# AN EXPLORATORY STUDY FOR UNDERSTANDING E-WASTE RECYCLING

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### ABSTRACT

This paper explores four aspects of e-waste: (1) the definition and scope of e-waste, and the challenges in e-waste recycling; (2) a framework that consists of the system structure, components, and software support for understanding how e-waste recycling systems are designed and operated; (3) a review of current e-waste recycling practices in both developed and developing countries; and (4) a case study of Worcester Polytechnic Institute's recycling program to provide a glimpse of e-waste recycling management in a higher-education setting. Possible research areas for Operations Management professionals generated by this exploratory study are then identified and presented.

**Keywords**: Sustainability, e-Waste Recycling, E-waste Strategies and Practices, Regulations and Policies

### INTRODUCTION

#### What Is e-Waste?

The term electronic waste, or e-waste, has diverse definitions, varying around two main ideas: (1) the product scope, and (2) the time when a device is considered as waste. Sinha [33] defines e-waste as "an electrically powered appliance that no longer satisfies the current owner for its original use." The satisfaction of the current owner is a subjective concept, and equipment considered as not useful by one person might be useful for another with lower requirements. Thus, this definition does not solely refer to waste. Similarly, CalRecycle [3] refers to e-waste as computers, televisions, VCRs, and similar items nearing their end of useful life, which can then be recycled, reused, or refurbished.

The Organization for Economic Co-operation and Development [27] presents another problematic definition, describing e-waste as "any appliance using electric power that has reached its end-of-life." A non-working device might indeed be considered as waste; however, huge quantities of electrical or electronic equipment (EEE) stockpiled by owners never enter the waste stream [30]. Puckett and Smith [28] state that e-waste encompasses a wide and increasing range of electronic devices comprising large and small households appliances, as well as cell phones, computers and consumer electronics that have been thrown away by their users. The European Union's WEEE Directive [6] agrees with this definition, considering e-waste as EEE including all components, subassemblies and consumables, which the holder disposes of.

When taking into consideration the most important elements of these definitions, EEE can thus be considered as waste when it is discarded by its owner, whether or not it has stopped working. In this paper, WEEE, or e-waste, refers to EEE that has reached its end of useful life and is discarded by its owner for recycling, landfilling, or incineration.

## **Challenges of e-Waste Management**

WEEE is the one of the fastest growing categories of municipal solid waste, increasing at annual rate of about 4% [9], and standing for 2-5% of the waste stream in the United States [32] and 8% in Europe [35]. With an estimated 40 million tons of e-waste generated worldwide each year [34] mainly in OECD countries that are saturated with huge quantities of EEE [43], the institutions seeking environmentally friendly waste management are facing significant challenges.

WEEE comprises 60 different elements, some hazardous, valuable, or both [31]. The fraction including copper, aluminum, gold, platinum and other metals represents 60% in e-waste [43] – a volume of considerable value; however, 2.7% of these elements are pollutants [43]. Toxic substances contained in e-waste such as arsenic, lead, cadmium, mercury, chromium, and brominated flame retardants (BFRs) [37] can have harmful consequences on human health and the environment if not handled and treated correctly [28].

Despite the establishment of the Basel Convention in 1992 that aims at reducing and controlling the export of hazardous waste from OECD countries to non-OECD counterparts, the export of e-waste remains a significant issue. The lack of enforcement in environment, health and safety controls, in addition to the cheap labor for dismantling in developing countries, combined, in some cases, with the legality of exports (e.g. the US does not ratify the Basel Convention), foster this practice. As much as 50-80% of e-waste collected for recycling in the US is exported to countries such as China, India or Nigeria [28], where the handling conditions are generally inappropriate and harmful to humans (e.g., respiratory and skin problems) and the eco-system (e.g., water pollution).

In addition to these concerns, even if over 90% of the base metals and the precious metals can be recovered [17], rudimentary treatment infrastructures can drop the recovery rates down to 25% [36]. As such, the export of e-waste not only results in pollution, but in the loss of valuable material as well.

The high cost of sanitary landfilling paired with decreasing landfill space due to the difficulty in finding acceptable sites [26] represents another reason why recycling WEEE has become so popular. Furthermore, e-waste has a significant impact on raw material resources. When

the metals contained in e-waste are not recovered, new raw materials have to be extracted to make new products, resulting in higher energy consumption and loss of resources. For example, the gold and copper concentrations in a printed circuit board can be respectively 800 and 40 times higher than in naturally mined gold and copper ore [2]. Recovering metals from e-waste in an environmentally appropriate manner needs only a fraction of energy compared to mining ores in nature [31] and can be more efficient than mining the earth. As the demand of metals for the manufacturing of EEE is large; e.g. out of worldwide mine production, over 30% is for silver (switches, contacts, etc.), 12% for gold (integrated circuits, contacts, etc.), 30% for copper (cable, wire, etc.), 19% for cobalt (rechargeable batteries), and 79% for indium (LCD glass, semiconductors, etc.), effective e-waste recycling is crucial to maintaining the supply of metals for manufacturers [31].

The increasing success of consumer electronic devices, associated with their rapid obsolescence, will toughen the challenges being faced by e-waste management systems. For instance, the worldwide sales of computers have grown from 128.1 million units in 2001[12] to 351 million units in 2010 [11], while the lifespan of PCs has shortened from 4.5 years in 1992 to 2 years in 2005 [18] Unless the price of raw materials used in EEE increases at such a point that recycling becomes economically vital, legislations are required to prevent and control human and environmental threats [10].

Recycling e-waste has thus become an undeniable concern in industrialized countries since the beginning of the 21<sup>st</sup> century. Many different systems for treating e-waste now exist worldwide. However, despite the obvious positive impacts of e-waste recycling on environment and resources, treatment cost has limited the growth of recycling markets. Thus, in the absence of clear legislations, recycling e-waste has been bound to private voluntary systems, treating only the most valuable devices. In response to the challenges brought by WEEE, the EU with the WEEE Directive in 2003 [6], as well as the US with 25 states [5] involved to date, have enacted legislations to manage, regulate and prevent e-waste.

However, despite significant efforts to define legislations to create a circular flow economy in developed countries [31] the collection rates of e-waste in Europe and in the US still remain insufficient (Details will be discussed in Section 3). Depending on the device considered, only 25 to 40% of WEEE in the EU [41] and 8 to 38% in the US is collected for recycling [39].

With the understanding of the concept of e-waste and of the scope and challenges of e-waste recycling, the objectives of the paper are fourfold: (1) to develop a framework for analyzing e-waste recycling systems so that their major functions, components, actors, and associated issues and pitfalls will become clear; (2) to review the major e-waste recycling practices in both developed and developing countries to reveal their similarities, differences, and gaps, which further identify more challenges in e-waste recycling endeavors; (3) to present a detailed case study of e-waste recycling in the US universities using Worcester Polytechnic Institute (WPI) as an example to provide a glimpse of the status-quo of this sustainability initiative in higher-education institutions that are often big generators of e-waste; and (4) to identify research directions for future efforts.

## DEFINING A FRAMEWORK FOR E-WASTE RECYCLING SYSTEMS

A very important step in understanding e-waste management is to examine the structure of the recycling systems. This section presents a framework for analyzing the structure of a

typical e-waste recycling system and for identifying the possible alternatives for each of its components with the consideration of their respective strengths and weaknesses.

## **E-waste Recycling System Structure**

Any e-waste recycling system tends to fulfill three main functions: (1) collection, (2) processing, and (3) system management. In addition, a financing scheme must be in place to enable a system to be implemented [13]. Thus, an e-waste recycling system structure can be presented in Figure 1.



Figure 1: Main Functions of an e-Waste Recycling System [13]

The presented structure is common to all sustainable systems; however, since many possibilities exist for each of these components, a diverse set of potential system architectures can be resulted. The system architecture implemented depends on the objectives the system attempts to reach, some of which include [31]:

- Involve manufacturers in the improvement of products recyclability through product design and reducing the use of hazardous.
- Prevent toxic materials from incineration and entering landfills.
- Recover valuable materials from e-waste, thus preserving resources.
- Ensure the environmentally sound treatment of e-waste.
- Share responsibility among stakeholders of the recycling chain.
- Promote the system and motivate consumers to improve collection rates.
- Build a cost efficient and sustainable system.

The potential conflicting interest among stakeholders represents a challenging in system optimization. The economic efficiency and environmental success of a system does not rely upon each single step but on the recycling chain as a whole. The following section describes the key elements of each system function as well as the financing schemes.

# Analysis of Recycling Systems

## System Management Components

The coordination of activities among stakeholders and the resulting financial, information and material flows require some form of management, as well as enforce rules and regulations. Several entities, outlined in Table 1, can play this role.

System Components	Brief Description and Remarks
1. Government	The government agency in charge of environmental issues is often tasked with supervising the operations of the e-waste recycling system. These responsibilities may include collecting the recycling fees, reimbursing collectors and recyclers, enforcing environmental standards, registering accepted manufacturers, enforcing sales ban for OEMs that are not complying with enforced laws, and approving which recyclers and collectors are taking part in the system.
2. Third-party Organization (TPO)	A TPO can be composed of only the manufacturers of the product, or include governmental entities or other members such as processors or collectors. Alternatively, it can be a single entity created by the government to manage the system. The activities performed by TPOs may vary from country to country. Two main TPO schemes exist:
	• <i>National collective system</i> : a nation-wide system responsible for the collection, recycling, and financing of all e-waste considered in a country. Some countries have implemented several national collective systems managing different product categories. This method results in a monopoly of the treatment of e-waste.
	• <i>Clearing house system</i> : a national framework in which several TPOs can compete in the operations of the system.
3. EEE Manufacturers	When giving the control to OEMs for the management of e-waste recycling systems, two approaches can be followed.
	• <i>Individual Producer Responsibility</i> (IPR): Manufacturers are in charge of paying for or managing individually the recycling of their own brand. IPR is mainly used in the treatment of products arising from businesses. Commercial returns (e.g. at the end of leasing periods) are common practices. Products are then quite often remanufactured, refurbished or spare parts components are recovered.
	• <i>Collective Producer Responsibility</i> (CPR): Multiple producers collaborate to manage their collective waste. In addition, the large majority of CPR systems established are nowadays collecting a share of e-waste rather than only products from their member's brands.

Table 1: e-Waste Recycling System Management Components

## **Collection Methods**

The collection of e-waste is of crucial importance as it determines the volume of material entering the recycling chain. Collection methods for e-waste from households often differ from those available for corporations. Three major collection options are available, as outlined in Table 2 with details provided as follows.

	Government	Retailer	Recycler	Manufacturer
Permanent Drop- Off Locations	Municipal waste facilities	One for one basis or if selling similar item	Located at entity	Location created in partnership with one of the three other stakeholders
Special Collection	One- or two-day event at a designated location for collection and education			

 Table 1: Actors and e-Waste Collection Methods [13]

Events	about e-waste			
Scheduled Pick-up	Curbside	Direct pick-up or logistics provider	Direct pick-up	Pick-up by mailing or logistics provider

- (1) <u>Permanent Drop-Off Locations</u>: This is the most common method used for e-waste collection from households. Drop-off facilities are often related to governmental entities, such as municipalities. Retailers are also widely used as drop-off locations. Some laws require that retailers collect e-waste only if they sell similar products, while others only require it when a similar item is purchased (one for one basis). Other collectors and commercial entities such as recyclers could accept e-waste from generators at their facility. OEMs often partner with one or several of the three other actors to create affiliated drop-off locations. Depending on the country legislation, drop-off facilities must comply with rules varying in severity. Collection locations must be able to store e-waste in an appropriate manner, as recyclers or their transportation companies may not pick up waste on a daily basis.
- (2) <u>Special Collection Events</u>: This collection method is generally spread over the course of one to two days, during which generators drop off e-waste at a designated location. These special collections can occur at permanent facilities or at a temporary location, such as a parking lot or a university. Promotion is a major factor in the efficiency of special events, to aim at not only increasing the collection of e-waste, but also educating people about ewaste. These special events are often the result of collaboration between processors, retailers, and the government.
- (3) <u>Scheduled Pick-up</u>: Scheduled pick-ups can take several forms. Some municipalities perform scheduled curbside pick-ups for brown and white goods. For significant amounts of e-waste generated by big corporations, collectors and recyclers often perform scheduled pick-ups. The economic incentives may even create situations in which scheduled pick-up is performed for households. Furthermore, some retailers propose scheduled pick-ups for WEEE at a charge that can be waived if a replacement is purchased. Manufacturers also often contract with logistics providers to offer take-back collection systems, products that are then supplied to the OEM or to an OEM-approved recycler.

## Processing

Once the collected e-waste has been transported to the recycling facility, it is tested and sorted. The collected equipment is sorted in two different categories, reusable or recyclable items, depending on the age of the equipment, its condition, and its value as such. Figure 2 represents the steps at a material recovery facility.



Figure 2: Processing Steps at a Material Recovery Facility [18]

In addition to the step-by-step recovery procedure, there are four major issues that require attention and careful management in processing the recycled e-waste.

- (1) *Sorting and dismantling*: Three different markets exist for equipment arriving at a recycling facility [18]. The first market is for reusable items that can be refurbished and resold. The second market is for components. The third market is for recycled materials. The examination and testing for reuse are time consuming and costly considering the amount of labor needed. Simple tests, such as plug and play, are used to identify whether or not the equipment is in working condition. Non-working equipment can be dismantled for components. The dismantling of EEE is a complex task that can be performed manually or mechanically. Employees must know how to disassemble the equipment, and recognize the valuable components and the components requiring special care (e.g. hard drives) for the recovery. The dismantling also consists of removing hazardous substances and batteries.
- (2) Material recovery: When valuable components and hazardous materials have been removed from e-waste, the material recovery process begins. Performed by shredders, the primary goal of this process is to separate the different materials composing e-waste. The material recovery leads to three main flows: metals (ferrous and non-ferrous), plastics and CRTs. Due to their high concentration in scarce metals, circuited printed boards are often treated separately.

- (3) Final metal recovery: The metal flows are then redirected: ferrous fractions are sent to steel plants for iron recovery; aluminum fractions are sent to aluminum smelters; copper and lead fractions, circuit boards, and other fraction-containing precious metals are directed to actors such as integrated metal smelters. The latter isolate hazardous substances while recovering precious metals, copper and other non-ferrous metals [31]. The recovery of precious metals from e-waste is one of the most profitable practices for the recycling industry.
- (4) Actors' localization: The requirements in investment and technology for the successful processing steps vary widely. "As a consequence, an international division of labor has been established over time. Collection, dismantling and partly mechanical pre-processing takes place at a national or regional level, as does metals recovery from less complex materials/ fractions such as ferrous, copper and aluminum. On the contrary treatment of complex materials such as circuit boards, batteries, cell phones in refining processes or specialized battery recycling plants takes place in a global context" [31]. Integrated smelters with the appropriate installations, representing the last node of the e-waste recycling chain, are currently located in Belgium, Canada, Germany, Japan and Sweden.

## **Financing Schemes**

The management of recycling systems, and the collection, transportation and processing costs of e-waste are, for many products, often higher than the value of recovered materials. Thus, most systems require financial contribution of some stakeholders. Financing methods have critical impact on the design and operation of e-waste systems. Three commonly used strategies for the financing of the recycling chain are implemented in existing systems, and are described Table 3.

### Software Support - Prodtect 1.3

IT software Prodtect WEEE LCA is a solution package for environmental design and analysis developed by the German company called Kerp-Engineering GmbH. This software evaluates the life cycle a product through a series of operational stages of model parameter input, calculation, assessment, and result comparison. In particular, this software uses methods-time measurement (MTM) algorithm to estimate the time required for equipment disassembly and recycling cost.

A group of scholars have demonstrated the application of this software (Prodtect version 1.3) to notebooks [7]. Specifically, the recycling rates, costs as well as the disassembly time of a notebook at its end-of-life stage are evaluated using the software, which generate 19 evaluation indices. The results show that the disassembly and recycle of a notebook at its end-of-cycle may exert positive influence on the environment by introducing the eco-design concept to the product re-design, thus creating more resource-conserving products and enhancing recycle efficiency. This in-depth case study indicates that the software is able to effectively assess the notebook recycling benefits and provide a new set of guidelines for the notebook designer to propose potential modifications of the re-design to reduce the environmental impacts arising from the next-generation products.

The consumer pays an end-of-life fee at the moment of disposal that covers the
otal cost incurred for the treatment of e-waste.
The consumer pays a fee covering the costs of collection, transportation and ecycling when buying new equipment. The amount of the fee can be calculated s a share of the current costs arising for recycling or as an estimation of the costs of recycling in the future.
Anufacturers are held responsible for financing operations in the recycling hain. This strategy can take several forms. It can be applied on an individual asis, where producers are responsible for financing their own take-back system. This format is referred to as individual producer responsibility (IPR). Due to obtential economies of scales, the most common approach is for manufacturers to join a compliance scheme in which they pay a specific amount of fees overing collection, recycling and transportation costs. This scheme is referred to as collaborative producer responsibility (CPR). The compliance costs are generally established by treatment and logistics partners based on the quantity or veight of the products under treatment. However, the treatment of historical e-waste (those resulted from appliances put on the market before the legislation was enacted) involves the consumer in the financing scheme. Producers still bear the cost for recycling the products they but on the market, but use a visible fee charged to consumers to cover historical vaste. In several cases, producers pay compliance schemes in advance when placing products on the market, but the visible fee charged to consumers covers
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 Table 3: Financing Schemes for e-Waste Recycling

## WORLDWIDE E-WASTE RECYCLING PRACTICES

## **Current E-waste Recycling Practices in the U.S.**

Table 4 documents the statistics associated with e-waste recycling in the US in 2010 [16]. It is evident to see that the recycling rate for all electronic products is far below 50%, indicating a strong need for better management frameworks, guidelines, tools and practices.

Products	<b>Recycling Rate</b>	E-Waste (1,000 ton)	E Waste (1,000 units)
Computera & Lontona	20.70/	Disposed: 423	Disposed: 51,900
Computers & Laptops	39.770	Recycled: 168	Recycled: 20,600
Callahanaa & Dagana	11 40/	Disposed: 19.5	Disposed: 152,000
Cempnones & Pagers	11.4%	Recycled: 2.24	Recycled: 17,400
Televisions	17 20/	Disposed: 1,045	Disposed: 28,500
Televisions	17.5%	Recycled:181	Recycled: 4,940
Computer Monitora	22 70/	Disposed: 595	Disposed: 35,800
Computer Monitors	52.170	Recycled: 194	Recycled: 11,700
Drintora/Conjora	22.20/	Disposed: 290	Disposed: 33,600
rimers/Copiers	33.370	Recycled: 97	Recycled: 11,200

Table 4: Current E-Waste Recycling in the US in 2010

The US is managing e-waste with various approaches and strategies ranging from simple landfill bans, to advanced recycling fee (ARF) and extended producer responsibility (EPR). However, there is no national-level legislation in the US. Many states in the U.S. have begun to collect (free e-waste collection events) and recycle e-waste from residential and business sectors. Of the 21 states/cities with bills pending, 15 of them have introduced *producer responsibility bills*: Connecticut, Hawaii, Illinois, Massachusetts, Maryland (where the bill would expand an existing program), Minnesota, Nebraska, New Jersey, New York, Oregon, Rhode Island, South Carolina, Tennessee, Vermont and New York City. Four of these states have also introduced *ARF bills*: Hawaii, Massachusetts, South Carolina and New Jersey. However, it is important to note that the status of the bills is constantly changing. The various e-waste collection options currently used in the U.S. include curbside, special drop-off event, permanent drop-off, take back and point-of-purchase.

Furthermore, some organizations such as the Northeast Recycling Council, Northeast Waste Management Officials' Association and the Northwest Product Stewardship Council have been working on developing regulations at regional, state and local community level [40]. In addition, some manufacturers and companies such as AT&T, Dell, Hewlett Packard, Motorola, Sony and others have sped up their recycling efforts.

The U.S. EPA encourages all electronics recyclers to become certified by demonstrating to an accredited, independent third-party auditor that they meet specific standards to safely recycle and manage electronics. Currently two accredited certification standards exist: (1) the Responsible Recycling Practices (R2), and (2) the e-Stewards® standards. These programs advance best management practices and offer a way to assess the environment, worker health, and security practices of entities managing used electronics. Specifically, these certification programs are based on strong environmental standards that maximize reuse and recycling, minimize exposure to human health or the environment, ensure safe management of materials by downstream handlers, and require destruction of all data on used electronics.

### **E-waste Recycling Practices in other Developed Countries**

### Extended Producer Responsibility (EPR)

Most developed countries have legislation in place to mandate electronic manufacturers and importers to take-back used electronic products at their end-of-life (EoL) based on the principle of EPR. The concept of EPR has been mentioned above several times, and a more detailed review and description of this approach is provided below.

EPR is defined as a pollution prevention policy that focuses on product systems rather than production facilities. It is a valuable tool for achieving sustainable development because it creates economic, environmental and social benefits. The main goals of ERP include six aspects: (1) waste prevention and reduction; (2) product reuse; (3) increased use of recycled materials in production; (4) reduced natural resource consumption; (5) internalization of environmental costs into product prices; and (6) energy recovery when incineration is considered appropriate. The EPR shifts responsibility – either financial or physical – upstream to the producers [44] and is intended to "provide incentives to producers to incorporate environmental considerations in the design of their products."

The EPR policy is implemented through administrative, economic and informative policy instruments, as summarized in Table 5, and the possible EPR approaches and their examples are given in Table 6.

Instruments	Brief Descriptions		
Administrative instruments	Collection and/or take-back of discarded products, reuse and recycling targets, setting emission limits, recovery obligation, product standards technical standards		
Economic instruments	Material/product taxes, subsidies, advance disposal fee systems, deposit-refund systems, upstream combined tax/subsidies		
Informative instruments	Environmental reports, environmental labeling, information provision to recyclers about the structure and substances used in products, consultation with authorities about collection network		

#### **Table 5: Policy Instruments Used in EPR Implementation**

Table 6:	Possible	Ap	proaches	to E	PR an	d Examp	les
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Type of EPR approach	Examples
Product take-back programs	Mandatory take-back; Voluntary or negotiated take-back programs
Regulatory approaches	Minimum product standards; Prohibition of certain hazardous materials or products; Disposal bans; Mandated recycling
Voluntary industry practices	Voluntary codes of products; Public/private partnership; Leasing and "servicing"; Labeling
Economic instrument	Deposit-refund schemes; Advance recycling fees; Fees on disposal; Material taxes/subsidies

As discussed before, a key issue in EPR design and implementation is whether the producer responsibility should be individual or collective. When producers have individual responsibility they pay specifically for the recycling of their own brand products; with collective responsibility, all producers jointly share the costs of managing all their waste products.

Lindhqvist and Lifset [23] agree with individual producer responsibility based on stronger economic incentive for company to design for recycling, but believe collective producer responsibility will share the same investment advantage. Raymond [29] thinks individual producer responsibility is not practical, because economies of scale are not suitable for small firms and importers. On the other hand, many major manufacturers including Electrolux, IBM and Sony (from the three major global EEE manufacturing regions: EU, US, and Asia) and others such as HP, Nokia and Ericsson supported individual responsibility [28], [8]. They advocated a system in which "the individual manufacturer has as much control over the takeback cost of its products as possible."

The European directive based on the EPR approach requires manufacturers and importers to provide a free take-back scheme for their products, and to ensure their products are disposed of using environmentally sound methods. The transposition of what was supposed to be a clear framework resulted in 27 different e-waste management systems. Thus, there is no agreement on how to best manage, design and coordinate e-waste systems. The other important initiative implemented by European countries is the EU's WEEE Directive, which will be reviewed with details in the following subsection.

## EU's WEEE Directive

The EU's WEEE Directive [6] is part of a shift in environmental legislation from processes to products that began in the early 1990s. This was a result of the upward trend in waste generation, which must be halted and reversed in terms of both volumes and environmental hazard and damage. The Directive stipulates the following:

- The design and production of EEE should facilitate dismantling and recovery for later reuse and recycling.
- WEEE should be collected separately from other forms of waste, and this collection should be free of charge to households.
- Best available treatment, recovery and recycling techniques should be used to ensure health and environmental protection.
- EEE put on the market after August 13, 2005 must be labeled with the 'wheelie bin' sign in order to keep the products out of general municipal waste collection.
- By the end of 2006, member states must meet a rate of 4 kg/year/inhabitant collected from private households.
- By the end of 2006, producers must meet a target of reuse and recycling for the WEEE that they receive. The target rate varies from 50% to 80% per category of WEEE.
- Producers are responsible for financing the take-back and management of WEEE.
- Information necessary to fulfill these requirements should be provided to users and to treatment facilities.
- Both producer and member states must report the result of their compliance with the Directive to the EU at regular periods as defined by each member state.

## Scope of Recycled Products

Existing e-waste recycling systems differ widely in the scope of products considered. As mentioned in Section 1.1., the EU considers a much wider range of products than does California. In the WEEE Directive [6], e-waste is classified into ten categories, covering over 100 products. The repartition of e-waste collected in the EU in 2005 according to these categories is presented in Table 7.

Products included in American e-waste recycling systems are limited to only a few devices belonging to categories 3 and 4, respectively – IT and telecommunications equipment, and consumer electronics. Electronic and electrical products vary widely in composition. Some products are much more profitable to recycle than others. Likewise, some products contain more toxic substances than others, making the recycling of these products in a sound manner more complex. Therefore, the scope of products covered in a system has significant impact on its operational costs as well as on its environmental benefits. In addition, adding more product types can result in economies of scale for the processing of e-waste. This positive aspect might however be lowered by the more complex collection process required and the increased number of stakeholders participating in the system. Thus, the scope of the products system that managers consider in e-waste recycling systems is of high importance.

EU Category #	Category description (examples)	Collection Rate
1	Large household appliances (refrigerators, freezers, washing machines, microwaves)	49.1
2	Small household appliances (vacuum cleaners, toasters, fryers)	7
3	IT and telecommunications equipment (cellular phones, laptop and personal computers)	16.3
4	Consumer equipment (television sets, video cameras)	21.1
5	Lighting equipment (lamps)	2.4
6	Electrical and electronic tools (drills, saws)	3.5
7	Toys, leisure and sports equipment (video games, coin slot machines)	0.1
8	Medical devices (radiotherapy equipment, pulmonary ventilators)	0.1
9	Monitoring and control instruments (smoke detectors, thermostats)	0.2
10	Automatic dispensers (money, hot drinks, can dispensers)	0.2
	Total amount	100

### Table 7: EU's Categories of e-Waste in 2005

## **Example Practices in Selected Developed Countries**

In what follows, we use two countries as specific examples to illustrate country-specific efforts in e-waste recycling.

**Finland:** The technology industries introduced the AWARENESS (Advanced WEEE Recovery and Recycling Management System) Project in summer 2003, which focuses on the influences of the WEEE Directive on manufacturers and producers of EEE. The goal of the project is to support companies in achieving a consensus on WEEE Directive implementation details. In addition, the project aims to initiate company collaboration in different product categories and to take optimal recycling processes into use. The AWARENESS project consists of two sub-projects called SELMA and RecISys. SELMA focuses on addressing issues related to operational recycling and promotes communications between national authorities and companies. The main objective of the RecISys is to develop the Internet-based information system that will meet the information needs of WEEE and RoHS (Restriction of Certain Hazardous Substances) Directives [25]. It is expected that controlling the operations of recycling processes and reporting to the authorities as well as informing customers and the recycling industry will be completed through this information system.

**Japan:** EPR has developed quite differently in Japan from in Europe. In particular, takeback is not necessarily free of charge – consumers pay when they bring used equipment back to retailers. In the Japanese system, the recycling of WEEE is a producer's responsibility. The law also specifies rate targets and imposes heavy penalties for non-compliance. The Japanese Specified Home Appliances Recycling law or the Electric Household Appliance Recycling Law (EHARL), which has been in force since April 2000, requires manufactures and importers to collect and recycle their own appliances [43]. A similar legislation is now in place for the collection and recycling used computers in Japan since 2003, which creates two different cost structures [41]. For those purchased prior to October 1, 2003, recycling is financed by EoL fees ranging from US \$27 to US \$37. For personal computers purchased after October 1, 2003, the costs of recycling are included in the price of the product as an advance-recycling fee. This new legislation also mandates manufacturers to take care of their respective products after they are handed in by the last owners or users.

## **Current E-Waste Recycling Practices in Developing Countries**

Developing countries are facing huge challenges in managing e-wastes, which are either internally generated or imported illegally as 'used' goods in an attempt to bridge the so-called 'digital divide'. Due to lack of adequate infrastructure to manage wastes safely, e-waste is often buried, burnt in the open air, or dumped into water. Crude 'backyard' recycling practices, which are not efficient but highly polluting, are also used in material recovery.

The development of e-waste systems in developing countries is the focus of several studies. Blaiser et al. [1] assess the economic feasibility of e-waste recycling systems in Morocco. Hicks et al. [15] evaluate the status of WEEE recycling and disposal in China, as well as how it impacts human health and the environment, while He et al. [14] review the implementation of treatment and recovery strategies for e-waste in China. Carisma [4] identifies and examines the drivers and barriers that threaten the implementation of an e-waste management system in the Philippines. The e-waste issue in developing countries is worsened by the import of hazardous waste including WEEE from industrialized countries. Puckett et al. [28] assess that 50 to 80 % of e-waste collected in the US is exported to Southeast Asian countries and Africa while the US Government Accountability Office [40] states that e-waste exports are virtually unrestricted. Ladou et al. [21] assess that less than 10% of e-waste is recycled and that China has become the receiver of 70% of the world's WEEE, making it the largest electronics garbage dump in the world.

It is currently difficult to apply EPR principle and even the fundamental management of ewaste in developing countries for the following reasons [25]:

- The unwillingness of consumers to handout their EoL goods;
- There is a general reluctance to pay for waste recycling and disposal services, particularly when consumers can make money by selling their old and broken appliances;
- Emotional attachment to EEE and the attachment of perceived value on such EoL EEE;
- There is a lack of awareness among consumers, collectors and recyclers of the potential hazards of WEEE;
- Lack of funds and investment to finance improvements in e-waste recycling;
- Absence of the infrastructure required for the recycling or appropriate management of ewaste following the principles of sustainable development;
- Absence of ineffective take-back programs for EoL WEEE;
- Lack of interest in e-waste management by multi-national IT companies in the developing countries;
- Absence of legislation dealing specifically with e-waste, or ineffective implementation of existing regulations on the trans-boundary movement and/or the e-waste management.

EPR should be a worldwide endeavor in order to achieve "real" sustainable (closed loop) product and material flow cycles. Scholars investigating this field have suggested various ways for implementing EPR worldwide, which are summarized below.

- Kibert [20] observed that government-run EPR programs, such as the EU WEEE Directive, have the potential to achieve sustainable development. The program can protect the developing countries and encourage them to use their comparative advantages in labor cost without sacrificing the environment;
- Regional recycling systems need to be closely coordinated and developed into a Global Recycle Network to improve recycle efficiency and cost reduction through sharing information and circulating resources and products [19];
- There is a need to establish legislations for effective e-waste management in developing countries as the format of the two EU directives -WEEE and RoHS [15];
- Programs need to be in line with the terms in Basel Convention, which provides a framework for the environmentally sound management of e-waste supporting traceability, predictability and transparency [25];
- Establishing Remanufacturing Centers in the developing countries where 'repair', 'refurbishing' and 'remanufacturing' for EEE can be carried out under the direct supervision of the OEMs or their subsidiaries, and warranties are issued for such remanufactured products [25].

## E-WASTE RECYCLING AT US UNIVERSITIES: A CASE STUDY OF WPI

It is not difficult to see that educational institutions are large consumers of electronic and computer devices, and thus are major producers of e-waste. As a result, e-waste recycling is imperative in every educational institution. In this section, we describe and discuss how e-waste recycling is managed and implemented at Worcester Polytechnic Institute (WPI) in Worcester, Massachusetts.

### **Overview of the Sustainability Program at WPI**

Sustainability is one of the ingredients embraced in several recent campus-wide initiatives at WPI. WPI defines sustainability as an integrated, three-part approach for achieving the goals of environmental preservation, social equity, and economic prosperity for all members of society. The institution is proudly engaged in each of these areas through their learning, research, service, and administrative operations. The President's Task Force on Sustainability was created in 2007 to lead the university's endeavors. Naturally, the recycling program, as a major part of the sustainability program, has been active since 2007 and aims to achieve the goal that 100% of WPI's waste is diverted from landfills either through recycling or a nearby energy incinerator.

Figure 4 shows the results of waste stream composition at WPI over the past three years [24] of which the electronic waste accounts for only 2-3%. Although the percentage is very small, it seems consistent with nation-wide average [32]. To address the low collection rate of e-waste, WPI held an e-waste drive this year, where various electronic devices were collected from the staff, the students and their respective households. This effort resulted in a total of 5,080 pounds of electronics collected at the end of 2012.







Figure 4: Waste Stream Analysis at WPI: 2009 – 2012

## E-Waste Recycling Partnership between WPI and IRN

The e-waste recycling program at WPI is not as complicated as those adopted in corporations, but the most important feature is the partnership with a local recycler called Institution Recycling Network (IRN; www.ir-network.com) established in 2000. WPI actively publicizes the importance of waste recycling and educates students, faculty and staff to facilitate their recycling process. Take e-waste for example, students are expected to toss used electronic devices in bins provided by IRN, and the campus recycling team will take responsibility to sort the used/ repaired items within one week to a month. If an electronic device only needs repairing and can be used again, the device will be first sent to Worcester Technical High School for fixture replacement and then transferred to one of the Worcester Public Schools after the repair. If the device cannot be fixed, WPI waste recycling team will collect them and wait for IRN to pick up.

IRN is a recycling organization established in 1999 and headquartered in Concord, NH. The company works with over 200 colleges and universities, hospitals, K-12 schools, and private companies to improve the performance and economics of recycling. IRN negotiates transportation, processing, and marketing of recycled commodities, provides a single point of contact to recycle different materials, and manages the logistics to get materials to market efficiently and cost effectively. IRN handles over 75 commodities ranging from cardboard and fluorescent lamps to construction and demolition wastes, including even nuclear accelerator. The company is known particularly as the most experienced entity of construction and demolition recycling in the U.S. (www.WasteMiser.com), and as a major channel that matches surplus furniture, equipment, and other property with domestic and international relief organizations (www.irnsurplus.com).

As one of the largest handlers of electronics in New England, IRN managed about 1.25 million pounds of computers, monitors, laptops, cell phones, and other electronics in 2010. For the past 12 years IRN has maintained a strict "domestic only" approach to electronics recycling. Every pound of electronics handled by IRN is processed locally – in Amesbury, Massachusetts. IRN's electronics are recycled according to the highest environmental standards without any export to trenches and dumps in the Third World. Doing so has also generated employment and wages for local communities.

While there is a cost for this level of service and security, IRN has always been one of the most cost-effective recyclers in New England. As their market presence has grown, they have been able to negotiate better and better prices and take advantage of their growing strength in commodity markets; for example, effective February 1, 2011, IRN was able to reduce the price for mixed electronics recycling by about 25%. For items such as TVs, laptops, or flat screen monitors, IRN offers the lowest prices for secure, reputable recycling in New England.

IRN provides its clients with high-quality service and cost efficiency through a six-step "OneStop" Program (<u>http://www.ir-network.com/prog\_onestop.html</u>), which picks up and recycles many different materials at the same time, with one pickup, on the same truck. This program makes it easy to track everything their clients recycle, as the customers see a single reconciliation for all one-stop commodities, a single invoice, and detailed monthly reporting for every material.

Since IRN is one of the largest waste handlers in New England, it has established a solid reputation. Although their waste handling fee is high compared to other waste handlers, it helps promote WPI's reputation, ensuring that 100% of WPI's waste is diverted from

landfills and will get properly handled. Besides the waste handling fee each time, WPI needs to pay IRN membership fee at \$500 per year. The partnership has been working effectively for WPI's recycling endeavors over the past decade.

## DISCUSSIONS AND CONCLUSIONS

This paper examines four aspects of e-waste: (1) the definition and scope of e-waste, and the challenges in e-waste recycling; (2) a framework comprising the system structure, components, and software support for understanding e-waste recycling systems; (3) a review of current e-waste recycling practices in both developed and developing countries; and (4) a case study of WPI's recycling program to understand the current practices in a higher-education setting.

We would like to point out some research directions based on the findings presented in the paper and especially focus on the opportunities for Operations Management (OM) scholars. We think both qualitative and quantitative researches on e-waste recycling are plausible and that at least two areas in each category deserve future studies. We present these possible research topics in Table 8. The goal of the qualitative studies will center on the identification of country-specific factors, assessment of the impacts of various regulatory approaches and of system players' actions on desired recycling performance, and drivers for best practices. The quantitative studies can focus on optimal system design, development of coordination mechanisms for orchestrating system player's decisions, and devise financial incentive programs or schemes that will improve system performance.

Category	Area 1	Area 2
Qualitative	<ul> <li><i>Comparative /Case Studies</i></li> <li>comparisons between countries</li> <li>regional comparison within a country</li> <li>university-industry collaboration</li> </ul>	Actors' Impacts on System Performance - impact of regulations and policies - key factors affecting the performance
Quantitative	<ul> <li>System Optimization</li> <li>optimal design of system structure with different objectives (e.g., financial vs. environmental)</li> <li>comparison of various system configurations</li> </ul>	<ul> <li>Coordination of System Actors</li> <li>coordination mechanisms for achieving certain system objective</li> <li>government vs. TPO vs. OEM</li> <li>incentives for consumers</li> <li>specific product recycling chain</li> <li>effective policies and regulations</li> <li>coordination of the entire chain</li> </ul>

Table 8: Sar	nple Research	<b>Opportunities</b> f	or OM Scholars	in e-Waste	Recycling
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In summary, e-waste recycling is a worldwide pressing issue and will continue to receive a great deal of attention from the society's every stratification. The research effort devoted to this subject will grow rapidly and stay active for the next decade. It is expected that scholars in many disciplines around the world will contribute to this important topic.

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