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Assessment framework and material flow analysis of material recovery facilities within the U.S. to track consumer electronics by product category

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Abstract

An assessment framework was developed to evaluate and characterize material recovery facilities within the U.S. that process e-waste. The framework consists of five key categories including, facility overview, operating model and process flows, product flows, collection methods, and facility resource use. The results were used to conduct a material flow analysis to develop a representative set of end-of-life pathways (e.g., reuse, refurbish, recycle) to better understand the flow of e-waste in the end-of-life management industry. The majority of products collected was from business sector collection routes. The largest number of products (by units) collected at 90% of facilities was mobile phones. It was also seen that most products went directly to recycling for material recovery and were not in the condition to be re-used or refurbished.

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Keywords: End-of-life phase; Consumer electronics; Material flow analysis; Material recovery

1. Introduction

Resource use is important in our society to enable new technological advancements. At the same time the extraction, use, and disposal of these resources contributes to environmental degradation and reduction of non-renewable resources. Electronic products contain both valuable and hazardous materials. Recovering the value and safely managing the toxins is the upmost priority during end-of-life (EoL) processing of these products. Due to the valuable material content, electronic products present an opportunity that is ideal for moving towards a closed loop economy. The concept of urban mining has gained traction in the last several years because of this opportunity. While recycling has always been motivated by this, products are often managed incorrectly and valuable materials can be lost in the process. Concern over resource scarcity and rare earth metals has also motivated the need for improvement in material recovery.

To sustainably manage these products during the EoL phase we must first understand the current state of the industry. An important strategy that is underutilized is the implementation of a feedback loop between EoL management programs and facilities to product managers and designers. To facilitate this information and data exchange, it is necessary to develop a standardized system. Currently, the focus of data collection within the industry is motivated by state regulation requirements. Most regulations focus on mass based metrics and landfill bans. While these metrics are important, additional indicators are needed in order to better characterize system performance and product and material flows through the EoL phase. To address these needs within industry, research is presented here on the development and implementation of a framework to characterize the EoL management phase of consumer electronics. The framework incorporated material flow analysis methods to map product flows within material recovery facilities. The flows were mapped according to collection method and the EoL pathway followed by each product category. Data was collected from 14 material recovery facilities operating within the U.S. EoL management industry. The study identified facilities across the

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U.S. that varied in size and operating models in order to capture the diverse business models used in this industry. From these assessments, a representative set of the most common EoL pathways followed by product category was determined in order to better understand the flow of e-waste within the EoL management industry in the U.S. based on current industry practices.

2. Material flow analysis

One method that can be used to characterize the current system and material flows within that system is material flow analysis (MFA). Material flow analysis is a method of quantifying the mass of a material or product of interest as it moves throughout specified temporal, economic, or geographic boundaries [1]. MFA builds on earlier concepts of material and energy balancing and is complementary to life cycle assessment (LCA) and input-output modeling methods.

2.1. Previous literature

Previous research has employed MFA to track waste flows of various consumer products. Streicher-Porte conducted a MFA of personal computer recycling in the informal recycling sector in Delhi, India [2]. Hischier combined MFA with simplified LCA to determine the environmental impact of a Swiss take-back and recycling system [3]. Huisman evaluated the performance of various recycling scenarios and equipment based on environmental performance [4]. Chancerel conducted an assessment of e-waste pre-processing and focused on the precious metal flows in a German facility [5]. Gregory used MFA in order to analyze the material recovery system for leaded glass in cathode ray tube (CRT) displays [6].

There have been several studies that have evaluated the performance of EoL management systems. Gutowski and Dahmus used information theory to compare product material mix and predict the likely EoL path of a product [7]. Gregory and Kirchain developed a framework for evaluating the economic performance of four North American electronics systems [8]. Fredholm developed a framework to evaluate recycling systems based on collection rates, operating models, and economic performance [9]. Kwak and colleagues conducted and e-waste stream analysis at an e-waste collection center in order to assess product quantity and age [10].

2.2. Challenges and importance of mapping product flows during the end-of-life phase

Previous studies have shown that material flow analysis can be used to assess waste management systems, as it considers the material and product flows. However, there are challenges to obtaining material flow data within the EoL management industry. The development of this type of system is stalled due to critical data gaps and challenges of characterizing such a young, diverse industry. Electronic recycling has a short history, so there is not a broad and fixed infrastructure in place, making these types of assessments difficult [11]. Exacerbating this shortcoming, recycler performance is typically assessed using indicators that do not consider key factors that in influence recycling performance (e.g., in low quality, product mix, or downstream material yields). Ideally this would be addressed in a detailed system-wide analysis. Unfortunately, time and expense preclude this approach beyond the occasional case study. While one-off studies provide valuable insights, they do not fill the operational need for continuous feedback and regular benchmarking within this industry.

As recycling systems become more widespread, understanding system performance becomes even more critical, both to enable improvement of existing systems and to design and implement new ones [7]. The importance of tracking these flows has been noted in literature as high priority due to the potential impact recycling processes have to contribute to the sustainable management of resources [12]. The variety, variability, and condition of products entering the system creates mixed material flows and the composition of the incoming flow is often unknown and complex [12,13,14]. Attaining a sustainable materials market requires understanding the nature and magnitude of the flows within the system.

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

3. Assessment methods

The primary goal of the assessment was to develop a representative set of the most common pathways that are followed during the EoL phase for each product category. By understanding the mix and quantity of products that are being collected at material recovery facilities, in addition to the pathways they follow through these facilities and decision points, we will be able to better characterize the EoL phase.

3.1. Overview of assessment framework

The framework (see Figure 1) consists of five sections: facility overview, operating model and process flows, product flows, collection methods, and facility resource use. Additional information about the facility was included in the framework to understand the operating model, processes and process flows performed at the facility, and facility level resource use.

The facility overview section of the framework provides basic facility information including facility size and location and the number of employees at the facility.

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

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

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

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

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

Fig. 1 Overview of assessment framework

The operating model and process flows section was included to understand how the products move through the process flow within the facility. This also provides insights into the operating model of the facility. For example, does the facility focus more on recycling or refurbishing of equipment? The product flows section identifies the incoming product mix collected by each facility and the EoL pathway it follows. The final section of the framework focused on resource use in the facility in order to provide a high level assessment of the energy used to process these products during the EoL phase. While the focus of this work was not an environmental assessment, it was an important consideration for future work.

3.2. Product scope and equipment collection methods

The following product categories were included in this study: desktop and laptop computers, monitors, mobile devices, televisions, and entertainment players. These products were chosen due to the ability of EoL management facilities to track these products and they are representative of a broad range of consumer electronic products that are most common in the marketplace today. In 2010, more than 62% of e-waste collected was from computing and information and communications technology (ICT) equipment [15]. It is important to note that while CRT technology is not currently used in new products; many CRT products are still being collected through e-waste streams.

Products ready for the end-of-life are collected through a variety of collection methods. The framework segments these methods by the consumer and business sectors, to better identify the collection performance of each of these sectors. Consumer sector includes retail return, collection program, direct from consumers, and OEM takeback program. Business sector includes equipment collected from OEMs, enterprise businesses, government agencies, and academic institutions.

4. Material flow analysis model

This section describes the material flow analysis model used to map the product flows through collection and subsequent EoL pathways within a given facility (see Figure 2). The dashed line represents the system boundary of the study.

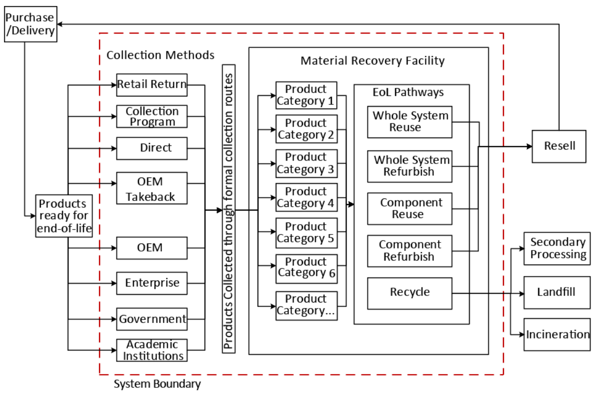

Fig. 2 Material flow analysis model and system boundary

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

4.1. Data collection

Facility surveys were used to collect the data to assess each facility and model the product flows, based on collection methods, EoL pathways, and incoming product mix. The collection of primary facility data is a key contribution of this work. The survey consisted of four main sections based on the assessment framework described in Section 3.1.

4.2. Overview of participating material recovery facilities

Survey requests were sent to thirty-five facilities with a response rate of 40%. A total of 14 facilities responded to the survey and of those three were small, six were medium, and five were large based on the number of employees: small (1-15), medium (15-30), and large (30-65). A past survey that was conducted by the International Data Corporation (IDC) indicated that this industry in the U.S. primarily consists of facilities that operate with 10 or less workers representing 50.5% of the industry [15]. The operational footprint was also determined for each facility and ranged from 7,000 to 150,000 ft^2. The majority of the facilities surveyed were located in the Mountain and Midwest regions, with four facilities from each. There were two participating facilities in the New England and the West, and one facility from both the Southwest and Southeast regions. This closely aligns with the distribution of total material recovery facilities in the U.S. Recent studies have suggested that material recovery facilities are primarily concentrated in the Midwest, New England, and Western regions of the U.S., each of which accounts for approximately one-quarter of recycling companies [11].

5. Results and discussion

5.1. Incoming products

Each facility provided the mass (lbs.) of incoming e-waste by product category for 2011. The majority of equipment collected by mass was CRT televisions and monitors, followed by desktop computers. As evidence that older equipment that has been out date for many years is still being collected for EoL management. CRT equipment is much heavier than newer technology which skews the data when only accounting for mass based collection. One of the main concerns that arise from the large amount of CRT collection is that currently there are stockpiles of this type of equipment. This is mainly due to the limited secondary uses for leaded glass which is found in the screens of the CRT equipment and lack of available processing facilities. In 2013, several processors abandoned warehouses with more than 10,000 tons of CRT equipment and glass [16]. While this issue is currently limited to CRTs, it could foreshadow future challenges for the recycling industry.

5.2. Challenges with using mass based collection metrics

Currently these facilities do not collect data by number of units; this is often due to time constraints in addition to mass based reporting metrics that are required by state takeback laws. Mass is not a good indicator to use when assessing the product mix of the incoming e-waste stream due to the varied mass of products and continued size reduction of technology products that are placed on the market. In order to gain more insight into what products are being collected, the mass based distribution was used to estimate a volume (by units) based distribution. The average mass of each product was determined using market data and literature [17,18,19,20]. Figure 3 presents the average product mass for each product category that was evaluated. Due to the large variation in product mass between product categories, the results are presented in two charts.

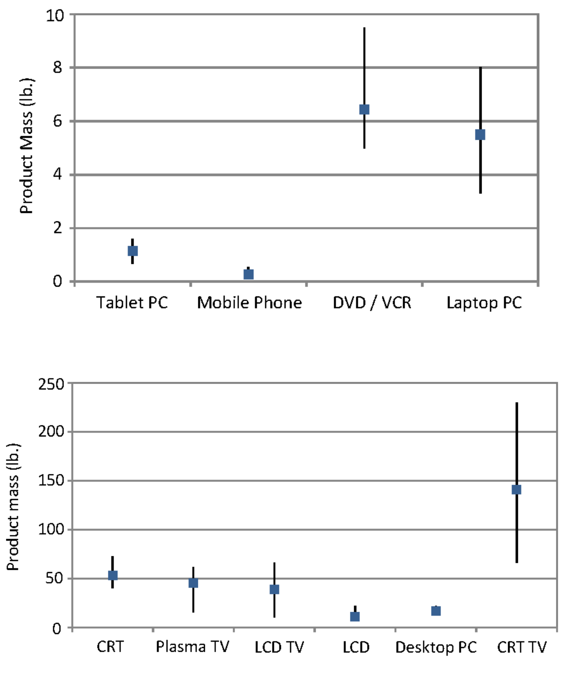

Fig 3. Average product mass (lb) by equipment type

Using the average product mass the number of units of collected for each product category was estimated. The data presented in Figure 4 provides a more accurate assessment of the incoming mix of products by units at each facility.

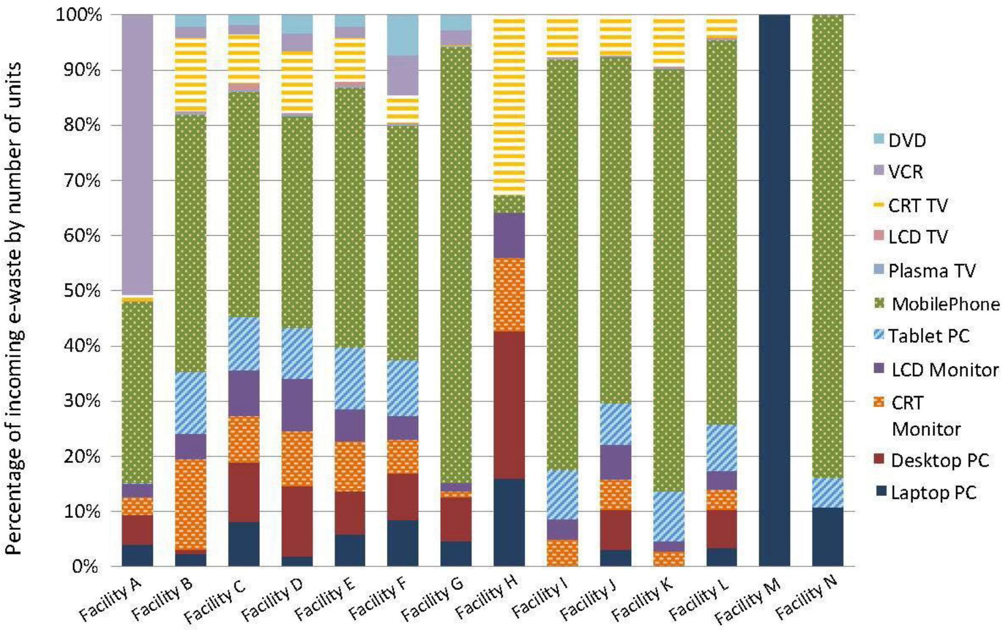

Fig. 4 Percentage of incoming e-waste by number of units for each product category at each facility (2011)

Based on number of units mobile phones make up the largest portion (often over 35%) of incoming products for almost all facilities. This is an interesting insight as mobile phones have a significant amount of valuable material per product mass compared to other product categories, because they are primarily composed of printed circuit boards where most of the valuable materials are located within an electronic product. Mobile phones have short lifespans compared to other products. Recently the lifespan of a mobile phone in the U.S. was estimated to be 18-22 months, the shortest compared to other countries [21]. Consumers are also more likely to donate and recycle mobile phones because they are easier to drop off at collection centers due to their size and are often not as expensive an investment as other products categories.

5.3. End-of-life pathways

In order to improve the EoL management system it is important to understand the pathways these products follow within the material recovery management system. Data that was collected from the survey was used to map the product flows for each facility. The analysis assessed the percentage of products, by product category, that are reused, refurbished, or recycled within each material recovery facility. Figure 5 shows the percentage of incoming products that followed each pathway based on aggregated data from all facilities.

The results of the MFA show that most products that enter the formal recycling stream are not in the condition to be directly reused without repair. The majority of products that are collected are sent to recycling either at the facility or downstream to a secondary processing facility. This was even true for facilities that focus more on repairing and refurbishing products. This is most likely due to the condition of products that are collected because they are not in working condition to make it economically viable to refurbish or repair. Laptop computers were the most likely product to be sent to reuse. There has been much research that has focused on designing products to be reused; however within the formal collection routes, are products actually being reused or refurbished? The results of this assessment show that once products enter the formal collection stream, most of the products go directly to recycling. It is important to note that reuse of products often occurs in the informal sector through consumers reselling, donating or gifting old equipment. Future work should focus on the decisions made within these facilities to understand why more products are not being reused and refurbished.

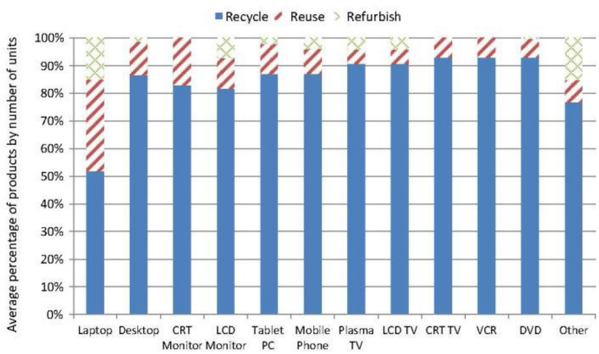

Fig. 5 Average percentage of products that followed each EoL pathway

6. Summary and need for future work

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

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

This study was based on current industry data of several facilities in the U.S. and provided useful insights into the recycling industry. However, the electronics and recycling industries are both ever-changing and there is a need for consistent data and reporting to facilitate continuous feedback and benchmarking in order to improve overall system efficiency. Technology and product types are evolving and continuous information gathering will be necessary. Collaboration between key stakeholders will be integral to ensuring the success of sustainably managing consumer electronics during the EoL phase.

Current indicators used within the industry are not good measures of true performance. As it was shown, mass based collection metrics do not effectively characterize the types and volume (by units) of the incoming product mix at material recovery facilities. In addition, the implementation of mass balance metrics that consider the incoming flow of products and their compositions and the output material streams at these facilities would be useful. The development of better metrics will allow for quantitative performance assessments and benchmarking within the industry.

Developing a better understanding of this EoL system will allow for improvements in product design, material recovery, and information exchange throughout the supply chain. While these products are ultimately treated as materials during the EoL phase they need to be characterized as products in order to provide valuable information back to designers and product manufacturers. Future work should extend the research developed here to gather more robust data on the out flows of the material processing facilities and consider product composition to evaluate the value of materials reclaimed and identify areas for opportunity.

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