Second, the lack of communication between EEE producers and preprocessing operators would make it difficult to quantify the impacts of improved product design, even if producers started to focus on the dismantling time of their products. In order for the program to bring benefits to each of the major stakeholders, recyclers would need to see a reduction in the cost to process WEEE to balance the reduced fees being paid by producers. Additionally, the lack of communication between preprocessing operators and downstream processors and refiners limits the ability of preprocessors to optimize their operations around market conditions. This communication gap can also limit the quality and quantity of valuable materials, such as PCBs, that reach end processors. Finally, this program would require buy in from a large number of producers, in conjunction with PROs, government agencies, and recyclers. While this level of coordination is possible within the EPR scheme established in Portugal, it would require an optimization of the system around total value recovery in comparison to costs, a step forward from the mass-based metrics of the WEEE Directive that drive the system today. A discussion of mass versus value based metrics follows in a later section.

5.1.3. Technological and Operational Best Practices

A key set of considerations within the Portuguese WEEE EPR system are the technologies and operations that are utilized in the preprocessing of materials. In Figure 16 above, I introduced the tradeoffs between recovery percentages, costs, material values, and tonnes preprocessed. Through this collaboration with Amb3E, I will look for ways to leverage the results of the dPFA presented here to assess the current state of the technologies being used across each of the preprocessing plants against a set of technological benchmarks. The benchmarks will focus specifically on the removal of PCBs and de-pollution activities.

5.1.3.1. European Electronics Recycling Association

The European Electronics Recyclers Association (EERA) is a professional association focused on the recycling of WEEE.[109] It is a non-profit organization, and was incorporated in 2004. Membership is open to WEEE processing and recycling companies based in Europe, and includes 38 companies across 17 countries.[110] The organization's long-term vision includes better product design for the end-of-life, increased collection, optimized recycling processes that return materials back from the urban mine, coordinated standards and regulations, and a reduction in the illegal export of WEEE.[109]

Within Portugal, the only preprocessing company that is a member of the EERA is Interecycling. Interecycling, which is located in Tondela, Portugal, was founded in 1999 as the first WEEE recycler in Portugal.[110, 111] The lack of widespread participation by preprocessors in Portugal may play a role in the absence of technological optimization across facilities. If a greater number of operators opted into the EERA, precompetitive conversations focused on best practices may lead to an increase in the overall recovery of key materials within the recycling supply chain. This optimization would hold the potential for increasing the revenues of the preprocessors and potentially leading to ways to decrease costs on a facility-by-facility basis.

5.1.3.2. WEEE Label of Excellence and EN 50625

The WEEE Label of Excellence (WEEELABEX) project was approved in 2008 and began in 2009 as a project initiated by the WEEE Forum. The purpose of the project was to establish a set of normative standards for the collection, transport, and preprocessing of WEEE, along with a framework to allow auditors to monitor compliance with the standards. The first set of WEEELABEX normative treatment standards were published in 2011. In 2013, the WEEELABEX Organization was founded in Prague in order to oversee the auditing process.[112-114]

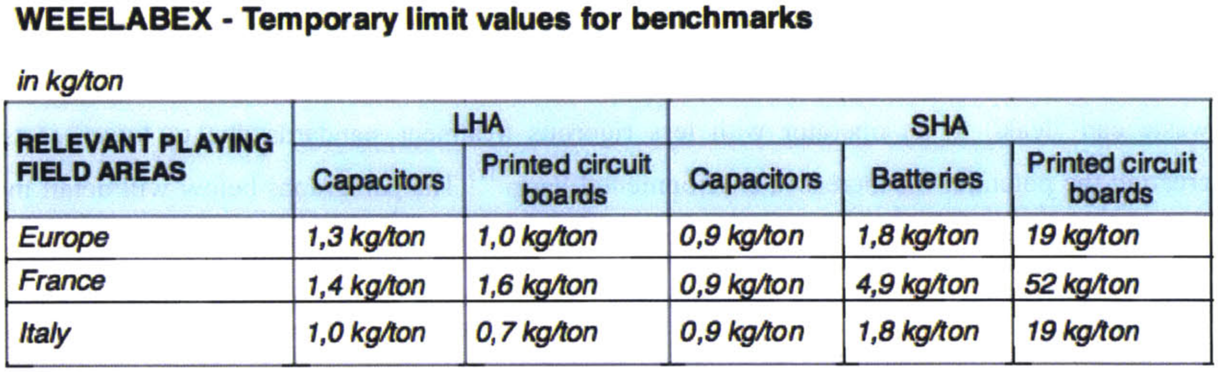
The WEEELABEX standards provide a useful set of benchmarks for operators throughout the recycling supply chain, but they are not mandated for all stakeholders. This means that only those operators that seek certification are audited and held to the standards, which are described in more detail below. In an attempt to bring all operators into compliance with these standards, CENELEC, the European Committee for Electrotechnical Standardization, is in the process of developing and publishing EN 50625: Collection, Logistics, and Treatment Requirements for WEEE.[112] These standards, which are based on the WEEELABEX normative treatment document, align with Article 8(5) of the WEEE Directive, which is titled "Proper Treatment" and reads:

> "For the purposes of environmental protection, Member States may set up minimum quality standards for the treatment of WEEE that has been collected. Member States which opt for such quality standards shall inform the Commission thereof, which shall publish these standards. The Commission shall ... request the European standardization organizations to develop European standards for the treatment, including recovery, recycling and preparing for re-use, of WEEE. Those standards shall reflect the state of the art. In order to ensure uniform conditions for the implementation of this Article, the Commission may adopt an implementing act laying down minimum quality standards based in particular on the standards developed by the European standardization organizations."[36]

In addition to the regulatory impetus to implement common standards in the EU, a number of organizations, including CECED, DIGITALEUROPE, EERA, and the WEEE Forum are calling to make compliance with EN 50625 mandatory following its publication and the completion of an impact assessment. These organizations, in a joint document, have taken the position that the widespread adoption of EN 50625 would level the playing field in WEEE recycling. Currently, waste can "leak" to an operator with less rigorous treatment standards due to lower costs, creating the potential for increased environmental harm.[115] The paragraphs below will detail the WEEELABEX normative treatment standards, which form the foundation of EN 50625.

The normative treatment standards include administrative and organizational, as well as technical requirements. The document provides general guidelines for all types of devices, and itemized requirements for CRT display appliances, flat panel displays, lamps, temperature exchange equipment, and cooling and freezing appliances. The treatment steps that are focused on include handling, storage, de-pollution, recycling, recovery, and disposal.[116] This work will focus on the de-pollution stage, and specifically, the removal of PCBs. In accordance with Annex VII of the WEEE Directive and the WEEELABEX normative treatment document, all PCBs with a surface area that exceeds 10 square centimeters must be removed from separately collected devices.[36, 116, 117]

In order to monitor compliance with this requirement, WEEELABEX has developed a *Documentation to Measure Depollution.* This document covers similar products as those found in the normative treatment standards, and covers in detail the sampling and analyses required in order to measure compliance with the depollution standards.[117] As a part of this document, WEEELABEX has set temporary benchmarks for the recovery of capacitors, batteries, and printed circuit boards from large household appliances (LHA), small household appliances (SHA), CRT screens, flat panel display screens, and cooling and freezing equipment. Due to the fact that these product classifications differ from the SACD discussed above, the products included in each category are included in Appendix H. Figure 21 shows the values that have been calculated for LHA and SHA across three areas, Europe, France, and Italy. Values have yet to be developed specifically for Portugal. However, using the data collected for and used in the dPFA described above, I have calculated an approximate value between 40 and 50 kg/tonne for Portugal's preprocessing facilities, however, there is significant uncertainty in this value due to the heterogeneity of WEEE. One goal of the collaboration with Amb3E will be to further validate this value and assess the possibility for including it in future WEEELABEX documents.



WEEELABEX - Temporary limit values for benchmarks

in kg/ton

RELEVANT PLAYING FIELD AREAS	LHA		SHA		
	Capacitors	Printed circuit boards	Capacitors	Batteries	Printed circuit boards
Europe	*1,3 kg/ton*	*1,0 kg/ton*	*0,9 kg/ton*	*1,8 kg/ton*	*19 kg/ton*
France	*1,4 kg/ton*	*1,6 kg/ton*	*0,9 kg/ton*	*4,9 kg/ton*	*52 kg/ton*
Italy	*1,0 kg/ton*	*0,7 kg/ton*	*0,9 kg/ton*	*1,8 kg/ton*	*19 kg/ton*

Figure 21. WEEE Forum Temporary Limit Values for Benchmarks (Figure Reproduced from WEEELABEX Documentation to Measure Depollution[117])

Within Portugal, the only preprocessing companies that are certified as WEEELABEX Operators are Interecycling – Sociedad de Reciclagem SA (Recycling Company) and Renascimento – Gestão e Reciclagem de Residuos LDA (Waste Management and Recycling).[118] Interecycling is audited for LHA, SHA, CRT, and cooling and freezing appliances and uses both manual dismantling and mechanical treatment. It is commissioned by Amb3E. Renascimento is audited for LHA and SHA and used both manual dismantling and mechanical recovery. It is also commissioned by Amb3E.[118] The small number of certified facilities helps to validate the findings presented in this thesis related to recycling system losses, and points to the need for mandated technological benchmarks. Therefore, even if EN 50625 does not become a mandate, the establishment of a benchmark around PCB recovery specific to Portugal could help to reduce economic losses and environmental impacts, and increase secondary materials recovery.

5.2. Mass Versus Value Based Metrics

Apart from the collaboration with Amb3E, another way to capture the economic value currently being lost in preprocessing operations would be to target the current regulatory infrastructure. This section will focus on the need to consider value based metrics in addition to mass based metrics in order to increase the recovery of valuable materials such as precious metals.

Figure 22 shows by product group, by mass (dotted, light grey), and by value (striped, dark grey), the percentage of material recovered from 2006 - 2014. These data were calculated using material recovery data within the PFA. Current EU legislation describes mass-based targets and

Figure 22 shows that these mass targets - ranging from 65-75% according to the WEEE Directive - are met. However the value recovered is approximately 40-50% for all categories except for printers. Previous authors have highlighted this gap between the metrics of system performance as well, and noted that mass-based recycling targets do not encourage the targeting of precious metals and other valuable materials locked into complex devices.[21] This work further supports this conclusion.

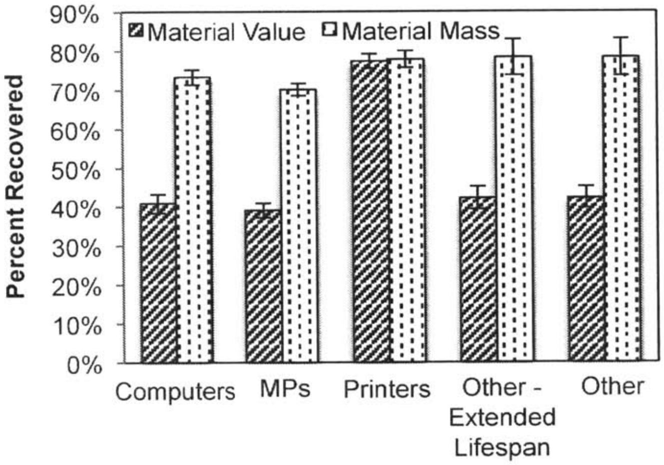


Figure 22. Comparison of material mass recovered versus material value recovered during preprocessing for all product groups as calculated in the recycling system dPFA

Researchers have also studied the environmental and resource availability impacts of electronic devices and the materials of which they are comprised. Several of these studies have included an analysis of effective metrics for measuring impact on a large scale.[6, 12, 13, 21, 67, 119-121] These studies are not confined to the economics of recycling, and therefore also identify and discuss critical materials such as certain rare earth elements (REE) that are oftentimes not recovered under present day policies and recovery infrastructures.

The WEEE and Battery Directives do point to the need for reducing toxins and protecting environmental health, but a more robust set of metrics that incorporate overall environmental impact in conjunction with the economic value and availability of those materials could help to strengthen the underlying goals of the directives. This could also help to lead to a cascading effect, where the Directives help to inform future decision making around device design, collection, and recycling.

There are two key factors that will help to drive the success of any metric aimed at improving the WEEE or Battery Directives. The first is to utilize industry best practices to form robust and innovative metrics that not only aim at increasing recycling rates, but also evaluate and help to improve the overall system, from device design and manufacturing to its end-of-life. Secondly, the actual implementation of these potential changes would require buy in both from policymakers and the public, meaning that the inclusion of these stakeholders throughout the process would be vital to its ultimate success. Overall, there is a need for additional research on the value of the materials lost during the processing of WEEE that can be directly attributed to the regulations as written. In addition, it will be necessary to consider more holistic metrics, beyond only mass or value-based components, in local and national policies.

5.3. European Commission Circular Economy Strategy

An example of research that is currently underway in the EU, and is seeking to identify connections between more holistic WEEE end-of-life policies and material impacts, is the European Commission Circular Economy Strategy. In order to do this, the European Commission has carried out a series of proposals and reports aimed at analyzing the impact of the WEEE and Battery Directives, as well as other regulations on resource recovery and the European economy.[122-130] Much of this work has centered on the group's Circular Economy Strategy, which is projected to be fully laid out by the end of 2015.[130] Among the findings listed, several relate to the connection between EU policies and the recovery of materials that can re-enter the market as secondary raw materials.[128] These reports stress the importance of considering the entire life cycle of the device when analyzing its environmental and economic impacts, and the role that metrics can play in the outcomes of implemented legislation.[124, 125] A specific example is discussed in relation to the Battery Directive, where mass-based targets that do not differentiate between chemical compositions can lead to the loss of lighter batteries that may contain more valuable, but difficult to recover materials.[124] In addition, a separate analysis of mobile phones stressed the importance of connecting market forces with appropriate policies in order to ensure that devices can be repaired, reused, and recycled as effectively as possible.[129] Lastly, progress towards the implementation of the Circular Economy in the EU has been aided by the WEEE and Battery Directives, but a focus on resource efficiency is needed in order to catalyze system-wide improvements in device design, manufacturing, use, and recycling.[126, 127]

The current framing and implementation of the WEEE and Battery Directives guide EU WEEE policies, but the present focus on mass-based metrics do not sufficiently target specific materials of importance. There are several steps that could be taken to increase the recovery of targeted materials, while continuing to carry out the present day objectives of lawmakers in the EU and the Circular Economy Strategy. Therefore, I offer the following two recommendations: (1) to better align the WEEE Directive and Battery Directive with the European Commission Strategy on the Circular Economy; and (2) to increase research on the impacts of the WEEE Directive on the availability of secondary materials resources, the profits generated from recycled goods, and the environmental impact of key materials. Aligning the WEEE and Battery Directives with the Circular Economy Strategy could allow for newly designed targets that focus on specific materials that can be cycled from end-of-life devices back to the secondary raw materials market. Lastly, increased research on materials availability, and economic and environmental impacts would aid more informed policy decisions about the metrics used in the Directives, and the devices that should be analyzed in most detail.

Chapter 6: Conclusions

In the preceding chapters, I set out to answer two major questions:

- Can the economics of the recycling of small appliances and computer devices drive increased materials recovery?
- What market level and operational dynamics must be leveraged to capture the value of small appliances and computer devices at the end-of-life given material composition information?

In Chapter 1, I provided motivation for the work by explaining that operators in the Portuguese WEEE recycling system, like many throughout the EU, do not properly account for the materials within devices when making decisions about how to recycle end-of-life SACD. In Chapter 2, I analyzed the current status of research related to EEE composition and material flow modeling, and also detailed the EPR scheme that forms the backbone of WEEE recycling in Portugal. In Chapter 3, I applied a dPFA to the case of Portugal using detailed data for SACD sales, generation, collection, and preprocessing, and identified a potential material value not recovered of at least \$70m for sixteen preprocessing plants from 2006-2014. I also provided a framework for informing future investments in SACD preprocessing. In Chapter 4, I detailed the methodology that I employed in order to qualitatively and quantitatively assess the composition of mobile phones outside of the PCB and the need to better understand the evolving composition of mobile phones over time. Future work should include a continuation of this analysis. Finally, in Chapter 5, I explored various methods for capturing the value that is currently going unrecovered during preprocessing, including, a collaboration between MIT, Amb3E, IST, and 3DRIVERS, and a drive towards value based metrics. I concluded with a synopsis of the European Commission Circular Economy Strategy, which holds the potential to impact several stages of the WEEE recycling system.

In response to my first research question, I believe that this work has shown that the economics of SACD recycling can in fact help to drive increased materials recovery, so long as preprocessing operators work diligently to optimize their facilities for the recovery of valuable materials.

In response to my second research question, this work proposed several market level and operational dynamics that must be leveraged, including collaborations between research institutions and PROs, a consideration of product recyclability and eco-efficiency when calculating eco-values, the establishment of technological benchmarks across all facilities, and a focus on value based metrics.

I recommend that the next steps in this work focus in on four key areas:

1. Additional materials characterization work aimed at identifying the material composition of devices outside of the battery and PCB, as well as the changing composition of devices over time
2. The establishment of mandatory technological benchmarks to be applied to all preprocessing operators to ensure that each facility is operating on a level playing field
3. An analysis of the WEEE Directive, the European Commission Circular Economy Strategy, and potential value based metrics to analyze their potential impacts on secondary materials recovery.
4. A quantitative analysis of different scenarios for the demand of secondary materials and the impact of demand evolutions on the overall materials recovery system.

Appendix A. Dynamic Product Flow Analysis Manual

Sales Data ("SDA_Sales_Generation_Collection" Tab)

- The sales data is shown in three forms, in units, by weight, and by unit weight
- In the "SDA_Sales_Generation_Collection" tab, data is shown for 2007, 2008, 2010, 2011, 2012, 2013, and 2014. The "Sales Data All" tab shows the data for the other years analyzed in the PFA.
- Only the data from 2007-2014 (excluding 2009) was itemized by product, so a challenge was connecting the itemized and not itemized data. The data that was not itemized by product was organized by WEEE Category. This data can be found in the "Sales Data All" tab.
- Within "Sales Data All" tab
  - Most concerned with 2000-2013
  - In order to combine different data sets, I needed to understand the composition of product groups 1-5 in WEEE Category 3 and into WEEE Categories 2 and 4-10. These values were calculated using the itemized data from 2007-2013, and can be found in the tables that start in cells I120 and I129 of the "SDA_Sales_Generation_Collection" tab. These tables can be read as "xx.xx% of WEEE Category x is composed of product group x." One key note is that for product groups 1, 2, and 3, the masses are only derived from WEEE Category 3.
  - The output of this analysis is a table with the units and mass sold for product groups 1-5 from 2000-2014. This table can be found starting in cell A170 in the "SDA_Sales_Generation_Collection" tab.

Lifespan Modeling ("SDA_Sales_Generation_Collection" Tab)

- The lifespan modeling was completed for each of the five product groups separately. There are a set of three tables for each of the product groups. The tables run concurrently horizontally. The titles of each are below:
  - Percent Sold in a Given Year that is Generated in a Given Year
    - The lifespans (mean and standard deviation) used for each of the product groups can be found in the table that starts in cell A125 in the "SDA_Sales_Generation_Collection" tab.

        - The formula used to calculate the lifespan distributions was developed based on work completed by T. Reed Miller, and can be found below.
        - =IFERROR(LOGNORM.DIST(year generated - year sold,LN(mean lifespan),LN(SD of lifespan),FALSE),0)
    - Quantity Sold in a Given Year that is Generated in a Given Year
        - =percent sold in a given year that is generated in that year * quantity sold in that year

Collection (“SDA_Sales_Generation_Collection” Tab)

- A table of collection rates by product group and year can be found starting in cell A214 of the “SDA_Sales_Generation_Collection” tab. These values were carried throughout the model, and were used to generate the tables titled “Quantity Sold in a Given Year that is Generated and Collected in a Given Year.” The formula used can be seen below.
        - =quantity sold in a given year that is generated in a given year * collection rate for that product group in that year
- A separate table, “Mass Sold in a Given Year that is Generated and Collected in a Given Year” is also included. This table is used to generate the table that shows the total tonnes collected by year and by material type (silver, gold, palladium, etc.). The values in the column labeled “Total (Tonnes),” such as those found in the column that begins in cell BT233, are carried throughout the model.
- *Calculating Uncertainty with Crystal Ball: A normal distribution was used to calculate the uncertainty, and the parameters used can be found in the tables that being in cells H214 and H234.*

Composition (“Composition_SDA” Tab)

- The “Composition_SDA” tab contains the material compositions used for each of the five product groups. The data is presented in two ways, in grams and in mass percentages. Only the percentages are carried throughout the model. The compositions are divided into two categories for each product group, 2001-2005 and 2006-2011. The values found in the columns labeled “CB Value,” referring to Crystal Ball, are carried throughout the model.
- *Calculating Uncertainty with Crystal Ball: Each of the mass percent tables contain the information used to define the uncertainty analysis as it related to the material*

composition data. Three different methods were used depending on the number of available data points, uniform distributions, triangle distributions (TD), or data quality indicators (Pedigree analysis). If a uniform distribution was used, the columns labeled "Minimum (a for TD)" and "Maximum (b for TD)" will be filled in. If a triangle distribution was used, those two columns will be filled in, in addition to the "Most Common (c for TD)" column. If a Pedigree analysis was performed, the columns labeled "PEDIGREE Values," "PEDIGREE (Uncertainty Factors)," "PEDIGREE (Associated Uncertainty (Ln(UI)^2)," "Geo Mean," "Geo SD," "Arithmetic SD," and "Arithmetic Mean" will be filled in. For the Pedigree analysis, it is important to note that there is a different data table for each individual source, since the uncertainty factors vary. The source is noted at the top of each table.

Preprocessing ("Preprocessing" Tab)

- The "Preprocessing" tab contains the data used to model the 16 facilities, including the intermediate and final waste fractions, the material compositions of those fractions, and the recovery percentages. The first sixteen tables, labeled "Company 1" through "Company 16," contain data that was input from 16 individual excel sheets, one for each company.
- Moving down the sheet, the table titled "Recovery Percentage by Company and Material," which starts in cell A635, contains a summary of the data in the 16 company level tables. This data was used to calculate total losses.
- Continuing down the sheet are two sets of tables, with five individual tables in each, one for each of the product groups. The first set corresponds to the material mass recovered during preprocessing by year, and the second set corresponds to the economic value recovered by material and year during preprocessing.
    - The material mass recovered was calculated by multiplying the total mass collected by the *sumproduct* of the percent of WEEE received and the recovery percentage of that material across the 16 companies.
    - The economic value recovered was calculated by multiplying the material mass recovered by the value of the material, including the appropriate conversion factor. The economic values used for all materials included in the analysis, along

with relevant conversion factors and adjustments for inflation, can be found in the "Economic Data" tab. All values in the dPFA are presented in USD.

- Additional analyses were carried out using data from Company 1, Company 2, and Company 3 in order to calculate the approximate fixed and variable costs associated with each preprocessing operation. This analysis focused on "other metals."
    - The first table begins in cell AT60, and calculates the mass of other metals in the output of each of the preprocessing operations for that company.
    - The next table, moving to the right, calculates the percent of the total mass, by material, of the input materials for preprocessing for each operation.
    - The tables that follow use the values for copper and gold (as a proxy for "other metals") to analyze the fixed and variable costs. Cost data for Companies 1-3 can be found in the "Preprocessing_Costs" and "Preprocessing_Costs_123_Edited" tabs.
- *Calculating Uncertainty with Crystal Ball: Uncertainty was calculated in the "Recovery Percentage by Company and Material" table, which begins in cell A635. A Beta Distribution was used to calculate the uncertainty, and the parameters used can be found in the tables that begin in cells O637, AA637, AN637, and AZ637.*

Appendix B. WEEE Subcategories

One of the major challenges in completing this analysis was assigning the 10 WEEE categories and the devices within each one to the 5 product groups that were defined in my model. WEEE category 3 was broken down into computers (product group 1), phones (product group 2), and printers (product group 3), with all other product types placed within one of the two "other" categories (product groups 4 and 5). All of the devices within product groups 1-3 fall into WEEE category 3. Then, each of the devices in WEEE categories 2 and 4-10 were characterized into one of the two "other" categories because no computers, phones, or laptops were included in these groups. WEEE category 1 was not included in this analysis.

These product groups were delineated using information available from the Associação Nacional para o Registo de Equipamentos Eléctricos e Electrónicos (ANREEE) in Portugal.[40] ANREEE is the national data registry entity for EEE in Portugal that was established by manufacturers and distributors.[39] Once each device was categorized properly, the sales data were used in the next stage of the model, generation.

WEEE Subcategories[58-64]	Product Groups
2.1. Vacuum cleaners	5
2.2. Carpet cleaners	5
2.3. Other cleaning devices	5
2.4. Equipment for sewing and textile transformation	4
2.5. Ironing equipment	5
2.6. Toasters	5
2.7. Fryers	5
2.8. Coffee machines	5
2.9. Electric knives	5
2.10. Hair dryers, shaving machine	5
2.11. Clocks, wrist watches	4
2.12. Scales	5
2.13. Other small appliances	5
3.1. Mainframe computers	1
3.2. Minicomputers	1
3.3. Printing units	3
3.4. Personal computers	1
3.5 Laptop computers	1
3.6. Notebook Computers	1

3.7. Notepad	1
3.8. Printers	3
3.9. Copiers	3
3.10. Electric type writing machines	5
3.11. Pocket and desk calculator	5
3.12. Other equipment to collect, store, process and present information electronically	4
3.13. Systems and user terminals	4
3.14. Fax Machines	3
3.15. Telex	5
3.16. Telephones	2
3.17. Public post telephones	4
3.18. Cordless telephones	2
3.19. Cell phones	2
3.20. Automatic answering machines	4
3.21. Other equipment to transmit sound, image or other information by telecommunication	5
3.22. Other telecom and informatics equipment	5
4.1. Radio devices	5
4.2. Televisions	5
4.3. Video camera	5
4.4. Video recorder	5
4.5. Hi Fi recorder	5
4.6. Audio amplifier	5
4.7. Music instruments	4
4.8. Other equipment to record, reproduce sound or image including other than telecommunication	5
4.9. Other consumer equipment	5
5.1. Lighting equipment for fluorescent lights	5
5.6. Other lighting equipment	5
6.1. Drills	5
6.2. Saws	5
6.3. Sewing machines	4
6.4. Equipment to sand, shred, cut, bend, drill, metal and other materials	5
6.5. Tools to nail, bolt, or similar use	5
6.6. Tools to weld	5
6.7. Equipment to spray	5
6.8. Tools to lawn cut or gardening activities	5
6.9. Other electric tools (except large fixed industrial)	5
7.1. Set of electric trains and track cars	5

7.2. Video game portable consoles	4
7.3. Video games	4
7.4. Computers for cycling, diving, etc.	5
7.5. Sports equipment with electrical or electronic components	5
7.6. Slot machines	4
7.7. Other toys	5
8.1. Radiotherapy equipment	4
8.2. Cardiology equipment	4
8.3. Dialysis equipment	4
8.4. Ventilator	4
8.5. Nuclear medicine equipment	4
8.6. In vitro diagnosis lab equipment	4
8.7. Analyzers	4
8.9. Fertility tests	4
8.10 Other devices to detect, avoid, control, treat injuries	4
8.11 Other medical devices	4
9.1. Smoke detectors	4
9.2. Heat regulators	4
9.3. Thermostats	4
9.4. Devices to measure, weight, regulate for domestic or lab use	4
9.5. Other control and command instruments used in industrial facilities	4
10.1. Automatic dispenser of hot beverages	5
10.3. Dispenser of solid products	5
10.4. Cash dispenser machines	4
10.5. Other dispenser machines	5

Appendix C. Material Composition Data for Product Groups 1- 5

The following tables contain the data used in the model to characterize the composition of the devices within each of the product groups. The data I cite to estimate relative material composition sometimes included composition of only the device PCB rather than the entire device. To account for this, the percent mass of each type of material within a given device was used in my analysis. The assumed total masses for product groups 1-5 can be found in the last row of each table. The tables contain the mass used for the material composition of each of the five product groups, and show which data sources contain material composition information for the device PCB only and the entire device. In addition, due to the heterogeneity of the devices in product groups 4 and 5, and the limited data on the material characterization of many of the devices, the material characterizations of these levels are assumed to be identical. In these tables, hyphens are not assumed to be zeros for the purposes of calculating the averages.

In order to calculate uncertainty for the composition of each product group, three methods were utilized: continuous distributions, triangle distributions, and data quality analyses. The parameters used in the uncertainty analysis for the device composition data are annotated in each table as shown below, and were decided based on the percent mass of each material in comparison to the total mass. If no cell in a given row is highlighted, then a data quality analysis was used to calculate uncertainty.

- Continuous Distribution: Minimum Max
- Triangle Distribution: Minimum Max Mode/Most Likely Value

Material composition data used for product group 1, computing devices

Material	Composition (Grams, 2001-2014)										Average
	Computer[14]	Computer[14]	Computer[14]	Desktop PC[8]	Notebook PC[8]	Laptop[131]	Laptop[131]	Laptop[131]	Laptop[131]	Laptop[131]	
Silver	1.80	0.97	-	0.21	0.60	-	-	-	-	-	0.90
Gold	0.82	0.30	-	0.09	0.35	-	-	-	-	-	0.39
Palladiu	0.88	0.11	-	0.06	0.11	-	-	-	-	-	0.29
Platinum	-	-	-	-	-	-	-	-	-	-	-
Copper	580	-	550	110	110	84	24	39	35	74	180
Cobalt	-	-	-	-	-	-	-	-	-	-	-
Nickel	66	4.4	6.8	-	-	-	-	-	-	-	26
Tin (Sn)	220	92	-	6.8	6.0	-	-	-	-	-	81
Tantalum	-	-	-	-	-	-	-	-	-	-	-
Tungsten	-	-	-	-	-	-	-	-	-	-	-
Other Non-Ferrous Metals	130	-	-	-	120	450	230	220	430	580	310
Ferrous	190	-	79	-	790	840	520	270	270	400	420
Plastics	1300	-	1300	-	1000	960	1,10	400	600	780	930
Composi	-	-	-	-	-	-	-	-	-	-	-
Glass	-	-	-	-	-	450	230	220	430	580	570
Other	-	-	-	-	-	-	-	-	-	-	910
Assumed Total Mass	4,000	4,000	4,000	4,000	4,000	3,400	2,700	1,700	2,400	3,500	3,400

Material composition data used for product group 2, telecommunications devices (2001-2005)

Material	Composition (Grams, 2001-2005)		Average
	Mobile Phone[16]	Mobile Phone[23]	
Silver (Ag)	0.11	0.26	0.19
Gold (Au)	0.026	0.030	0.03
Palladium (Pd)	0.01	0.02	0.02
Platinum (Pt)	0.004	0.008	0.01
Copper (Cu)	9.3	9.8	9.6
Cobalt (Co)	-	-	-
Nickel (Ni)	0.70	0.75	0.73
Tin (Sn)	0.43	0.75	0.59
Tantalum (Ta)	-	-	-
Tungsten (W)	-	-	-
Other Non-Ferrous Metals	2.6	-	2.6
Ferrous Metals	6.6	-	6.6
Plastics	51	-	51
Composite	-	-	-
Glass	8.6	-	8.6
Other	-	-	.03
Assumed Total Mass	80	80	80

Material composition data used for product group 2, telecommunications devices (2006-2014)

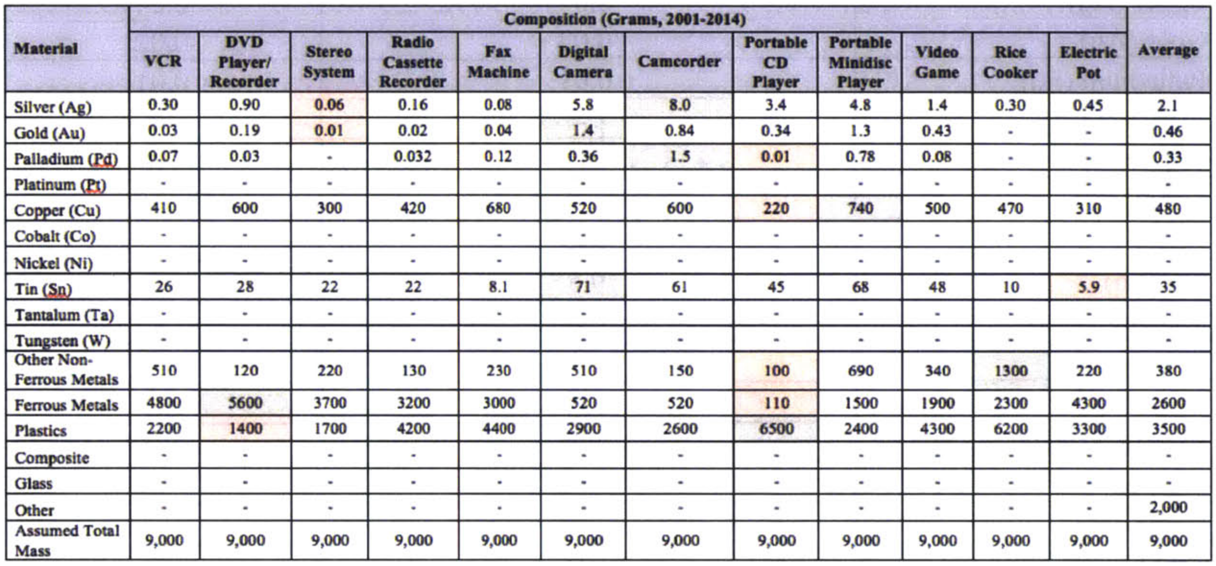
Material	Composition (Grams, 2006-2014)			Average
	Mobile Phone[19]	Mobile Phone[18]	Mobile Phone[15]	
Silver (Ag)	0.25	0.50	-	0.38
Gold (Au)	0.02	0.03	.02	0.023
Palladium (Pd)	0.01	-	-	0.01
Platinum (Pt)	-	-	-	-
Copper (Cu)	9.0	15	-	12
Cobalt (Co)	3.8	4.0	-	3.9
Nickel (Ni)	-	2.0	-	2.0
Tin (Sn)	-	1.0	1.0	1.00
Tantalum (Ta)	-	0.50	.02	0.26
Tungsten (W)	-	-	1.2	1.2
Other Non-Ferrous Metals	-	2.0	-	2.0
Ferrous Metals	-	3.0	-	3.0
Plastics	-	50	-	50
Composite	-	4.0	-	4.0
Glass	-	15	-	15
Other	-	-	-	3.2
Assumed Total Mass	98	98	98	98

Material composition data used for product group 3, printers

Material	Composition (Grams, 2001-2014)	Average
	Printer[8]	
Silver (Ag)	0.04	0.04
Gold (Au)	0.02	0.02
Palladium (Pd)	0.01	0.01
Platinum (Pt)	-	-
Copper (Cu)	340	340
Cobalt (Co)	-	-
Nickel (Ni)	-	-
Tin (Sn)	9.5	9.5
Tantalum (Ta)	-	-
Tungsten (W)	-	-
Other Non-Ferrous Metals	130	130
Ferrous Metals	2900	2900
Plastics	3700	3700
Composite	-	-
Glass	-	-
Other	-	920
Assumed Total Mass	8,000	8,000

Material composition data used for product group 4, other with 20+ year lifespan

Note: The data shown is for a collection of devices included in the "other" product group, and is assumed to be a representative sample.[8]



Material	Composition (Grams, 2001-2014)												Average
	VCR	DVD Player/ Recorder	Stereo System	Radio Cassette Recorder	Fax Machine	Digital Camera	Camcorder	Portable CD Player	Portable Minidisc Player	Video Game	Rice Cooker	Electric Pot	
Silver (Ag)	0.30	0.90	0.06	0.16	0.08	5.8	8.0	3.4	4.8	1.4	0.30	0.45	2.1
Gold (Au)	0.03	0.19	0.01	0.02	0.04	1.4	0.84	0.34	1.3	0.43	-	-	0.46
Palladium (Pd)	0.07	0.03	-	0.032	0.12	0.36	1.5	0.01	0.78	0.08	-	-	0.33
Platinum (Pt)	-	-	-	-	-	-	-	-	-	-	-	-	-
Copper (Cu)	410	600	300	420	680	520	600	220	740	500	470	310	480
Cobalt (Co)	-	-	-	-	-	-	-	-	-	-	-	-	-
Nickel (Ni)	-	-	-	-	-	-	-	-	-	-	-	-	-
Tin (Sn)	26	28	22	22	8.1	71	61	45	68	48	10	5.9	35
Tantalum (Ta)	-	-	-	-	-	-	-	-	-	-	-	-	-
Tungsten (W)	-	-	-	-	-	-	-	-	-	-	-	-	-
Other Non-Ferrous Metals	510	120	220	130	230	510	150	100	690	340	1300	220	380
Ferrous Metals	4800	5600	3700	3200	3000	520	520	110	1500	1900	2300	4300	2600
Plastics	2200	1400	1700	4200	4400	2900	2600	6500	2400	4300	6200	3300	3500
Composite	-	-	-	-	-	-	-	-	-	-	-	-	-
Glass	-	-	-	-	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-	-	-	-	2,000
Assumed Total Mass	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000

Material composition data used for product group 5, other with 0-19 year lifespan

Note: The data shown is for a collection of devices included in the “other” product group, and is assumed to be a representative sample.[8]

Material	Composition (Grams, 2001-2014)												Average
	VCR	DVD Player/ Recorder	Stereo System	Radio Cassette Recorder	Fax Machine	Digital Camera	Camcorder	Portable CD Player	Portable Minidisc Player	Video Game	Rice Cooker	Electric Pot	
Silver (Ag)	0.30	0.90	0.06	0.16	0.08	5.8	8.0	3.4	4.8	1.4	0.30	0.45	2.1
Gold (Au)	0.03	0.19	0.01	0.02	0.04	1.4	0.84	0.34	1.3	0.43	-	-	0.46
Palladium (Pd)	0.07	0.03	-	0.032	0.12	0.36	1.5	0.01	0.78	0.08	-	-	0.33
Platinum (Pt)	-	-	-	-	-	-	-	-	-	-	-	-	-
Copper (Cu)	410	600	300	420	680	520	600	220	740	500	470	310	480
Cobalt (Co)	-	-	-	-	-	-	-	-	-	-	-	-	-
Nickel (Ni)	-	-	-	-	-	-	-	-	-	-	-	-	-
Tin (Sn)	26	28	22	22	8.1	71	61	45	68	48	10	5.9	35
Tantalum (Ta)	-	-	-	-	-	-	-	-	-	-	-	-	-
Tungsten (W)	-	-	-	-	-	-	-	-	-	-	-	-	-
Other Non-Ferrous Metals	510	120	220	130	230	510	150	100	690	340	1300	220	380
Ferrous Metals	4800	5600	3700	3200	3000	520	520	110	1500	1900	2300	4300	2600
Plastics	2200	1400	1700	4200	4400	2900	2600	6500	2400	4300	6200	3300	3500
Composite	-	-	-	-	-	-	-	-	-	-	-	-	-
Glass	-	-	-	-	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-	-	-	-	2,000
Assumed Total Mass	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000

Appendix D. Summary of Mobile Phones Analyzed

Number	Brand	Model	Year	Batch Number	Weight - With Battery (g)
49	Nokia	NHE-5NX (1610)	1996	1	255
50	Nokia	NHE-5SX (1611)	1996	1	255
51	Nokia	NHE-5SX (1611)	1996	1	255
52	Nokia	NHE-5SX (1611)	1996	1	255
44	Nokia	3510i	2002	1	106
45	Nokia	3510i	2002	1	106
46	Nokia	3510i	2002	1	106
47	Nokia	3510i	2002	1	106
48	Nokia	3510i	2002	1	106
21	Motorola	601(Y) (V60i)	2002	1	103
43	Nokia	6010	2003	1	107
5	LG	VX6100	2004	1	110
10	Samsung	SPH-A660	2004	1	100
17	Motorola	610214611277 (V188)	2004	1	79
19	LG	VX3100	2004	1	88
32	Nokia	3120b (RH-50)	2004	1	84
39	Motorola	V3 Razr	2004	1	95
37	LG	C2000	2005	1	96
38	Motorola	V325i H/W	2005	1	116
4	LG	VX8100	2005	1	116
36	Nokia	6133 (RM-126)	2006	1	112
3	LG	VX8300	2006	1	110
11	Nokia	6085H	2006	1	84
23	Nokia	6133	2006	1	112

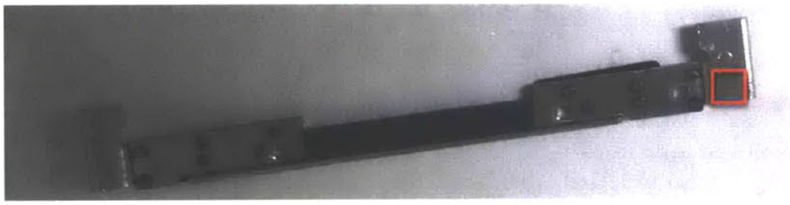
Number	Brand	Model	Year	Batch Number	Weight - With Battery (g)
6	Samsung	SCH-U340	2007	2	80
13	UTStarcom	PCS1450VMR	2007	2	71
15	LG	VX10000	2007	2	133
24	Samsung	SCH-U540	2007	2	80
26	LG	VX8550RLK	2007	2	92
30	Apple	A1203	2007	2	135
33	LG	VX8350	2007	2	94
35	Sanyo	SCP-3200	2007	2	96
42	Blackberry	8320	2007	2	111
7	Samsung	SGH-A777	2008	2	96
9	Samsung	SGH-A137	2008	2	81
16	LG	VX9100M	2008	2	120
22	Blackberry	9000	2008	2	136
31	LG	LX165	2008	2	77
41	LG	LX165	2008	2	77

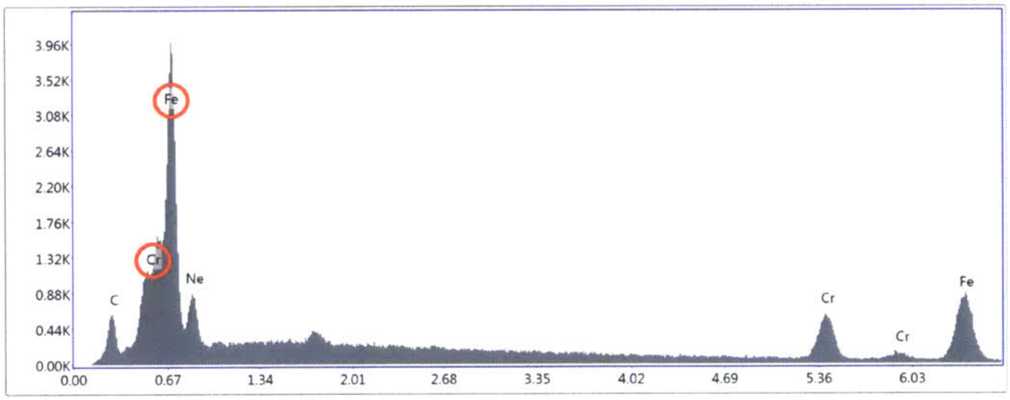
Number	Brand	Model	Year	Batch Number	Weight - With Battery (g)
1	LG	VX9200M	2009	3	107
2	LG	VX9600WOK	2009	3	108
8	Nokia	2320c-2b	2009	3	76
12	Nokia	1661-2b	2009	3	82
14	LG	GR500	2009	3	108
18	LG	VX9200M	2009	3	107
34	Samsung	SGH-A167	2009	3	88
40	Samsung	SCH-U960	2009	3	140
25	Samsung	SGH-A927	2010	3	99
20	Pantech	P6010	2011	3	127
29	Apple	A1349	2011	3	136
28	LG	440G	2012	3	102
27	Samsung	SGH-S150G (GP)	2013	3	79

Appendix E. SEM/EDS Results

For this analysis, only the qualitative portion of the scanning electron microscopy/energy dispersive spectroscopy (SEM/EDS) output data was used. The machine used to carry out the analysis was a Philips XL30 FEG ESEM. The Philips machine is a "high performance, extremely flexible and well-equipped microscope for general-purpose microscopy, low-vacuum and environmental scanning microscopy (ESEM). It is also equipped with a Peltier Stage. Resolution at 30KV is 3.5 nm. The minimum magnification is about 20x." Elements marked with a red circle denote potential elements of interest when analyzing the possibility of increasing the recovery of materials located outside of the PCB. This data was used in Chapter 4.

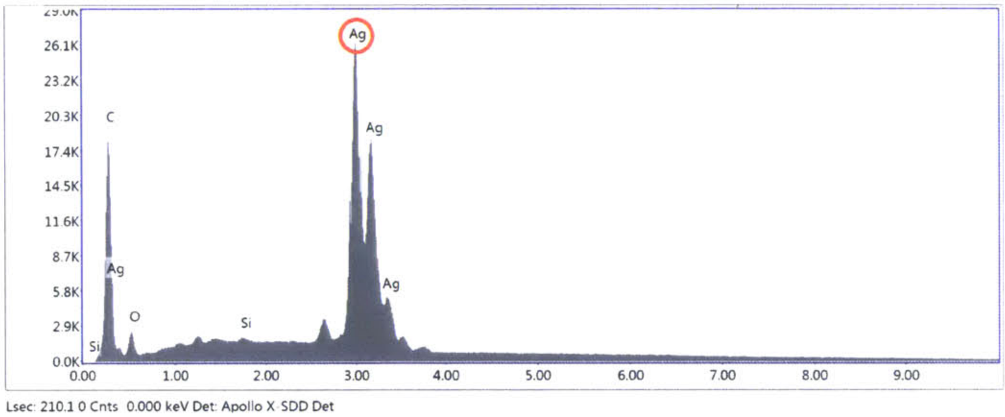
Phone 1 – Sample 1



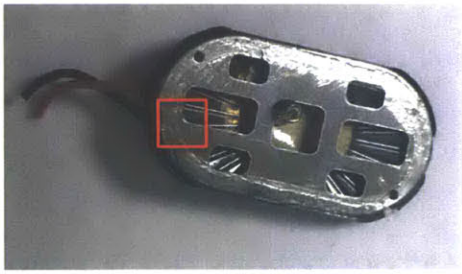


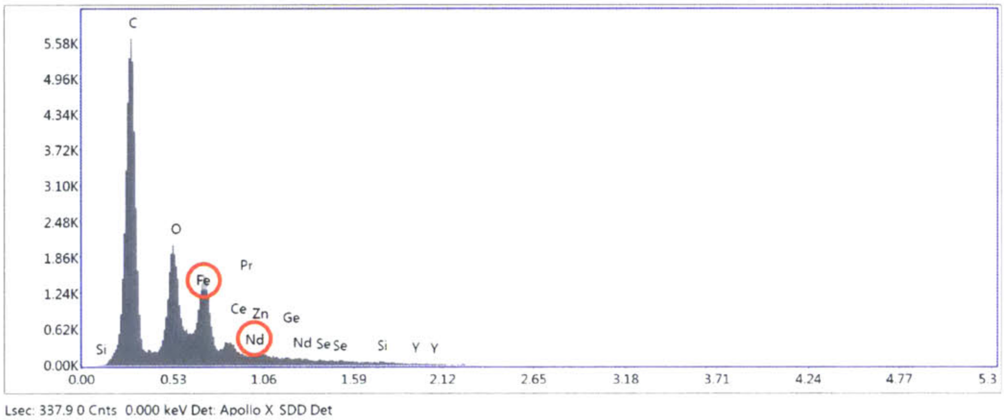
Lsec: 81.9 0 Cnts 0.000 keV Det: Apollo X SDD Det

Phone 1 – Sample 2

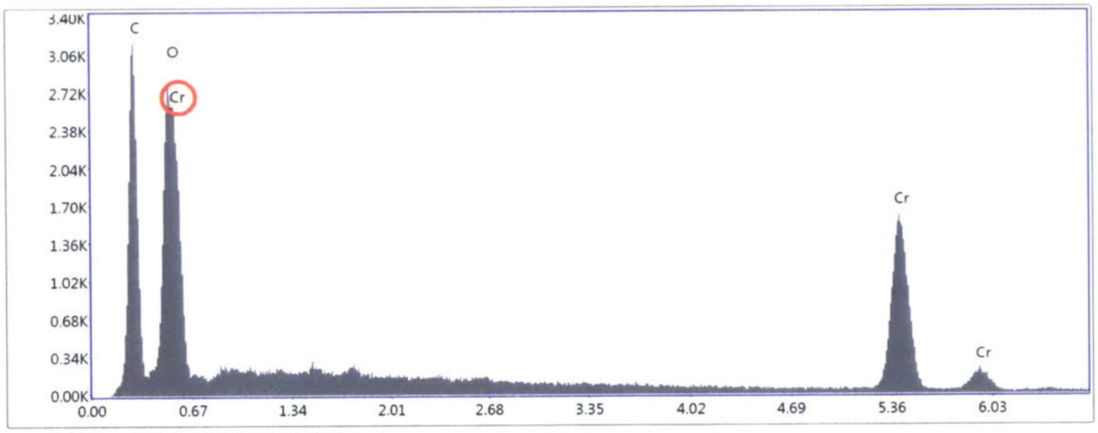


Phone 1 – Sample 3



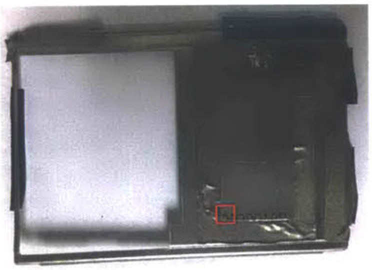


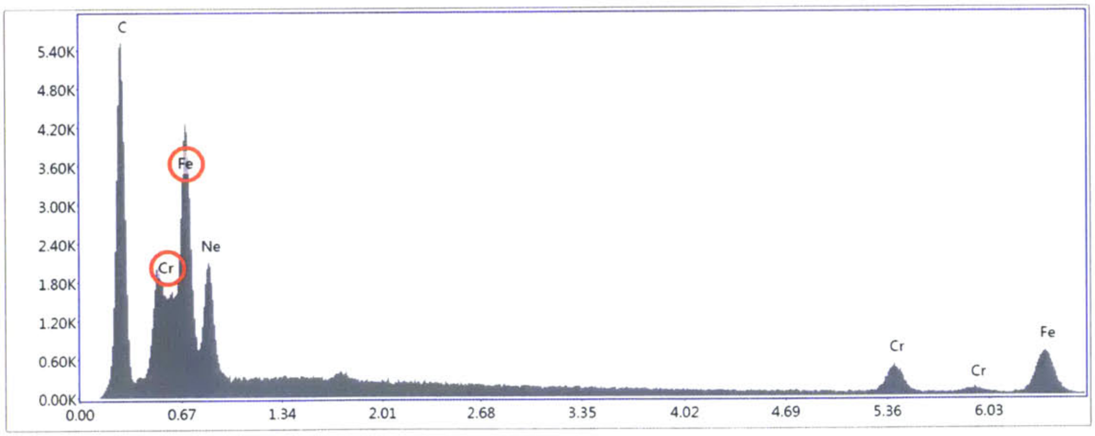
Phone 1 – Sample 4



Lsec: 81.9 0 Cnts 0.000 keV Det: Apollo X-SDD Det

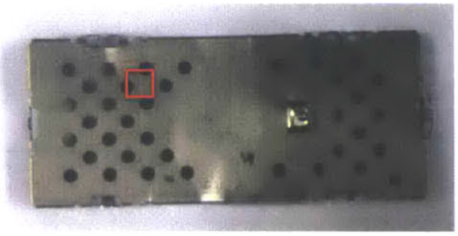
Phone 1 – Sample 5

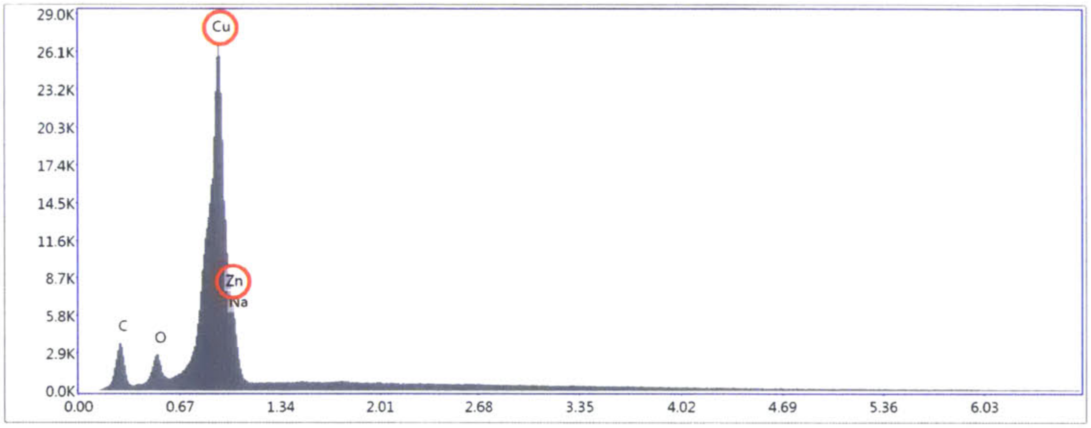




Lsec: 327.6 0 Cnts 0.000 keV Det: Apollo X-SDD Det

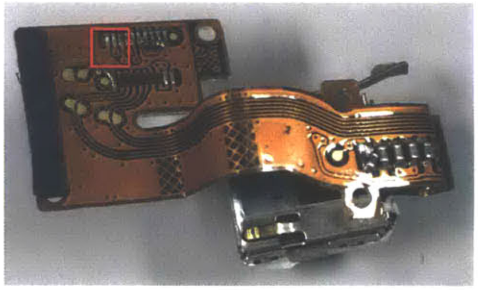
Phone 23 – Sample 1

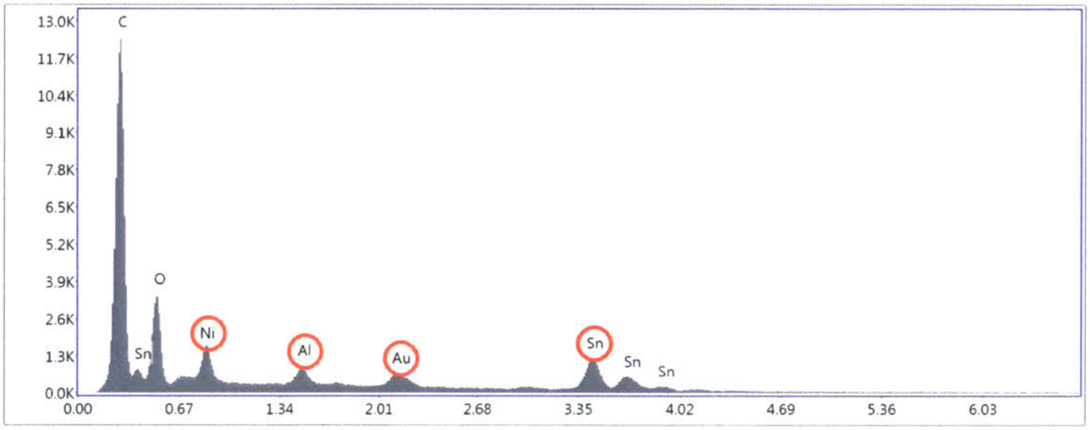




Lsec: 310.9 0 Cnts 0.000 keV Det: Apollo X-SDD Det

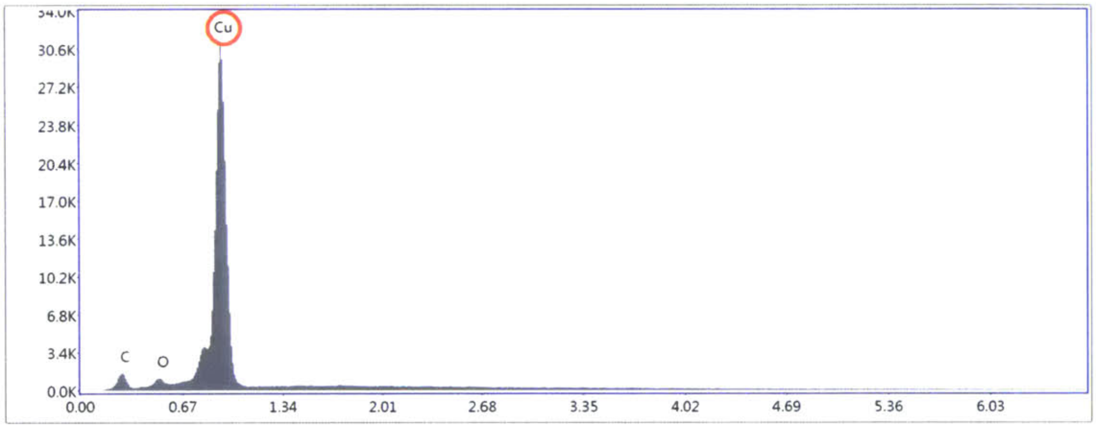
Phone 23 – Sample 2





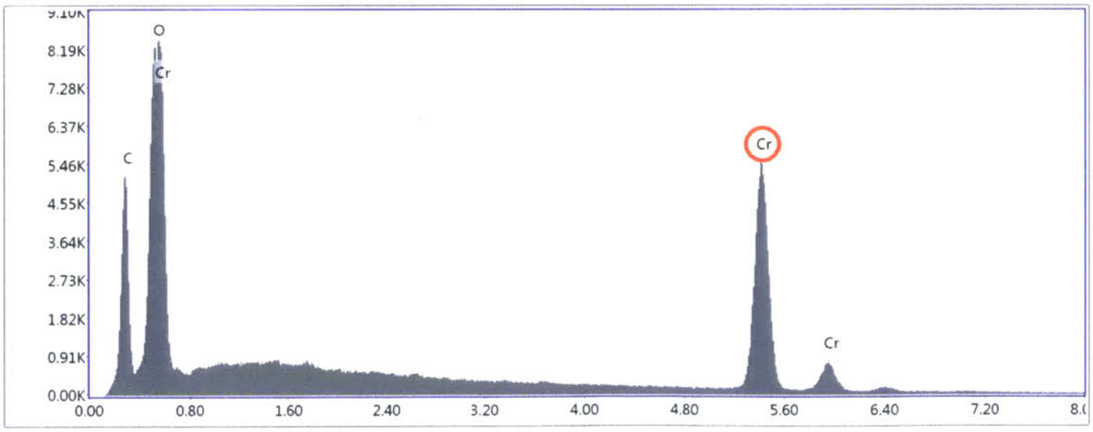
Lsec: 326.9 0 Cnts 0.000 keV Det: Apollo X-SDD Det

Phone 23 – Sample 3



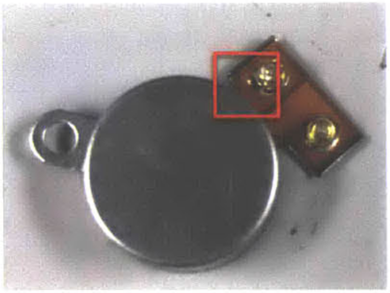
Lsec: 316.4 0 Cnts 0.000 keV Det: Apollo X-SDD Det

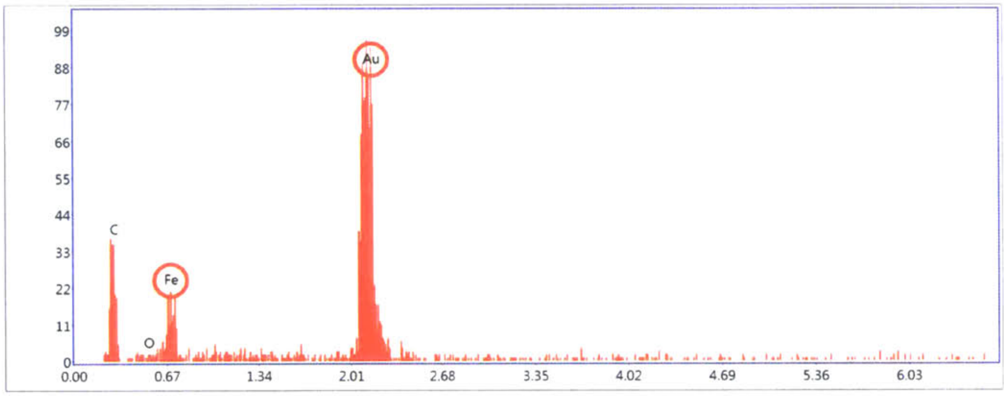
Phone 23 – Sample 4



Lsec: 327.2 0 Cnts 0.000 keV Det: Apollo X-SDD Det

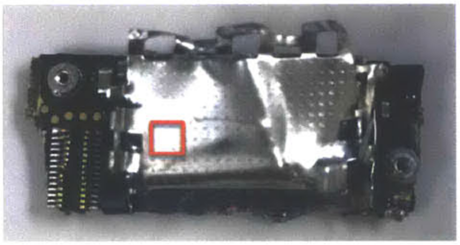
Phone 29 – Sample 1

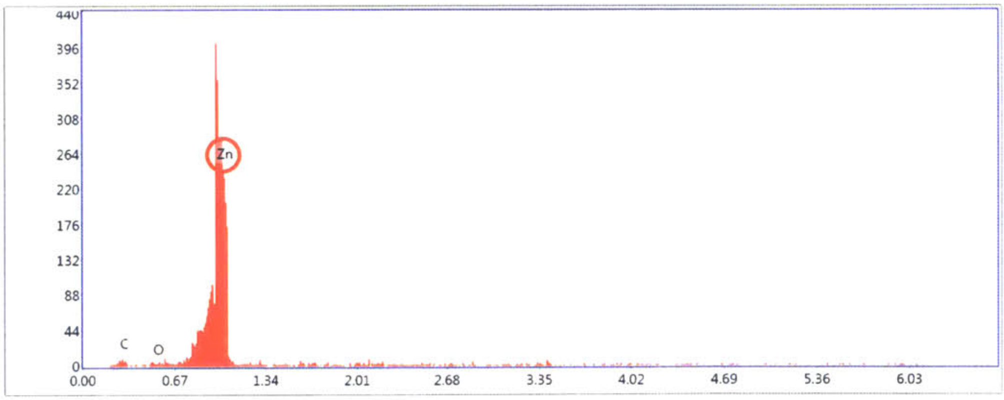




Lsec: 0.4 0 Cnts 0.000 keV Det: Apollo X SDD Det

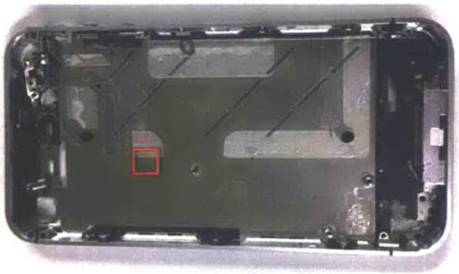
Phone 29 – Sample 2

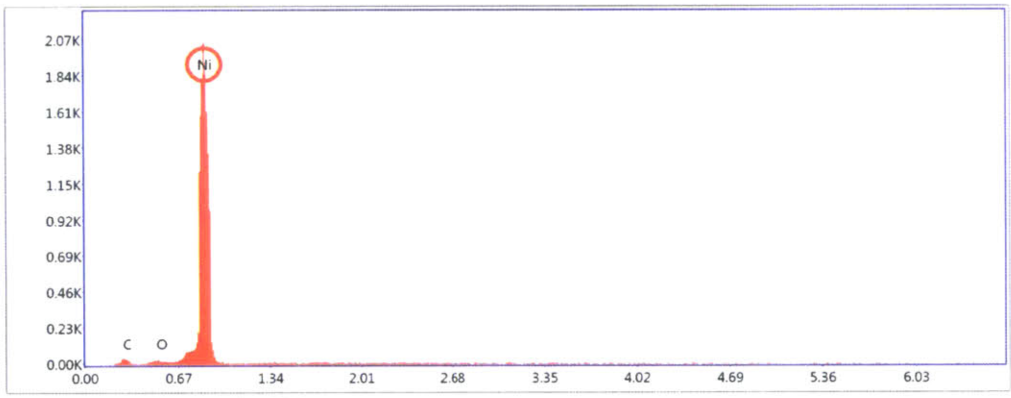




Lsec: 1.0 0 Cnts 0.000 keV Det: Apollo X SDD Det

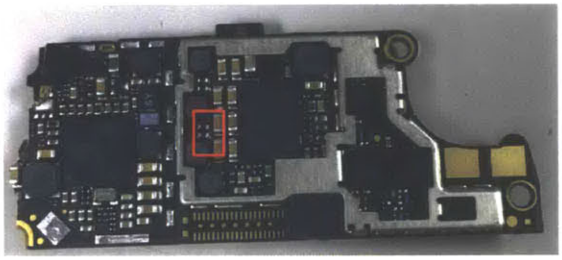
Phone 29 – Sample 3

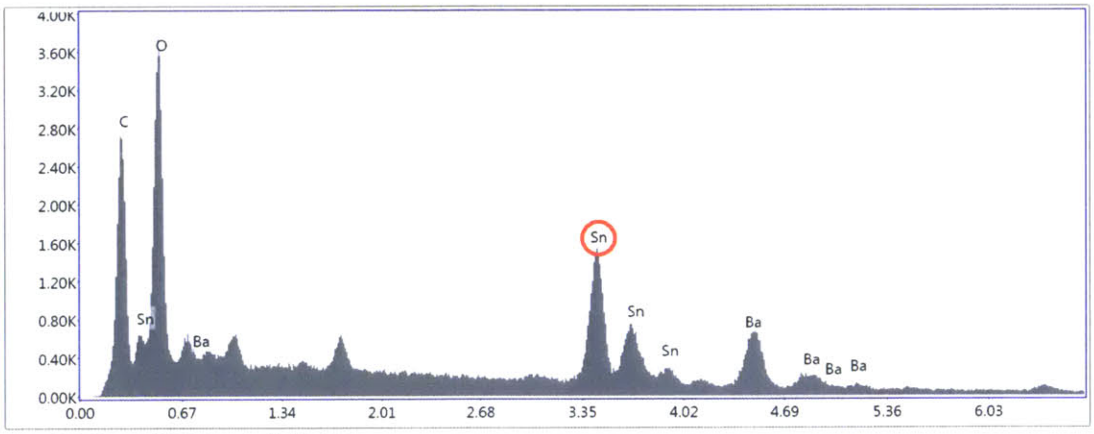




Lsec: 4.8 0 Cnts 0.000 keV Det: Apollo X SDD Det

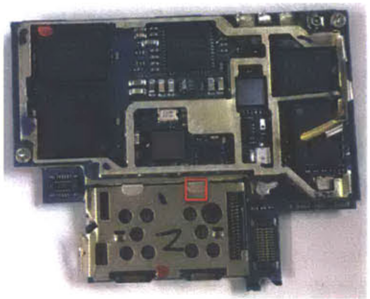
Phone 29 – Sample 4

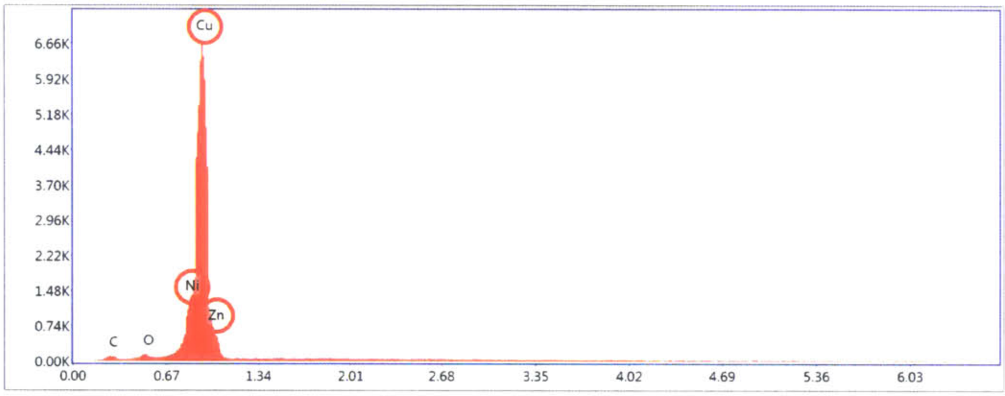




Lsec: 327.5 0 Cnts 0.000 keV Det: Apollo X-SDD Det

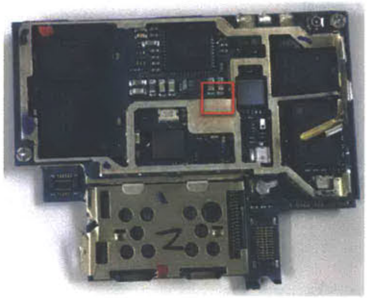
Phone 30 – Sample 1

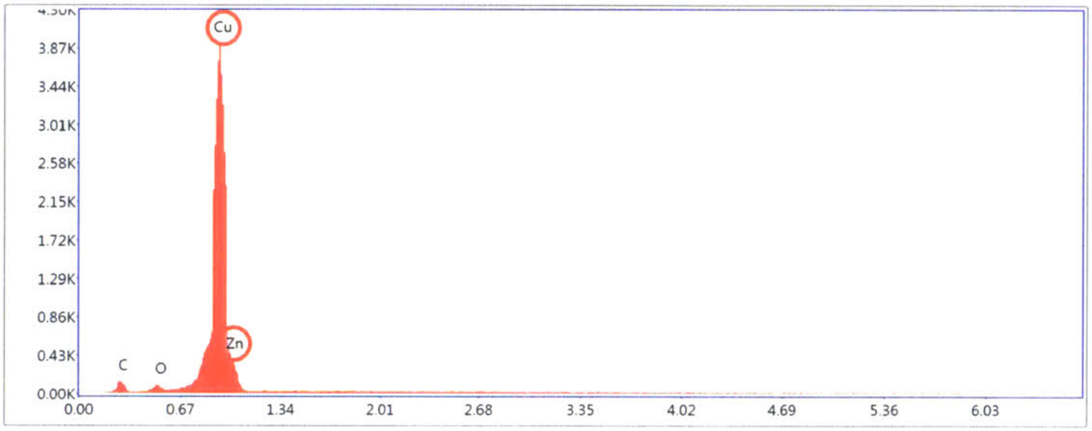




Lsec: 19.1 0 Cnts 0.000 keV Det: Apollo X SDD Det

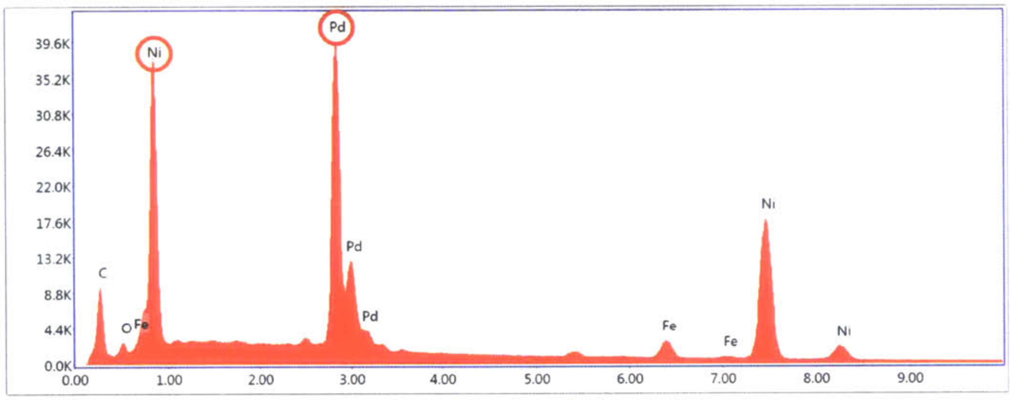
Phone 30 – Sample 1a





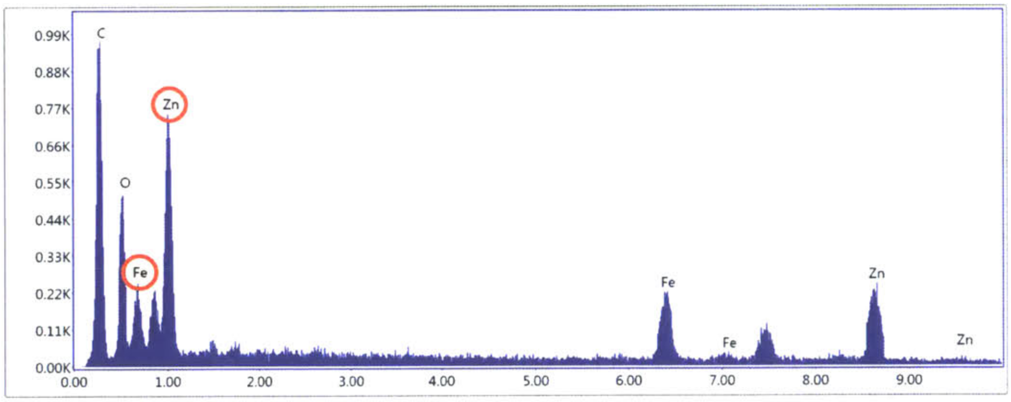
Lsec: 10.6 0 Cnts 0.000 keV Det: Apollo X-SDD Det

Phone 30 – Sample 2



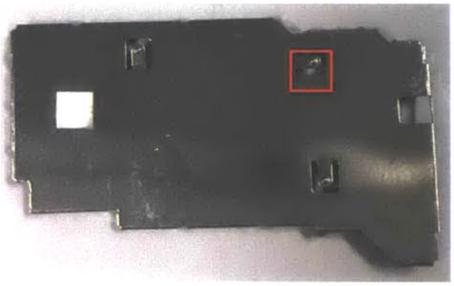
Lsec: 135.6 0 Cnts 0.000 keV Det: Apollo X SDD Det

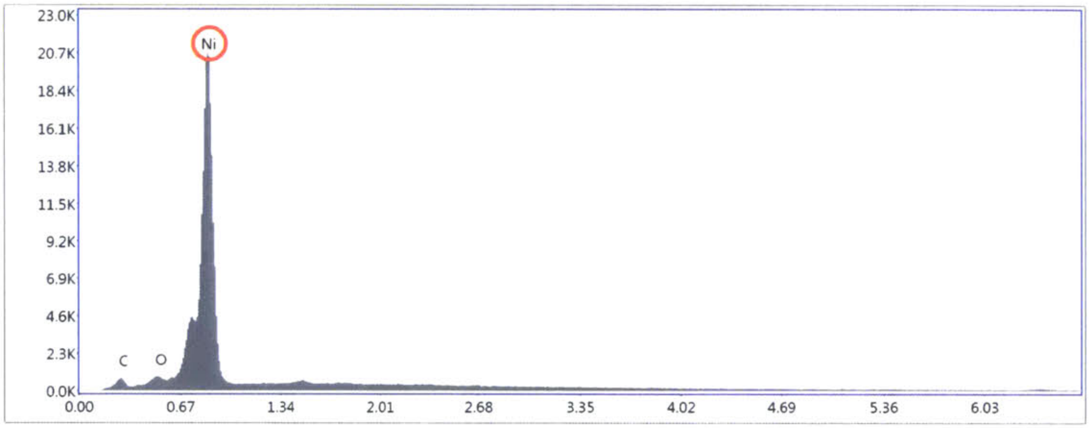
Phone 30 – Sample 3



Lsec: 3.3 0 Cnts 0.000 keV Det: Apollo X SDD Det

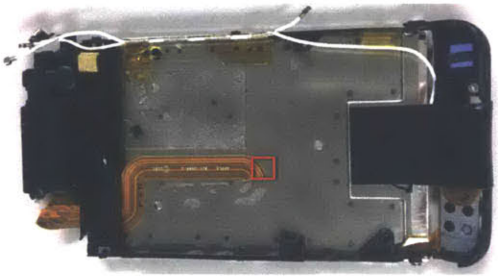
Phone 30 – Sample 4

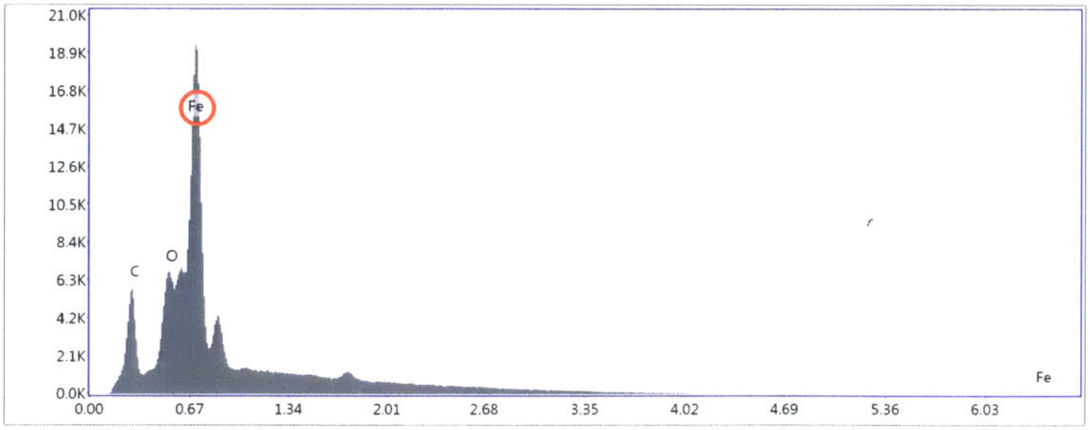




Lsec: 322.5 0 Cnts 0.000 keV Det: Apollo X-SDD Det

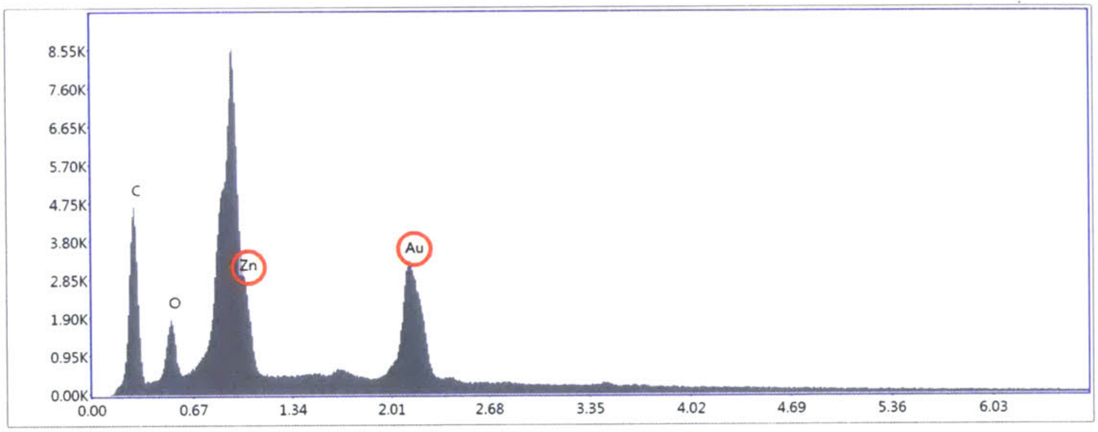
Phone 30 – Sample 5





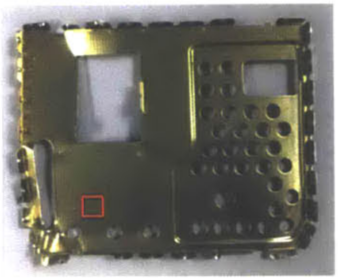
Lsec: 325.8 0 Cnts 0.000 keV Det: Apollo X-SDD Det

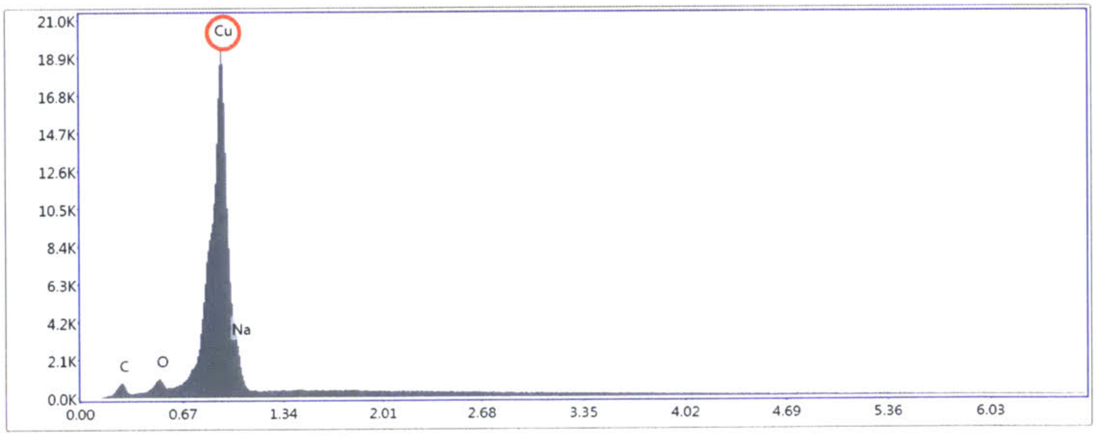
Phone 43 – Sample 1



Lsec: 327.4 0 Cnts 0.000 keV Det: Apollo X-SDD Det

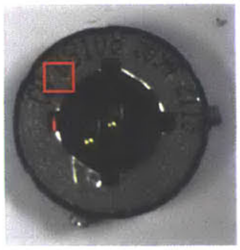
Phone 43 – Sample 2

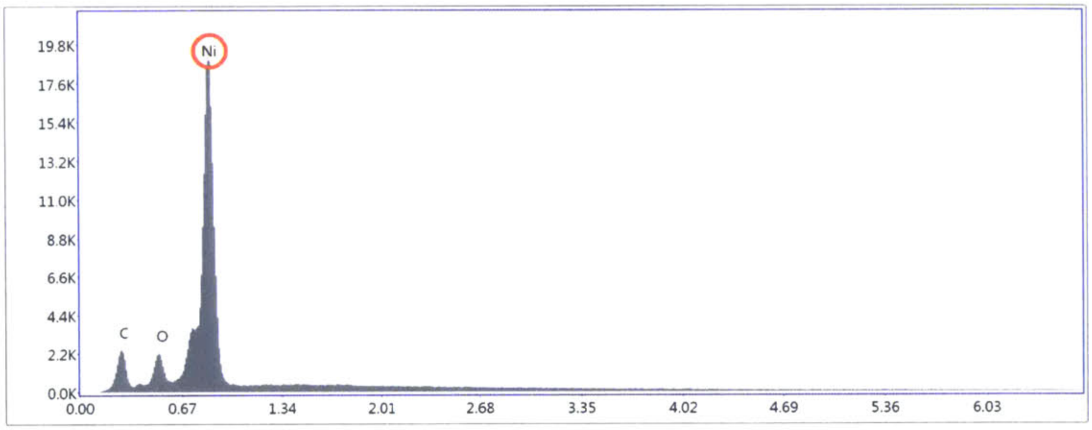




Lsec: 325.3 0 Cnts 0.000 keV Det: Apollo X-SDD Det

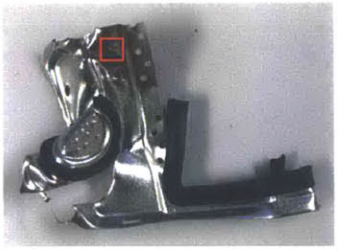
Phone 43 – Sample 3

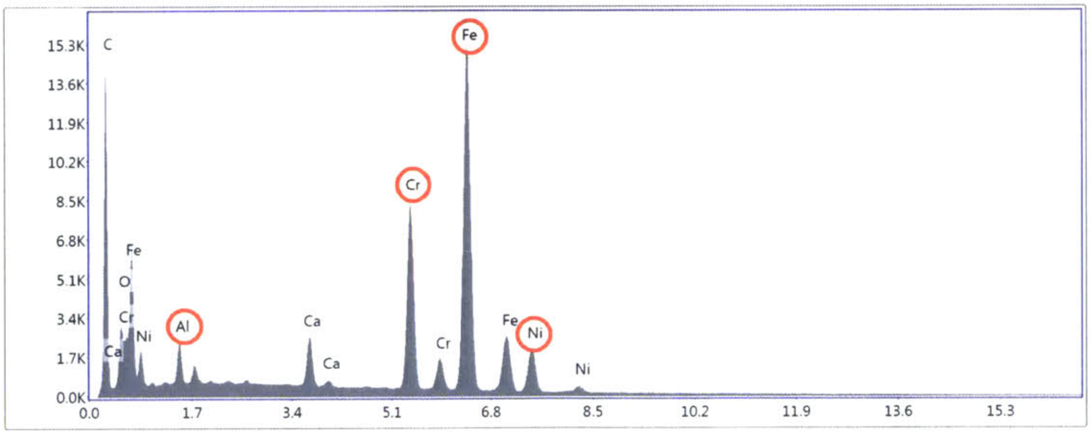




Lsec: 325.8 0 Cnts 0.000 keV Det: Apollo X-SDD Det

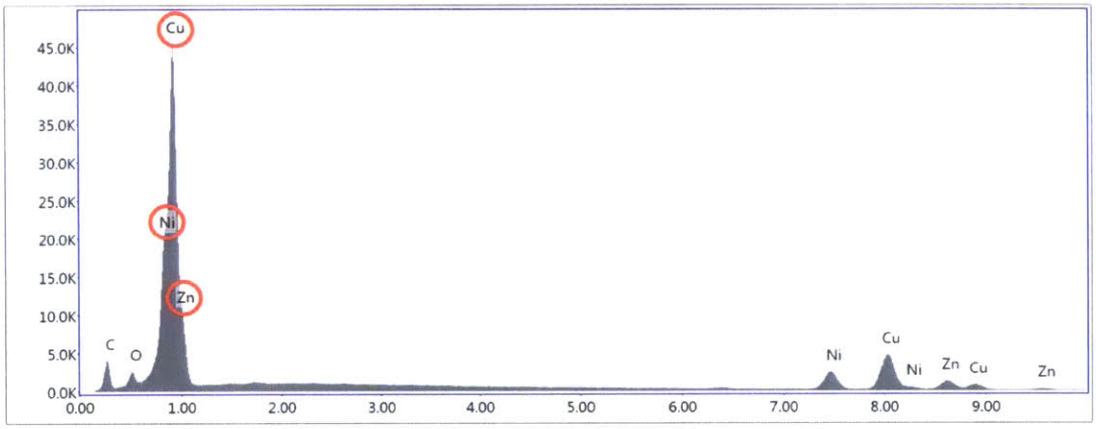
Phone 43 – Sample 4





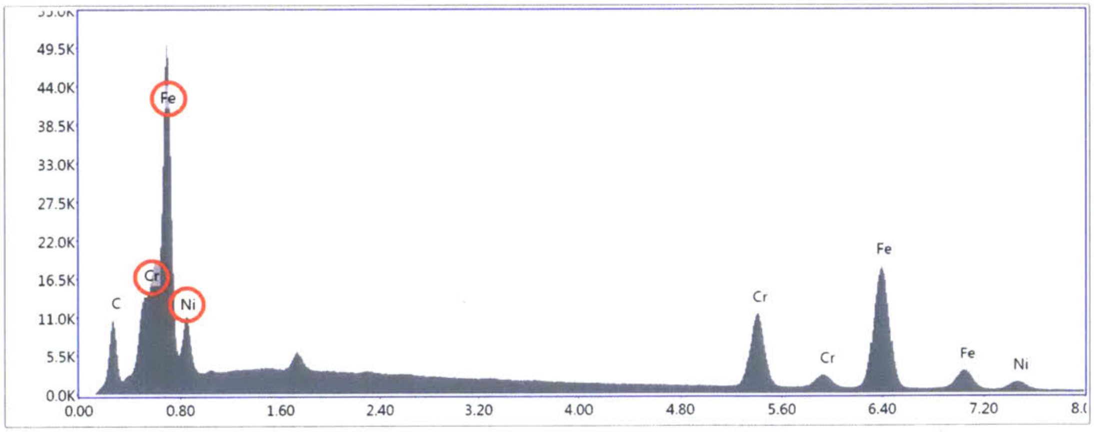
Lsec: 302.4 0 Cnts 0.000 keV Det: Apollo X-SDD Det

Phone 45 – Sample 1



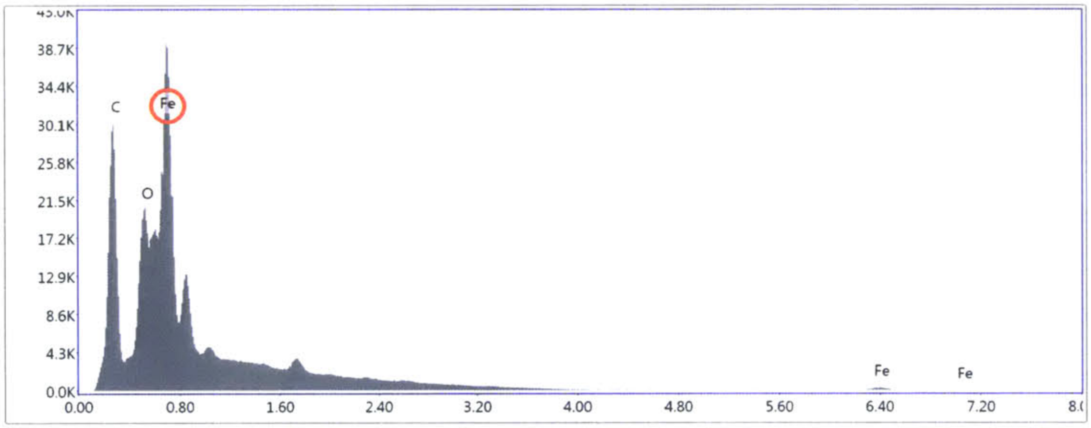
Lsec: 324.4 0 Cnts 0.000 keV Det: Apollo X-SDD Det

Phone 45 – Sample 2



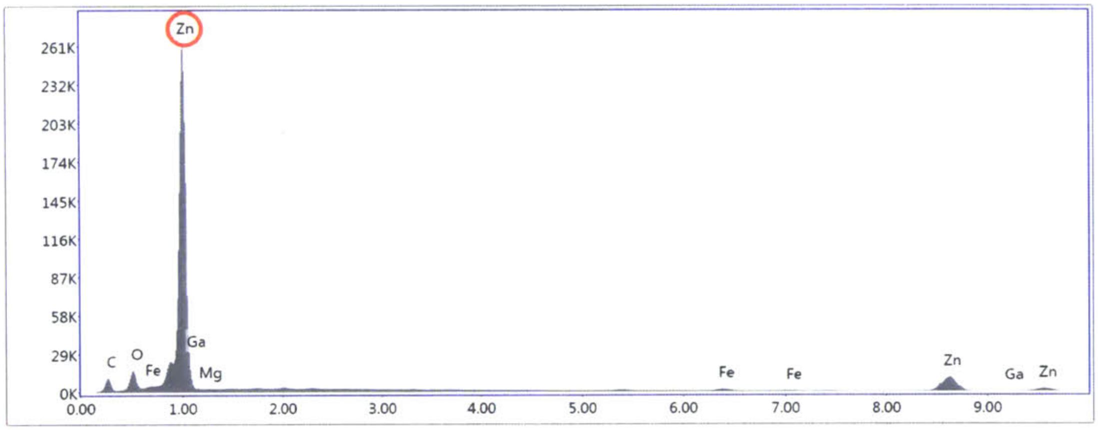
Lsec: 290.8 0 Cnts 0.000 keV Det: Apollo X-SDD Det

Phone 45 – Sample 3



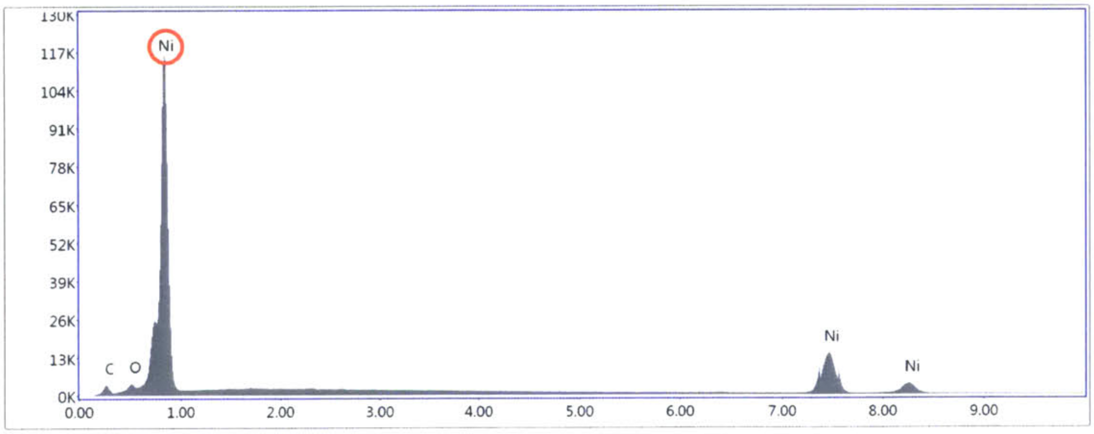
Lsec: 252.4 0 Cnts 0.000 keV Det: Apollo X-SDD Det

Phone 51 – Sample 1



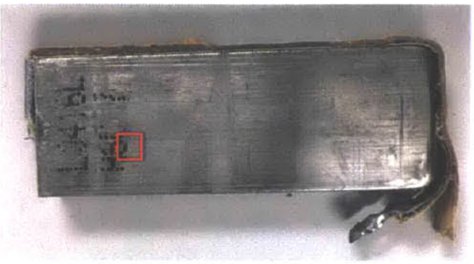
Lsec: 199.0 0 Cnts 0.000 keV Det: Apollo X-SDD Det

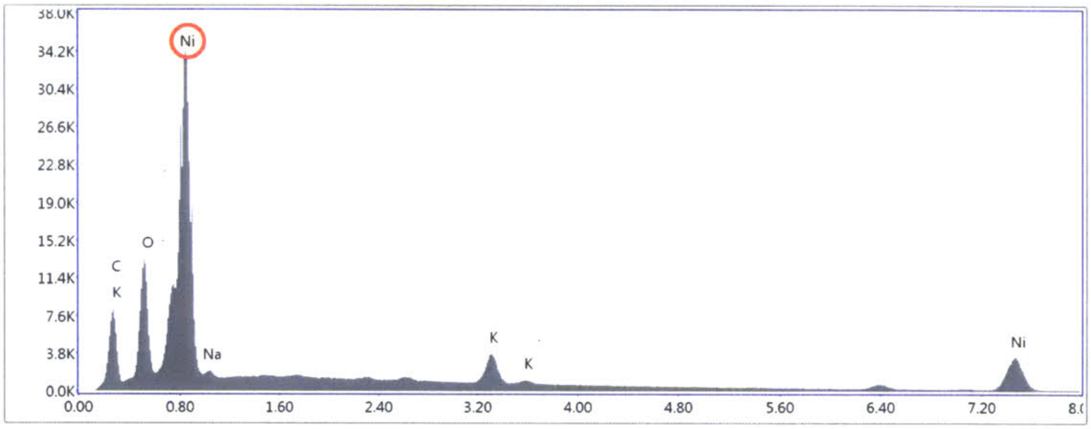
Phone 51 – Sample 2



Lsec: 153.8 0 Cnts 0.000 keV Det: Apollo X-SDD Det

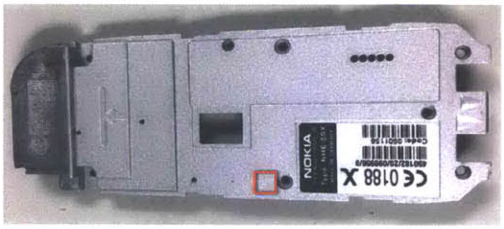
Phone 51 – Sample 3

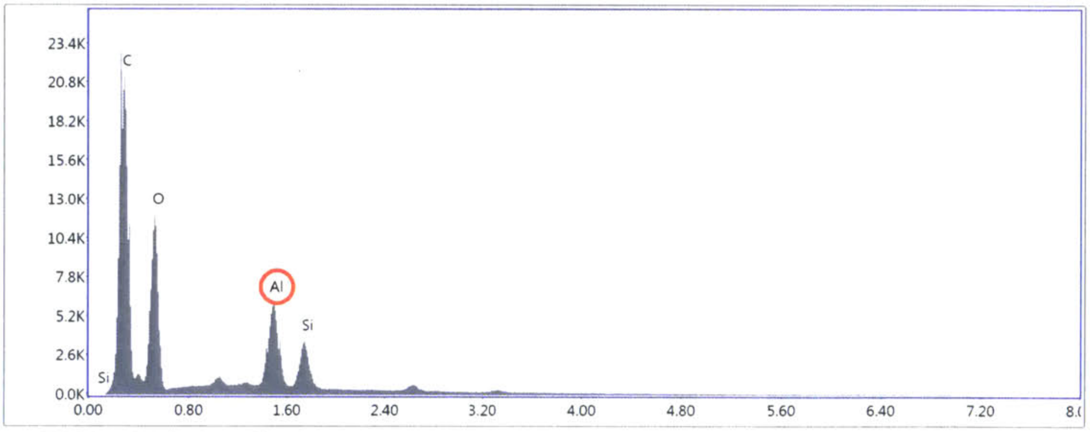




Lsec: 196.7 0 Cnts 0.000 keV Det: Apollo X-SDD Det

Phone 51 – Sample 4





Lsec: 76.6 0 Cnts 0.000 keV Det: Apollo X-SDD Det

Appendix F. ICP-OES Results

The inductively coupled plasma – optical emission spectroscopy (ICP-OES) testing was carried out by ALS Environmental, who reported that “approximately 50mg of sample was digested with HNO_3, HF, and HCL, brought to 50.0 mL with DI water, and analyzed by ICP-OES.” The elements tested for were: aluminum, antimony, arsenic, barium, beryllium, cadmium, calcium, chromium, cobalt, copper, dysprosium, gallium, gold, iron, lead, lithium, magnesium, manganese, molybdenum, nickel, palladium, phosphorous, platinum, potassium, selenium, silicon, silver, sodium, strontium, tantalum, tin, titanium, tungsten, vanadium, zinc, and zirconium. Each of the tables below shows the results for three different batches of the same material, labeled as MP1, MP2, MP3 and MP1b, MP2b, and MP3b. The right most column shows the average mass per PCB. This data was used in Chapter 4.

Sample 1 - PCBs	MP1	MP2	MP3	Average Mass/ PCB
1mm Shred Size	Mass/PCB	Mass/PCB	Mass/PCB	
Aluminum	0.23	0.21	0.33	0.26
Antimony	0.01	0.01	0.01	0.012
Arsenic	0.00	0.00	0.01	0.005
Barium	0.35	0.32	0.19	0.29
Beryllium	0.00	0.00	0.00	0.000
Cadmium	0.00	0.00	0.00	0.000
Calcium	0.34	0.32	0.35	0.34
Chromium	0.01	0.02	0.19	0.073
Cobalt	0.01	0.00	0.00	0.005
Copper	5.10	5.18	4.77	5.02
Dysprosium (Dy)	0.00	0.00	0.00	0.000
Gallium (Ga)	0.00	0.00	0.00	0.000
Gold (Au)	0.04	0.03	0.02	0.030
Iron	0.28	0.78	0.90	0.66
Lead	0.18	0.05	0.32	0.19
Lithium	0.00	0.00	0.00	0.000
Magnesium	0.02	0.02	0.02	0.019
Manganese	0.03	0.07	0.11	0.066
Molybdenum	0.00	0.00	0.00	0.001
Nickel	0.29	0.32	0.26	0.29
Palladium (Pd)	0.00	0.00	0.00	0.000
Phosphorus	0.00	0.00	0.00	0.000
Platinum (Pt)	0.01	0.00	0.00	0.004
Potassium	0.00	0.00	0.00	0.000
Selenium	0.00	0.00	0.00	0.000
Silicon	0.91	0.90	0.88	0.89
Silver (Ag)	0.05	0.06	0.04	0.053
Sodium	0.01	0.01	0.01	0.008
Strontium	0.01	0.00	0.01	0.007
Tantalum (Ta)	0.03	0.01	0.01	0.015
Tin	0.62	0.45	0.69	0.59
Titanium	0.22	0.19	0.12	0.18
Tungsten (W)	0.02	0.01	0.05	0.028
Vanadium	0.00	0.00	0.00	0.000
Zinc	0.20	0.19	0.12	0.17
Zirconium	0.10	0.08	0.04	0.075

Sample 2 - PCBs	MP1b	MP2b	MP3b	Average Mass/ PCB b
0.25mm Shred Size	Mass/PCB	Mass/PCB	Mass/PCB	
Aluminum	0.26	0.28	0.26	0.269
Antimony	0.01	0.01	0.01	0.007
Arsenic	0.00			0.001
Barium	0.23	0.25	0.22	0.233
Beryllium	0.00	0.00	0.00	0.002
Cadmium				
Calcium	0.33	0.33	0.34	0.333
Chromium	0.02	0.04	0.03	0.029
Cobalt	0.01	0.01	0.02	0.014
Copper	5.23	5.26	5.38	5.290
Dysprosium (Dy)				
Gallium (Ga)				
Gold (Au)	0.02	0.02	0.02	0.020
Iron	0.32	0.46	0.53	0.433
Lead	0.07	0.08	0.08	0.074
Lithium	0.00	0.00	0.00	0.001
Magnesium	0.02	0.02	0.02	0.021
Manganese	0.01	0.02	0.02	0.015
Molybdenum	0.00	0.00	0.00	0.001
Nickel	0.23	0.27	0.25	0.250
Palladium (Pd)	0.00	0.00	0.00	0.003
Phosphorus	0.02	0.03	0.02	0.025
Platinum (Pt)	0.00	0.00	0.00	0.002
Potassium	0.01	0.01	0.01	0.006
Selenium				
Silicon	1.11	0.97	1.01	1.029
Silver (Ag)	0.01	0.02	0.02	0.015
Sodium	0.01	0.01	0.01	0.011
Strontium	0.01	0.01	0.01	0.010
Tantalum (Ta)	0.03	0.02	0.04	0.028
Tin	0.08	0.07	0.07	0.072
Titanium	0.13	0.15	0.13	0.137
Tungsten (W)	0.15	0.05	0.07	0.088
Vanadium				
Zinc	0.12	0.12	0.18	0.143
Zirconium	0.06	0.07	0.06	0.060

Appendix G. Proposal Letter for Amb3E Collaboration

Massachusetts Institute of Technology
TÉCNICO LISBOA
3DRIVERS

February 25, 2016

To Amb3e
General Manager Eng. Pedro Nazareth,

We are writing to propose a collaboration between Associação Portuguesa de Gestão de Resíduos (Amb3e), Professors Elsa Olivetti and Krystyn Van Vliet and their student Mr. Patrick Ford at the Massachusetts Institute of Technology (MIT), Professor Fernanda Margarido at Instituto Superior Técnico (IST), and Dr. Eduardo Santos at 3Drivers. The proposed collaboration would include a sharing of knowledge and expertise, and would not require a monetary contribution. Through this effort, we would look to Amb3e to provide support and guidance based on its position within the Portuguese WEEE recycling network. Any analysis would be performed at MIT also under advisement of collaborators at IST and 3Drivers.

Over the past year and a half, we have developed a dynamic product flow analysis (dPFA) of the Portuguese WEEE recycling network with a focus on 16 preprocessing facilities within the country. The goal of this research, which built upon work completed at IST by Dr. Eduardo Santos (http://in3.dem.ist.utl.pt/edam/docs/ 2014-thesis-Eduardo-Santos.pdf), was to quantify the material and economic losses within the recycling infrastructure, and identify potential leverage points in regards to the operations and materials being recovered. Through this work, we estimated that up to $70M USD may have been unrecovered in computers and mobile phones during preprocessing from 2006 – 2014. This result shows the potential for leveraging inefficiencies within the recycling infrastructure, especially in regard to the recovery of printed circuit boards. We believe that these findings, coupled with the strategic improvement scenarios for the Portuguese recycling network that were modeled and analyzed as a part of Dr. Santos's thesis, provide an opportunity for system wide improvements and economic gains.

We feel that the most effective way to leverage these findings is to work with Amb3e to review potential strategic and policy measures that could be used to unlock the lost value in the system. This not only holds the possibility of changing the structure of the eco-fees paid by Amb3e, but also the quantity of secondary raw materials that are recovered. In addition, the findings in our research could help to identify where Ambe3e should invest the required 3% of total annual treatment costs in research and development.

Overall, we anticipate that this collaboration will allow for all sides to benefit and effectively leverage existing data and modeling results. We ask that you consider this idea and let us know if you have any questions about the information detailed above. We would be happy to hold a meeting to go over potential next steps.

Sincerely,

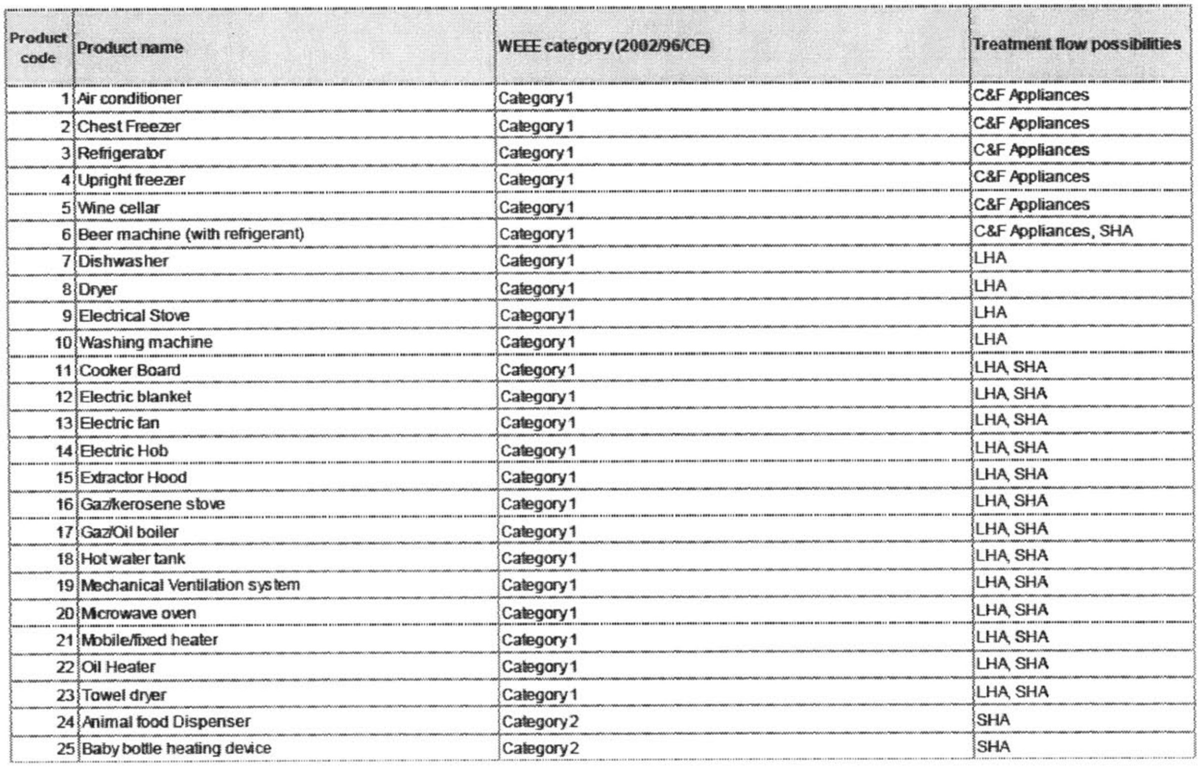
Signature redacted
Professor Elsa Olivetti
MIT, Materials Science and Engineering

Signature redacted
Professor Fernanda Margarido
IST, Mechanical Engineering

Signature redacted
Professor Krystyn J. Van Vliet
MIT, Materials Science and Engineering
and Biological Engineering

Signature redacted
Dr. Eduardo Santos
3Drivers – Engenharia, Inovação e Ambiente, Lda

Appendix H. Product Categories Used in WEEELABEX Documentation[117]



Product code	Product name	WEEE category (2002/96/CE)	Treatment flow possibilities
1	Air conditioner	Category 1	C&F Appliances
2	Chest Freezer	Category 1	C&F Appliances
3	Refrigerator	Category 1	C&F Appliances
4	Upright freezer	Category 1	C&F Appliances
5	Wine cellar	Category 1	C&F Appliances
6	Beer machine (with refrigerant)	Category 1	C&F Appliances, SHA
7	Dishwasher	Category 1	LHA
8	Dryer	Category 1	LHA
9	Electrical Stove	Category 1	LHA
10	Washing machine	Category 1	LHA
11	Cooker Board	Category 1	LHA, SHA
12	Electric blanket	Category 1	LHA, SHA
13	Electric fan	Category 1	LHA, SHA
14	Electric Hob	Category 1	LHA, SHA
15	Extractor Hood	Category 1	LHA, SHA
16	Gaz/kerosene stove	Category 1	LHA, SHA
17	Gaz/Oil boiler	Category 1	LHA, SHA
18	Hot water tank	Category 1	LHA, SHA
19	Mechanical Ventilation system	Category 1	LHA, SHA
20	Microwave oven	Category 1	LHA, SHA
21	Mobile/fixed heater	Category 1	LHA, SHA
22	Oil Heater	Category 1	LHA, SHA
23	Towel dryer	Category 1	LHA, SHA
24	Animal food Dispenser	Category 2	SHA
25	Baby bottle heating device	Category 2	SHA

26	Balneotherapy set	Category 2	SHA
27	Bathroom scale	Category 2	SHA
28	Beer machine	Category 2	SHA
29	Blender	Category 2	SHA
30	Bread oven	Category 2	SHA
31	Breast pump	Category 2	SHA
32	Car Hand stick cleaner	Category 2	SHA
33	Chocolate maker	Category 2	SHA
34	Citrus press	Category 2	SHA
35	clock/ alarm clock	Category 2	SHA
36	Coffee grinder	Category 2	SHA
37	Coffee maker	Category 2	SHA
38	Combined electric toothbrush	Category 2	SHA
39	Curling iron	Category 2	SHA
40	Deep fryer	Category 2	SHA
41	Dish/Plate warmer	Category 2	SHA
42	Eggs beater	Category 2	SHA
43	Electric can opener	Category 2	SHA
44	Electric epilator	Category 2	SHA
45	Electric grinder	Category 2	SHA
46	Electric insect killer	Category 2	SHA
47	Electric knife	Category 2	SHA
48	Electric mincer	Category 2	SHA
49	Electric razor	Category 2	SHA
50	Electric tea machine	Category 2	SHA

Product code	Product name	WEEE category (2002/96/CE)	Treatment flow possibilities
51	Electric thermometer (no medical)	Category 2	SHA
52	Electric Toothbrush	Category 2	SHA
53	Electrolysis set	Category 2	SHA
54	Electronic trash can with sensitive cell	Category 2	SHA
55	Electrostimulation device	Category 2	SHA
56	Espresso-Systems	Category 2	SHA
57	Facial sauna	Category 2	SHA
58	Facial styling set	Category 2	SHA
59	Fan brush	Category 2	SHA
60	Floor polisher	Category 2	SHA
61	Fondue set	Category 2	SHA
62	Food slicer	Category 2	SHA
63	Foodproccesor	Category 2	SHA
64	Hair dryer	Category 2	SHA
65	Hair styling set	Category 2	SHA
66	Hair trimmer	Category 2	SHA
67	Hand dryer	Category 2	SHA
68	Hand stick cleaner	Category 2	SHA
69	Hot dog device	Category 2	SHA
70	Ice cream maker	Category 2	SHA
71	Ice maker without refrigerant	Category 2	SHA
72	Immersion heater	Category 2	SHA
73	Infrared lamp	Category 2	SHA
74	Iron	Category 2	SHA
75	Juice extractor	Category 2	SHA

76	Kettle	Category 2	SHA
77	Kitchen scale	Category 2	SHA
78	Knife sharpener	Category 2	SHA
79	Light Therapy set	Category 2	SHA
80	Luminous mirror	Category 2	SHA
81	Vaccum appliance for food	Category 2	SHA
82	Manicure and chiropodist set	Category 2	SHA
83	Massage device	Category 2	SHA
84	Meat grill	Category 2	SHA
85	Mini-oven	Category 2	SHA
86	Miniwasher	Category 2	SHA
87	pancakedevice	Category 2	SHA
88	Popcorn device	Category 2	SHA
89	Raclette set	Category 2	SHA
90	Sandwich toaster	Category 2	SHA
91	Saniflow	Category 2	SHA
92	Sauce maker	Category 2	SHA
93	Shoe polisher	Category 2	SHA
94	Slicer	Category 2	SHA
95	Solar lamp	Category 2	SHA
96	Steam cleaner	Category 2	SHA
97	Steam cooker	Category 2	SHA
98	Steam cooker	Category 2	SHA
99	Steam iron, Active ironing board, Ironing press	Category 2	SHA
100	Sterilising equipment	Category 2	SHA
101	Timer	Category 2	SHA
102	Toaster	Category 2	SHA
103	Ultrasonic cleaner	Category 2	SHA
104	Vacuum cleaner, Floor model	Category 2	SHA
105	waffle iron	Category 2	SHA
106	Watch	Category 2	SHA
107	Water filter	Category 2	SHA
108	Xhisk	Category 2	SHA
109	Yoghurt maker	Category 2	SHA
110	Centrifuge	Category 2	SHA, other
111	CRT monitor	Category 3	Screens
112	Laptop computer	Category 3	Screens, SHA
113	LCD monitor	Category 3	Screens, SHA
114	Answering machine	Category 3	SHA
115	Babyphone	Category 3	SHA
116	Calculator	Category 3	SHA
117	CD/DVD burner	Category 3	SHA
118	Central processing unit	Category 3	SHA
119	Computer keyboard	Category 3	SHA
120	copier	Category 3	SHA
121	Electric graphic board	Category 3	SHA
122	External drive	Category 3	SHA
123	External modem	Category 3	SHA
124	Fax machine	Category 3	SHA
125	GPS	Category 3	SHA

126	Handheld computer	Category 3	SHA
127	Interphone	Category 3	SHA
128	Inverter	Category 3	SHA
129	Mobile Phone	Category 3	SHA
130	Mouse	Category 3	SHA
131	Organiser	Category 3	SHA
132	PC Helmet	Category 3	SHA
133	PC loudspeaker	Category 3	SHA
134	PC microphone	Category 3	SHA
135	Printer	Category 3	SHA
136	Printer (not exclusively photo)	Category 3	SHA
137	Scanner	Category 3	SHA
138	Switch	Category 3	SHA
139	Talkie walkie	Category 3	SHA
140	Telephone (cordless/wire)	Category 3	SHA
141	USB key	Category 3	SHA
142	Webcam	Category 3	SHA
143	WI-FI	Category 3	SHA
144	Bank-Bill detector	Category 3	SHA, other
145	Bar code Scanner	Category 3	SHA, other
146	Cash register	Category 3	SHA, other
147	Commercial scale	Category 3	SHA, other
148	Label/tag printer	Category 3	SHA, other
149	Minitel	Category 3	SHA, other
150	Server	Category 3	SHA, other
151	Terminal	Category 3	SHA, other
152	CRT TV set	Category 4	Screens
153	LCD TV	Category 4	Screens, SHA
154	Plasma TV	Category 4	Screens, SHA
155	Aerial	Category 4	SHA
156	Alarm clock/Radio alarm clock	Category 4	SHA
157	Amplifier	Category 4	SHA
158	Audio & video player	Category 4	SHA
159	Battery charger	Category 4	SHA
160	Camcorder	Category 4	SHA
161	Digital camera	Category 4	SHA
162	DVD recorder	Category 4	SHA
163	Effects pedal	Category 4	SHA
164	Headphones	Category 4	SHA
165	Karaoke player	Category 4	SHA
166	Loudspeaker	Category 4	SHA
167	MD player	Category 4	SHA
168	Microphone	Category 4	SHA
169	MP3 loudspeaker	Category 4	SHA
170	Multimedia hardrive	Category 4	SHA
171	Musical instrument	Category 4	SHA
172	Personal radio	Category 4	SHA
173	Photo printer	Category 4	SHA
174	Remote control	Category 4	SHA
175	Set top box	Category 4	SHA

176	Slide projector	Category 4	SHA
177	Sound mixer/mixing board	Category 4	SHA
178	Stereo system / micro hi-fi system	Category 4	SHA
179	Tape recorder	Category 4	SHA
180	Tuner	Category 4	SHA
181	Turntable	Category 4	SHA
182	Video projector	Category 4	SHA
183	Video recorder	Category 4	SHA
184	Microfiche player	Category 4	SHA, other
185	Negatoscope	Category 4	SHA, other
186	Professionnal luminaire	Category 5	SHA, other
187	Chain saw	Category 6	SHA
188	Compressor	Category 6	SHA
189	Electrical saw	Category 6	SHA
190	Electrical screwdriver	Category 6	SHA
191	Gardening tool	Category 6	SHA
192	Glue pistol	Category 6	SHA
193	Hammer drill	Category 6	SHA
194	Mower	Category 6	SHA
195	Pressure washer	Category 6	SHA
196	Pump	Category 6	SHA
197	Sander	Category 6	SHA
198	Sewing machine	Category 6	SHA
199	Soldering iron	Category 6	SHA
200	Soldering machine	Category 6	SHA
201	Tool sharpener	Category 6	SHA
202	Computers for biking, diving, running, rowing	Category 7	SHA
203	Hand-held video game consoles	Category 7	SHA
204	Other small toys	Category 7	SHA
205	Other Sports equipment with electr. component	Category 7	SHA
206	Sports equipment with electric or electronic component	Category 7	SHA
207	Toys: Electric trains or car racing set	Category 7	SHA
208	Video game	Category 7	SHA
209	Coin slot machines	Category 7	SHA, other
210	Electrical scooter	Category 7	SHA, other
211	Exercise bike	Category 7	SHA, other
212	Medical treatement set	Category 8	SHA
213	Analyser	Category 8	SHA, other
214	Cardiology	Category 8	SHA, other
215	Dialysis	Category 8	SHA, other
216	Laboratory equipment for in-vitro diagnosis	Category 8	SHA, other
217	Pulmonary ventilator	Category 8	SHA, other
218	Radiotherapy equipment	Category 8	SHA, other
219	Alarm	Category 9	SHA
220	Am-/voltmeter	Category 9	SHA
221	Control panel	Category 9	SHA
222	Heating regulators	Category 9	SHA
223	Power charger	Category 9	SHA
224	Smoke detector	Category 9	SHA
225	Thermostat	Category 9	SHA

226	Weather station	Category 9	SHA
227	Automatic dispenser for hot drinks	Category 10	SHA, LHA, other
228	Automatic dispenser for hot or cold bottles, cans, drinks	Category 10	SHA, C&F, LHA, other
229	Automatic dispenser for solid products	Category 10	SHA, LHA, other
230	Automatic dispenser for money	Category 10	SHA, LHA, other
231	Parts of WEEE (printed circuit boards…)	cannot be linked up to a category	SHA, other
232	Car Fittings	Electrical equipment Out of scope of WEEE directive 2002/96/CE	SHA, other
233	Extension cord	Electrical equipment Out of scope of WEEE directive 2002/96/CE	SHA, other
234	Generator	Electrical equipment Out of scope of WEEE directive 2002/96/CE	SHA, other
235	Housing antifoudre	Electrical equipment Out of scope of WEEE directive 2002/96/CE	SHA, other
236	Light Switch	Electrical equipment Out of scope of WEEE directive 2002/96/CE	SHA, other
237	Luminaires in households	Electrical equipment Out of scope of WEEE directive 2002/96/CE	SHA, other
238	Multiplug/Plug	Electrical equipment Out of scope of WEEE directive 2002/96/CE	SHA, other
239	Batteries (free)	Non WEEE	SHA, other
240	Inkjet/laser cartridge (free)	Non WEEE	SHA, other
241	Non electric waste : coffers, kitchenware, CDs, food, etc.	Non WEEE	SHA, other
242	Packaging waste	Non WEEE	SHA, other

Bibliography

1. Ford, P.; Santos, E.; Ferrao, P.; Margarido, F.; Van Vliet, K. J.; Olivetti, E., Economics of End-of-Life Materials Recovery - A Study of Small Appliances and Computer Devices in Portugal. *Environmental Science & Technology* **2016**.
2. Widmer, R.; Oswald-Krapf, H.; Sinha-Khetriwal, D.; Schnellmann, M.; Boni, H., Global perspectives on e-waste. *Environmental Impact Assessment Review* **2005,** *25*, (5), 436-458.
3. Lam, C. W.; Lim, S. R.; Schoenung, J. M., Linking material flow analysis with environmental impact potential. *Journal of Industrial Ecology* **2013,** *17*, (2), 299-309.
4. Williams, E.; Kahhat, R.; Allenby, B.; Kavazanjian, E.; Kim, J.; Xu, M., Environmental, social, and economic implications of global reuse and recycling of personal computers. *Environmental Science & Technology* **2008,** *42*, (17), 6446-6454.
5. Mianqiang, X.; Alissa, K.; Zhenming, X.; Schoenung, J. M., Waste management of printed wiring boards: A life cycle assessment of the metals recycling chain from liberation through refining. *Environmental Science & Technology* **2015,** *49*, (2), 940-947.
6. Bauer, D.; Diamond, D.; Li, J.; McKittrick, M.; Sandalow, D.; Telleen, P., U.S. Department of Energy Critical Materials Strategy. In Energy, D. o., Ed. U.S. Department of Energy Office of Policy and International Affairs (PI): 2011; p 196.
7. Duan, H.; Miller, T. R.; Gregory, J.; Kirchain, R.; Linnell, J. *Quantitative Characterization of Domestic and Transboundary Flows of Used Electronics; Analysis of Generation, Collection, and Export in the United States*; StEP Initiative: 2013.
8. Oguchi, M.; Murakami, S.; Sakanakura, H.; Kida, A.; Kameya, T., A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources. *Waste Management* **2011,** *31*, 2150-2160.
9. Kang, H. Y.; Schoenung, J. M., Economic analysis of electronic waste recycling: Modeling the cost and revenue of a materials recovery facility in California. *Environmental Science & Technology* **2006,** *40*, (5), 1672-1680.
10. Jianbo, W.; Zhenming, X., Disposing and recycling waste printed circuit boards: Disconnecting, resource recovery, and pollution control. *Environmental Science & Technology* **2015,** *49*, (2), 721-733.
11. Jinhui, L.; Xianlai, Z.; Mengjun, C.; Ogunseitan, O. A.; Stevels, A., "Control-Alt-Delete": Rebooting solutions for the e-waste problem. *Environmental Science & Technology* **2015,** *49*, (12), 7095-7108.
12. Nicolli, F.; Johnstone, N.; Söderholm, P., Resolving failures in recycling markets: The role of technological innovation. *Environmental Economics & Policy Studies* **2012,** *14*, (3), 261-288.
13. Georgiadis, P.; Besiou, M., Environmental and economical sustainability of WEEE closed-loop supply chains with recycling: A system dynamics analysis. *International Journal of Advanced Manufacturing Technology* **2010,** *47*, (5), 475-493.
14. Szalatkiewicz, J., Metals content in printed circuit board waste. *Polish Journal of Environmental Studies* **2014,** *23*, (6), 2365-2369.

15. Fitzpatrick, C.; Olivetti, E.; Reed Miller, T.; Roth, R.; Kirchain, R., Conflict minerals in the compute sector: Estimating extent of tin, tantalum, tungsten, and gold use in ICT products. *Environmental Science & Technology* **2015,** *49,* (2), 974-981.
16. Huisman, J. *QWERTY and Eco-Efficiency Analysis on Cellular Phone Treatment in Sweden*; TU Delft: Delft, 2004; pp 1-33.
17. *Materials Case Study 1: Critical Metals and Mobile Devices*; OECD: Belgium, 2010; pp 1-84.
18. Marin, C. GRID-Arendal - Cell Phone Composition. http://www.grida.no/graphicslib/detail/cell-phone-composition_1057.
19. Meskers, C. E.; Hageluken, C.; Van Damme, G.; Howard, S. M. In *Green Recycling of EEE: Special and Precious Metal Recovery from EEE*, EPD Congress 2009, San Francisco, CA, USA, 2009; Howard, S. M., Ed. Metals & Materials Society (TMS): San Francisco, CA, USA, 2009.
20. Meskers, C. E. M.; Hageluken, C.; Salhofer, S.; Spitzbart, M. In *Impact of Pre-Processing Routes on Precious Metals Recovery from PCs*, European Metallurgical Conference, Innsbruck, Austria, 2009; Harre, J., Ed. GDMB: Innsbruck, Austria, 2009; p 16.
21. Chancerel, P.; Marwede, M.; Nissen, N. F.; Lang, K.-D., Estimating the quantities of critical metals embedded in ICT and consumer equipment. *Resources, Conservation & Recycling* **2015,** *98,* 9-18.
22. Müller, E.; Hilty, L. M.; Widmer, R.; Schluep, M.; Faulstich, M., Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environmental Science & Technology* **2014,** *48,* (4), 2102-2113.
23. Valero Navazo, J.; Villalba Méndez, G.; Talens Peiró, L., Material flow analysis and energy requirements of mobile phone material recovery processes. *International Journal of Life Cycle Assessment* **2014,** *19,* (3), 567-579.
24. Chancerel, P.; Meskers, C. E. M.; Hagelüken, C.; Rotter, V. S., Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. *Journal of Industrial Ecology* **2009,** *13,* (5), 791-810.
25. Chancerel, P.; Rotter, V. S., Assessing the management of small waste electrical an electronic equipment through substance flow analysis: the example of gold in Germany and the USA. *Revue De Metallurgie-Cahiers D Informations Techniques* **2009,** *106,* (12), 547-553.
26. Bollinger, L. A.; Davis, C.; Nikolić, I.; Dijkema, G. P. J., Modeling metal flow systems. *Journal of Industrial Ecology* **2012,** *16,* (2), 176-190.
27. Deng, L.; Babbitt, C. W.; Williams, E. D., Economic-balance hybrid LCA extended with uncertainty analysis: case study of a laptop computer. *Journal of Cleaner Production* **2011,** *19,* 1198-1206.
28. Biganzoli, L.; Falbo, A.; Forte, F.; Grosso, M.; Rigamonti, L., Mass balance and life cycle assessment of the waste electrical and electronic equipment management system implemented in Lombardia Region (Italy). *Science of the Total Environment* **2015,** *524-525,* 361-375.
29. Gaustad, G.; Olivetti, E.; Kirchains, R., Toward Sustainable Material Usage: Evaluating the Importance of Market Motivated Agency in Modeling Material Flows. *Environmental Science & Technology* **2011,** *45,* (9), 4110-4117.

30. Duygan, M.; Meylan, G., Full length article: Strategic management of WEEE in Switzerland—combining material flow analysis with structural analysis. *Resources, Conservation & Recycling* **2015,** *103*, 98-109.
31. Hageluken, C. In *Improving Metal Returns and Eco-Efficiency in Electronics Recycling - A Holistic Approach for Interface Optimisation between Pre-Processing and Integrated Metals Smelting and Refining*, 2006 IEEE International Symposium on Electronics and the Environment (IEEE Cat. No. 06CH37796), Scottsdale, AZ, USA, 2006; IEEE: Scottsdale, AZ, USA, 2006.
32. Hageluken, C.; Meskers, C. *Technology Challenges to Recover Precious and Special Metals from Complex Products*; http://ewasteguide.info/files/Hageluecken_2009_R09.pdf, 2009.
33. Chancerel, P.; Bolland, T.; Rotter, V. S., Status of pre-processing of waste electrical and electronic equipment in Germany and its influence on the recovery of gold. *Waste Management & Research: The Journal of the International Solid Wastes & Public Cleansing Association, ISWA* **2011,** *29*, (3), 309.
34. *Impact Assessment of the Recast Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE)*; Department for Business, Innovation and Skills (BIS): United Kingdom, 2013.
35. Decree-Law No. 67/2014. In Portugal, 2014; pp 1-22.
36. Directive 2012/19/EU Of The European Parliament And Of The Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). In European Union: European Union, 2012; pp 1-34.
37. Directive 2008/98/EC Of The European Parliament And Of The Council of 19 November 2008 on waste and repealing certain Directives. In European Commission: European Union, 2008; pp 1-28.
38. Directive 2006/66/EC Of The European Parliament And Of The Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC. In Council, E., Ed. European Union: 2006; p 14.
39. Santos, E. L. M. Mapping, Modelling and Improving the WEEE Treatment and Recovery: A Portuguese Case Study. Universidade de Lisboa Instituto Superior Técnico, Portugal, 2013.
40. ANREEE Home. https://www.anreee.pt/uk/.
41. Niza, S.; Santos, E.; Costa, I.; Ribeiro, P.; Ferrão, P., Extended producer responsibility policy in Portugal: a strategy towards improving waste management performance. *Journal of Cleaner Production* **2014,** *64*, 277-287.
42. Portuguese Environment Agency (APA). http://www.apambiente.pt/index.php?ref=x178 (March), 2016.
43. Salema, M. I. G.; Barbosa-Povoa, A. P.; Novais, A. Q. In *Design of a Recovery Network in Portugal: The Electric and Electronic Equipment Case*, 2008 IEEE International Engineering Management Conference (IEMC-Europe 2008), Estoril, Portugal, 2008; IEEE: Estoril, Portugal, 2008.
44. *Relatorio de Actividades 2014*; Portugal, 2015; pp 1-185.
45. *Relatorio Anual de Actividades 2013*; Portugal, 2014; pp 1-144.
46. Electrao a rede da Amb3E. http://www.amb3e.pt/ (February), 2016.
47. Joint Dispatch No. 354/2006. In Portugal, 2006; pp 6142-6148.
48. Dispatch No. 1516/2012. In Portugal, 2012; pp 3939-3940.

49. *Relatorio de Actividade - REEE 2011*; Portugal, 2012; pp 1-75.
50. *Relatorio de Actividade REEE - 2012*; Portugal, 2013; pp 1-73.
51. Kindergarn, A., Portugal: A Peripheral Country at a Crossroads. In *The Financialist by Credit Suisse*, Credit Suisse: 2013.
52. Dispatch No. 2103/2015. In Ministry of Economy and the Environment, Spatial Planning and Energy - Offices of the Assistant Secretaries of State and Economy and the Environment: Portugal, 2015; pp 5117-5119.
53. WEEE Forum - What is the WEEE Forum. http://www.weee-forum.org/what-is-the-weee-forum (March), 2016.
54. ERP Portugal. http://www.erp-recycling.pt/ (March), 2016.
55. Despacho Conjunto 353/2006, de 27 of Abril. https://dre.tretas.org/dre/197406/ (February), 2016.
56. Monforte, R. *10 Years Promoting Competition in the Waste's Sector*; Portugal, 2015; pp 1-11.
57. Dispatch No. 2104/2015. In Portugal, 2015; p 5119.
58. *Valores do Mercado Português de EEE em 2007*; Portugal, 2008; pp 1-6.
59. *Valores do Mercado Português de EEE em 2008*; Portugal, 2009; pp 1-6.
60. *Portugal 2009: Market Data of Electrical and Electronic Equipments*; Portugal, 2010; pp 1-9.
61. *Dados de Mercado EEE em Portugal 2010*; Portugal, 2011; pp 1-14.
62. *Dados de Mercado EEE 2011*; Portugal, 2012; pp 1-10.
63. *Dados de Mercado de 2012 de Equipamentos Eléctricos e Eletrónicos*; Portugal, 2013; pp 1-12.
64. *Dados de Mercado Equipamentos Elétricos e Eletrónicos 2013*; Portugal, 2014; pp 1-12.
65. *Market Report - Electric and Electronic Equipment*; Portugal, 2014; pp 1-12.
66. WEEE Compliance - Categories of WEEE. http://weee.clarity.eu.com/categories_of_eee.php.
67. Geyer, R.; Blass, V. D., The economics of cell phone reuse and recycling. *International Journal of Advanced Manufacturing Technology* **2010,** *47*, (5-8), 515-525.
68. Daigo, I.; Hashimoto, S.; Murakami, S.; Oguchi, M.; Tasaki, T. Lifespan Database for Vehicles, Equipment, and Structures: LiVES. http://www.nies.go.jp/lifespan/index-e.html.
69. Eurostat - Waste Electrical and Electronic Equipment (WEEE). http://ec.europa.eu/eurostat/web/waste/key-waste-streams/weee.
70. *2008 Key Figures - Key Figures on Quantities of Electrical and Electronic Equipment Put on the Market, Quantities of WEEE Collected, and Costs Related to WEEE Management*; European Union, 2010; pp 1-14.
71. *WEEE Forum Key Figures Report 2010-2012*; European Union, 2014; pp 1-18.
72. Haig, S.; Morrish, L.; Morton, R.; Wilkinson, S. *Electrical Product Material Composition*; United Kingdom, 2012; pp 1-10.
73. Fichtner, R. *Technical Assistance For Waste from Electrical and Electronic Equipment (WEEE) Directive Implementation; Study on Costs Related to the Implementation of the WEEE Directive*; 2007; pp 1-27.
74. *Metal Prices in the United States Through 2010*; United States Geological Survey: Reston, Virginia, 2013; p 204.

75. *Mineral Commodity Summaries 2015*; United States Geological Survey: Reston, Virginia, 2015; p 196.

76. Weidema, B. P.; Wesnæs, M. S., Paper: Data quality management for life cycle inventories—an example of using data quality indicators. *Journal of Cleaner Production* **1996,** *4*, 167-174.

77. Frischknecht, R.; Jungbluth, N.; Althaus, H.-J.; Doka, G.; Dones, R.; Heck, T.; Hellweg, S.; Hischier, R.; Nemecek, T.; Rebitzer, G.; Spielmann, M., The ecoinvent database: Overview and methodological framework. *International Journal of Life Cycle Assessment* **2005,** *10*, (1), 3-9.

78. Laner, D.; Rechberger, H.; Astrup, T., Systematic Evaluation of Uncertainty in Material Flow Analysis. *Journal of Industrial Ecology* **2014,** *18*, (6), 859-870.

79. Hedbrant, J.; Sörme, L., Data Vagueness and Uncertainties in Urban Heavy-Metal Data Collection. *Water, Air & Soil Pollution: Focus* **2001,** *1*, (3/4), 43-53.

80. Waste Electrical and Electronic Equipment (WEEE) - Reference Metadata in Euro SDMX Metadata Structure (ESMS). http://ec.europa.eu/eurostat/cache/metadata/en/env_waselee_esms.htm - quality_mgmnt1444126190544.

81. Eurostat Quality Grading System. http://ec.europa.eu/eurostat/cache/metadata/Annexes/Quality-Grading-System.pdf.

82. Cucchiella, F.; D'Adamo, I.; Lenny Koh, S. C.; Rosa, P., Recycling of WEEEs: An economic assessment of present and future e-waste streams. *Renewable and Sustainable Energy Reviews* **2015,** *51*, 263-272.

83. Buchert, M.; Manhart, A.; Bleher, D.; Pingel, D. *Recycling Critical Raw Materials from Waste Electronic Equipment*; 2012; pp 37-41, 58-74.

84. Tojo, N.; Manomaivibool, P. *The Collection and Recycling of Used Mobile Phones; Case Studies of Selected European Countries*; Lund University: IEEE, 2011; p 66.

85. van Schaik, A.; Reuter, M. A., Dynamic modelling of E-waste recycling system performance based on product design. *Minerals Engineering* **2010,** *23*, 192-210.

86. Menad, N.; Kanari, N.; Menard, Y.; Villeneuve, J., Process simulator and environmental assessment of the innovative WEEE treatment process. *International Journal of Mineral Processing* **2016,** *148*, 92-99.

87. Palmieri, R.; Bonifazi, G.; Serranti, S., Recycling-oriented characterization of plastic frames and printed circuit boards from mobile phones by electronic and chemical imaging. *Waste Management* **2014,** *34*, 2120-2130.

88. Yamane, L. H.; de Moraes, V. T.; Espinosa, D. C. R.; Tenório, J. A. S., Recycling of WEEE: Characterization of spent printed circuit boards from mobile phones and computers. *Waste Management* **2011,** *31*, 2553-2558.

89. Christian, B. b. b. c.; Romanov, A. a. b. c.; Romanova, I. i. g. c.; Turbini, L. l. t. y. c., Elemental Compositions of Over 80 Cell Phones. *Journal of Electronic Materials* **2014,** *43*, (11), 4199-4213.

90. Ardente, F.; Mathieux, F.; Recchioni, M., Full length article: Recycling of electronic displays: Analysis of pre-processing and potential ecodesign improvements. *Resources, Conservation & Recycling* **2014,** *92*, 158-171.

91. Ziout, A.; Azab, A.; Atwan, M., A holistic approach for decision on selection of end-of-life products recovery options. *Journal of Cleaner Production* **2014,** *65*, 497-516.

92. Chen, C.; Zhu, J.; Yu, J.-Y.; Noori, H., Production, Manufacturing and Logistics: A new methodology for evaluating sustainable product design performance with two-stage network data envelopment analysis. *European Journal of Operational Research* **2012,** *221*, 348-359.
93. Terziovski, M.; Guerrero, J.-L., ISO 9000 quality system certification and its impact on product and process innovation performance. *International Journal of Production Economics* **2014,** *158*, 197-207.
94. Ardente, F.; Mathieux, F., Environmental assessment of the durability of energy-using products: method and application. *Journal of Cleaner Production* **2014,** *74*, 62-73.
95. Ardente, F.; Mathieux, F., Identification and assessment of product's measures to improve resource efficiency: the case-study of an Energy using Product. *Journal of Cleaner Production* **2014,** *83*, 126-141.
96. Allacker, K.; Mathieux, F.; Manfredi, S.; Pelletier, N.; De Camillis, C.; Ardente, F.; Pant, R., Allocation solutions for secondary material production and end of life recovery: Proposals for product policy initiatives. *Resources, Conservation & Recycling* **2014,** *88*, 1-12.
97. The EU Ecolabel. http://ec.europa.eu/environment/ecolabel/index_en.htm (March), 2016.
98. *EU Ecolabel Work Plan for 2016-2018*; European Union, 2016; pp 1-55.
99. Commission Decision of 12 March 2009 Establishing The Revised Ecological Criteria For the Award of the Community Eco-label to Televisions. In Commission, E., Ed. Official Journal of European Union: 2009; Vol. 2009/300/EC, pp 1-6.
100. Commission Decision of 17 December 2013 Establishing The Ecological Criteria For the Award of the EU Ecolabel for Imaging Equipment. In Commission, E., Ed. Official Journal of the European Union: 2013; Vol. 2013/806/EU, pp 1-11.
101. Commission Decision of 9 June 2011 On Establishing The Ecological Criteria For the Award of the EU Ecolabel for Personal Computers. In Commission, E., Ed. Official Journal of the European Union: 2011; Vol. 2011/337/EU, pp 1-10.
102. Commission Decision of 6 June 2011 On Establishing The Ecological Criteria For the Award of the EU Ecolabel for Notebook Computers. In Commission, E., Ed. Official Journal of the European Union: 2011; Vol. 2011/330/EU, pp 1-8.
103. *EU Ecolabel Work Plan for 2011-2015*; European Union, 2014; pp 1-39.
104. Kougoulis, J.; Kaps, R.; Weber, R.; Posner, S., Promoting the frontrunners - EU ecolabel criteria requirements on the use of substances for printers, copiers and multifunc-tional devices (MFDs). *2012 Electronics Goes Green 2012+* **2012**, 1.
105. Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-Related Products (Recast). In Parliament, E., Ed. Official Journal of the European Union: 2009; Vol. 2009/125/EC, pp 1-26.
106. Directive 2010/30/EU of the European Parliament and of the Council of May 19 2010 on the Indication by Labeling and Standard Product Information of the Consumption of Energy and Other Resources by. In Official Journal of the European Union: 2010; Vol. 2010/30/EU, pp 1-12.
107. Pastor, M. C.; Mathieux, F.; Brissaud, D., Influence of Environmental European Product Policies on Product Design-current Status and Future Developments. *Procedia CIRP* **2014,** *21*, 415-420.

108. Communication from the Commission to the European Parliament, the Council, and the European Economic and Social Committee and the Committee of the Regions - Public Procurement for a Better Environment. In Communities, C. o. t. E., Ed. Brussels, Belgium, 2008; pp 1-11.
109. *EERA Prospectus for Membership*; The Netherlands, N.D.; pp 1-7.
110. EERA - European Electronics Recyclers Association. http://www.eera-recyclers.com/ (April), 2016.
111. Interecycling | Company Presentation. http://www.interecycling.com/cgibin/eloja21.exe?myid=interecycling_uk&lang=pt&titles=04&mn=empresa&sbmn=apresentacao&main=normal&sh=/interecycling_uk/areas/apresentacao.htm (March), 2016.
112. *Equivalent Conditions for the Treatment of WEEE Exported Outside of the European Union*; European Union, 2014; pp 1-10.
113. WEEE Forum - WEEELABEX. http://www.weee-forum.org/weeelabex-0 (April), 2016.
114. WEEELABEX Organization. http://www.weeelabex.org/ (April), 2016.
115. Compliance with EN 50625 - CECED, DIGITALEUROPE, EERA, and the WEEE Forum call on the European Commission to Take the Appropriate Measures to Make Compliance with the EN 50625 Series Mandatory. In European Union, 2016; pp 1-4.
116. *WEEELABEX Normative Document on Treatment*; European Union, 2013; pp 1-76.
117. *WEEELABEX A10 Documentation to Measure Depollution Performances*; European Union, 2015; pp 1-103.
118. List of Attested WEEELABEX Treatment Operators. http://www.weeelabex.org/conformity-verification/operators/ - weeelabex_operator_list (April), 2016.
119. Olivetti, E.; Field, F.; Kirchain, R., Understanding dynamic availability risk of critical materials: The role and evolution of market analysis and modeling. *MRS Energy & Sustainability - A Review Journal* **2015,** *2*, 1-16.
120. Alonso, E., *Material scarcity from the perspective of manufacturing firms : case studies of platinum and cobalt*. c2010.: 2010.
121. Atlee, J.; Kirchain, R., Operational Sustainability Metrics Assessing Metric Effectiveness in the Context of Electronics-Recycling Systems. *Environmental Science & Technology* **2006,** *40*, (14), 4506-4513.
122. Commission Staff Working Document Impact Assessment Accompanying the document Proposal for reviewing the European waste management targets. In European Commission: Brussels, Belgium, 2014; pp 1-128.
123. Proposal for a Directive Of The European Parliament And Of The Council amending Directives 2008/98/EC on waste, 94/62/EC on packaging and packaging waste, 1999/31/EC on the landfill of waste, 2000/53/EC on end-of-life vehicles, 2006/66/EC on batteries and accumulators and waste batteries and accumulators, and 2012/19/EU on waste electrical and electronic equipment. In European Commission: Brussels, Belgium, 2014; pp 1-32.
124. Ex-Post Evaluation of Five Waste Stream Directives. In European Commission: Brussels, Belgium, 2014; pp 1-89.
125. Progress Report on the Roadmap to a Resource Efficient Europe. In European Commission: Brussels, Belgium, 2014; pp 1-19.

126. Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions Towards a circular economy: A zero waste programme for Europe. In European Commission: Brussels, Belgium, 2014; pp 1-14.
127. Annex To The Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions Towards a circular economy: A zero waste programme for Europe. In European Commission: Brussels, Belgium, 2014; pp 1-3.
128. Analysis of an EU target for Resource Productivity. In European Commission: Brussels, Belgium, 2014; pp 1-30.
129. Vanner, R.; Bicket, M.; Hestin, M.; Tan, A.; Guilcher, S.; Withana, S.; Brink, P. t.; Razzini, P.; van Dijl, E.; Watkins, E.; Hudson, C., Scoping study to identify potential circular economy actions, priority sectors, material flows and value chains. In European Union: Luxembourg, 2014; pp 1-321.
130. Roadmap - Circular Economy Strategy. In European Commission: European Union, 2015; pp 1-9.
131. Kahhat, R.; Poduri, S.; Williams, E. *Bill of Attributes (BOA) in Life Cycle Modeling of Laptop Computers: Results and Trends From Disassembly Studies*; Arizona State University & University of Arkansas, 2011; pp 5-12.