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An Ecological Framework to Assess Sustainability Impacts for an Evolving Consumer Electronic Product System

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An Ecological Framework to Assess Sustainability Impacts for an Evolving Consumer Electronic Product System

By Erinn G. Ryen

A Dissertation Submitted in Partial Fulfillment of the
Requirements for the Degree of
Doctorate of Philosophy in Sustainability

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An Ecological Framework to Assess Sustainability Impacts for an Evolving Consumer Electronic Product System

By

Erinn G. Ryen

Submitted by Erinn G. Ryen in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Sustainability and accepted on behalf of the Rochester Institute of Technology by the dissertation committee.

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ABSTRACT

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Degree: Doctor of Philosophy

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Title: An Ecological Framework to Assess Sustainability Impacts for an Evolving Consumer Electronic Product System

Consumer electronics have revolutionized the manner in which we work, read, and entertain ourselves. However, this transformation comes at a high cost, with significant energy input and emissions releases across all stages of the electronic product life cycle. The limited success of ‘per product’ efficiency improvements, often formulated in the field of industrial ecology, does not address the electronic product system as a whole because escalating consumption may actually offset any individual impact reductions. Additionally, existing industrial ecology models fail to effectively capture energy, material, and waste flows associated with real consumption patterns, as consumers purchase, use, and discard a *group* of interrelated devices such as desktops, laptops, printers, mobile phones, and digital cameras.

To address this challenge, this dissertation develops and applies novel industrial ecology methodologies to more effectively characterize changes to rapidly evolving and interrelated product systems. Notably, these approaches borrow heavily from underutilized biological ecology concepts from community ecology and optimal foraging theory, but adapted for use as applied to a complex product system like consumer electronics. These approaches can lead to more effective design, production, green purchasing decisions, and end of life practices and policies, while at the same time expand industrial ecology’s traditional focus on the ecosystem metaphor and ‘per product’ approaches and strengthen its connection to the source science: biological ecological roots.

Abstract Approval:

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Finally, a special acknowledgement to my personal 'community.' My children Hannah and Ethan, husband Matthew, parents, siblings, extended family, and close friends who stood by me and gave me the encouragement and friendship (in addition to carpools, meals, and childcare coverage) to help me finish this adventure.

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I. Introduction

1.1. Background and Rationale

The continual evolution and rapid adoption of consumer electronic devices has changed the way people read books, watch movies, manipulate data, and snap pictures. In 1990, the average American household owned 10 electronic products, and its residents watched television (TV) on cathode ray tube (CRT) TV screens, worked at desktop computers and perused hardcopy books. Twenty years later, the average number devices per household more than doubled to 24 (CEA 2008, 2010). Product innovations have un-tethered people from outlets and cables, allowing them to read books on tablets and e-readers, view or stream movies and TV programming on liquid crystal display (LCD) and plasma TV screens, and talk, play games, browse the web, and snap photographs on smartphones. Technological advances have contributed to increased productivity, economic growth, and more efficient use of resources (Berkhout and Hertin 2004; Weber et al. 2010; Masanet and Matthews 2010; Koomey et al. 2011).

Unfortunately, digital transformation has come at a high environmental cost. Increased consumer demand and rapid innovation cycles compound impacts across a product's life cycle: embodied energy in manufacturing materials and devices (Köhler and Erdman 2004; Malmodin et al. 2010), electricity consumption during use (Köhler and Erdman 2004), and environmental and human health risks of managing these products in the waste stream when toxics (lead, mercury, and arsenic, among others) may be released in uncontrolled environments (Williams et al. 2008). In response to these environmental challenges, the field of industrial ecology, which attempts to model industrial systems after biological processes to achieve sustainability objectives, has developed strategies including dematerialization, eco-design, energy efficiency, life cycle management, and extended producer responsibility policies. For example, in the U.S., the Electronic Product Environmental Assessment Tool (EPEAT®) green purchasing tool and the U.S. EPA's Energy Star® efficiency standard have aimed to reduce the environmental footprint of electronics on a 'per product' basis. At the same time, improved computing efficiencies and reduced sales prices have led to a 'rebound effect:' increased consumer demand across the spectrum of all electronics (Berkhout and Hertin 2004). Further confounding environmental improvement strategies and the rebound in consumption is the reality that electronic products are consumed in a highly interrelated fashion, where ownership of one influences the purchase of another. For example, when purchasing a laptop, a consumer is also likely to purchase a printer, cable modem, digital music player, and external data storage drive that all work together to provide the desired computing services. Thus, escalating consumption may actually offset any individual impact reductions since ‘per product’ management strategies do not address the electronic product system as a whole.

Industrial ecology’s premise that industrial systems are part of a broader natural ecosystem (Frosch and Gallopoulos 1989; Ashton 2002) has been a widely appealing organizing concept and, as a result, provided a foundation upon which to build models to advance the sustainability science. The success of industrial ecology to date may be largely attributed to recognizing that natural systems are the only real model available for sustainability (Bey 2001) because ecosystems have evolved over millions of years to exhibit qualities such as robustness, efficient functionality, and effective material recycling (Nielsen 2007). Thus, sustainability practitioners endeavor to understand and emulate properties of natural systems containing desirable qualities that lack in existing ‘unsustainable’ industrial systems (Nielsen 2007).

Subsequently, a wide body of industrial ecology literature has traditionally focused on concepts found in stable biological ecosystems such as food webs, metabolism, material cycling, interdependence, and symbiosis (Harper and Graedel 2004; Korhonen 2001). The ecosystem point of view is appropriate and attractive to many scholars because of industrial ecology’s emphasis on systematic thinking and emergent behavior and proprieties from complex techno-industrial systems. However, the implementation of tools can be challenging due to the complexity of scale, number of interacting organisms, diversity of biotic and abiotic material flows, temporal and spatial heterogeneity, and dynamic evolution towards increasing complexity (Jorgensen 1992/1997; Hermansen 2006). For instance, many tools have been developed in a static mindset, in contrast to constantly evolving natural ecosystems and communities that need to be evaluated in a dynamic manner (Ricklefs and Miller 2000). Moreover, the focus on the concepts of ecosystems and symbiosis have resulted in a limited number of successfully designed sustainable industrial systems due to a lack of social and political context (one design does not fit all), regulatory barriers, lack of awareness or trust, and difficulty of sharing information (Boons and Howard-Grenville 2009).

Although other ecological concepts are potentially applicable and scholars agree there is a need to move beyond the ecosystem-scale metaphors (Bey 2001; Spiegelman 2003; Mayers 2008), limited examination has occurred. Levine (1999, 2003) has suggested that a product approach would add value and complement existing ecosystem-centered studies. One example of research applied to products is Babbitt et al. (2009)'s application of age-structured model of population dynamics to predict computer lifespan and electronic waste generation. While some novel concepts like diversity or community structure have been applied previously in industrial ecology, these models have remained at the ecosystem level and focused on firms (Matutinovíc 2001; Korhonen and Snäkin 2005; Wright et al. 2009; Nieuwenhuis and Lammgård 2010) or economic sectors (Templet 1999, 2004; Ashton 2009) rather than groups of products.

Addressing household electronics as a group or a 'portfolio' in the case of Williams (2011) builds upon Levine's product-centered approach (1999, 2003) and a limited number of preceding studies that have examined various combinations and types of consumer electronics (Hertwich and Roux 2011; Malmodin et al. 2010; Teehan and Kandlikar 2013). In addition, a limited analysis on other groups of products has occurred including an 'ensemble' of energy generating systems (Gutowski 2010; Kotaro et al. 2012), 'fleet' of ferry vessels (Winebrake et al. 2005) or fishing boats (as reviewed by Van Putten et al. 2012), a 'fleet' of automobiles (Field et al. 2000; Levine et al. 2007; Stasinopoulos 2012), and group of mobile telephony (Michalakelis et al. 2010). The field of biological community ecology, which studies groups of organisms living and interacting in a defined habitat, offers a promising approach to modeling and managing groups of interacting consumer electronics. Furthermore, using community ecology and optimal foraging as a basis for new approaches responds to a repeated theme in the industrial ecology literature: a need for more connection to the underlying source science, biology itself (Templet 2004; Wells and Darby 2006; Mayer 2008; Jensen et al. 2011).

Analyzing the 'meso scale' (e.g., household, group of related technologies, or fleet) has been noted as a promising and appropriate functional unit for groups of related technologies (Guinée et al. 2010) and for products that are undergoing technology transitions

(Levine et al. 2007). Focusing on the meso scale is important because impacts for emerging technologies (in addition to land use, agriculture, and transportation) are often linked to consumption behavior (Guinée et al. 2010). Moreover, the household scale is critical in pro-environmental behavior research because residents generally have more control over the household's purchasing decisions, in contrast to the larger macro scale (firm or nation), in which only a few people hold overall responsibility (Reid et al. 2010). Systematic understanding of how interactions within households can lead to more effective policies that encourage behavioral changes, reduce overall household environmental impacts (Reid et al. 2010), and broaden the application and scope of LCA methodology (Guinée et al. 2010). For example, considering products as an interconnected group rather than on a single product or 'per product' basis has already facilitated the development of pollution reduction standards and policies (e.g., vehicle mileage standards) (Winebrake et al. 2005).

1.2. Research Goals and Objectives

The overall goal of this research is to build new industrial ecology methodologies to characterize a group of rapidly evolving consumer electronics products and lend insight to more effective design, purchasing, and end of life (EOL) management decisions. The goal is achieved by:

1) Identifying research methodologies inspired by community and behavioral ecology for use in the field of industrial ecology, the 'science of sustainability' that is otherwise primarily focused on ecosystem metaphors and product-based models,
2) Adapting these methodologies from their biological basis into innovative practical tools relevant for industrial and product systems, and
3) Applying these methods to a case study of household consumer electronics in the U.S. that supply information, communication, and entertainment services.

By demonstrating the utility of the 'community' approach for a complex system such as products that provide information and communication services, findings from this research may be applied to product systems in other complex, emerging fields such as nanotechnology, biotechnology, and renewable energy infrastructure. Moreover, this research may also help validate existing biological models.

The novel research methodologies and assessment tools found in this dissertation are as follows:

- Chapter II - adapting ecological concepts into industrial equivalents for a community of consumer electronics;
- Chapter III – establishing a framework to measure the structural composition and functional diversity of a group or community of consumer electronics devices owned by an average U.S. household (i.e., electronic product community);
- Chapter IV - linking the electronic product community's structural changes with ecosystem level energy flows; and
- Chapter V – evaluating EOL processing decisions to manage an increasingly diverse e-waste stream.

II. Adapting Ecological Concepts

As a whole, a biological community is a collection of populations of plants, animals, bacteria, and fungi that live and interact with one another in a delineated area and form a "distinctive living system with its own composition, structure, environmental relations, development, and function" (Whittaker 1970, 1). A biological community can be as large as all the plants and animals in the world, or as small as a single rabbit and bush (Dice 1968). Ecologists generally focus on changes in community's structure (i.e., number and distribution of species), interaction of species (e.g., competition, commensalism, and mutualism), and the variety of functions provided by these species subsiding in the community (Krebs 2009). While the field initially began with simply descriptions and enumerations about the number and type of species in a given environment or locale, modern community ecology has progressed to using experiments and models exposing underlying processes that are created from particular patterns or structure in a community (Hairston 1989).

To demonstrate the utility of applying ecological concepts for the study of product communities, relevant concepts from community and behavioral ecology are adapted from their biological basis into terminology germane to the electronic product community. Ecological concepts selected must be expressly applied and understood in the context of industrial ecology. Table 1 provides a sample of terminology adapted specifically for a group of consumer electronic devices. As noted in Table 1, biological *species* is an evolutionary unit with the potential to reproduce with another individual within its classification (Ricklefs and Miller 2000; Smith and Smith 2000). Species are characterized by *attributes* or traits, such as morphology or size (Smith and Smith 2000; Krebs 2009), whereas a population, or group of individuals from the same species living in the same habitat at the same time, is measured in terms of *abundance* (i.e., population size) (Smith and Smith 2000). A species fulfills one or more ecological *functions* or roles in a system. Functions are defined by consumption (e.g., predator eating prey) (Bengtsson 1998), influence on ecosystem processes (e.g., nutrient cycling) (Díaz and Cabido 2001), or response to external perturbations (e.g., changes in climate) (Díaz and Cabido 2001). For example, the bacterial species *Rhizobium leguminosarum* facilitates the uptake of nitrogen for legumes (Masson-Boivin et al. 2009). A species' potential role(s) in community and/or the range of conditions in which it exists is known as a species' *niche* (Hutchinson 1957; Whittaker 1970).

Table 1 Adaption of community ecology concepts to a household electronics community.

Concept	Ecology Description	Industrial Ecology Equivalent	Consumer Electronics Example
Species	Group of organisms having the ability or potential to reproduce with each other, and/or sharing similar genes	A specific type of product, classified by trade associations or retail sales	Laptop computer
Function	A species' role in the system	Service(s) provided by each product	Manipulating and analyzing data
Functional Group	Grouping of species that share a similar function	Products that were purchased to fulfill similar primary purposes	A laptop and desktop purchased for the purpose of data manipulation
Population	Group of individuals belonging to the same species in a define habitat and at the same point in time	All individual electronic devices classified within a 'species'	All the laptop computers owned by an average U.S. household in 2010
Community	Collection of organisms living and interacting together in a defined habitat and at the same point in time	Total system of electronic products purchased and used in U.S. households	Interrelated ownership of products by an average U.S. household in 2010.
Foraging	Activities and behaviors involved in searching, capturing, and consuming food	End of life management decisions at an electronic waste processing facility	Disassemble a laptop for higher value material recovery or shred intact for lower value material recovery

As shown in Figure 1a, a community's structure and the functions provided by its species are affected by inputs (nutrient and resource availability), outputs (biomass from deceased organisms), and exogenous factors, such as food limitations or temperature fluctuations (Ricklefs and Miller 2000).

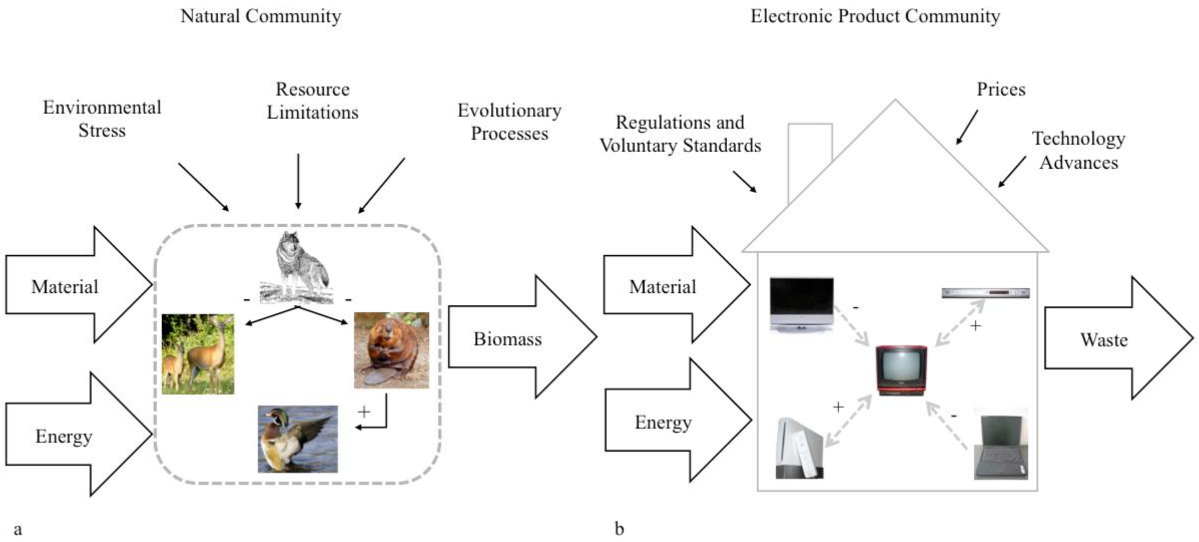


Figure 1 Adoption of community ecology principles to a the electronic product community: a) illustrates the community ecology concepts in terms of an example animal community (e.g., grey wolf, white tail deer, and beaver) in the Adirondack Park, New York State, and b) applies community ecology concepts to a select group or 'community' of consumer electronics owned by an average U.S. household. Images are from the NYS Department of Environmental Conservation (2012) and Wikimedia Commons (2012).

One of the interactions noted in Figure 1a is competition or the predator-prey relationship (e.g., wolf eating a deer). Foraging, or the activities and behaviors associated with locating, handling (i.e., capturing and taking apart) and consuming, is an important interaction that is critical to a natural species' health and reproductive success (Reilly et al. 2007). Foraging strategies are widely studied in ecology because the "..stomach sways the world" (Fabre 1913 as noted in O'Brien et al. 1990), or in other words, influences ecosystem processes (O'Brien et al. 1990). As a result, ecologists have constructed prey selection, search strategy, and patch selection optimization models (Stephens and Krebs 1986).

Following Figure 1b and as noted in Table 1, ecological concepts are adapted to the test case, with a species defined as the product type sold within a given electronics industry-defined category (e.g., laptop computer). Following Whittaker's (1970) definition, an *electronic product* community would be an assemblage of products that exist and interact directly or indirectly in a shared spatial and temporal setting. This research defines the boundary of the electronic product community as the average U.S. household between 1990 and 2010. Moreover, consumer electronics provide *functions*, such as a laptop initially purchased to fulfill a function of manipulating and analyzing data, images, and text, but also provides additional functions (e.g., playing audio, messaging, and e-mailing). An electronic product community, as with natural communities, has its own composition, internal and external interactions, functions, inputs, and outputs (Figure 1b). Energy inputs are electricity and fuel; material inputs include plastics, base and precious metals, and glass; and outputs are obsolete products. Similar to natural communities, changes in electronic product inputs and outputs are a function of household purchase and usage behaviors. Additionally, the electronic product community would respond to external perturbations, such as technological improvements and price fluctuations. Considering household electronic devices as a group or community also enables the evaluation of 'foraging' strategies faced by an e-waste processing facility such as shredding a product lower value material recovery or disassembling for higher value material recovery. Thus, the field of community ecology offers a systematic approach to assessing the electronic product community's dynamic net environmental impacts.

Jensen et al. (2011) criticizes industrial ecology for cherry picking ecological concepts. In an attempt to address this concern, the similarities and differences between both systems is compared throughout. Learning from the differences between ecological and industrial systems is just as significant as the similarities, because the descriptive divergences may "limit the value of a prescriptive model we might derive" (Levine 2003, p.). The goal here is to operationalize ecological concepts as relevant and useful tools for the selected industrial product system (consumer electronics). Methodologies from this research would need to be re-adapted to other product groupings, as the structures and interactions may vary, especially for product systems with fewer unique species (automobile) or for ones with less rapid technological turnover (heating and cooling products).

Analysis of ecological structural and functional diversity is typically augmented by studying the interactions among members of the community (e.g., predator-prey or competition) that result in a given structure. However, the first stage in understanding interactions among electronic devices in terms of purchase and use patterns and resultant environmental implications is the characterization and quantification of the community's species and functions, as described in Chapter III. The connection between community structure and ecosystem energy flows is then described in Chapter IV, in which a methodology is developed to analyze the net environmental impact for the entire community of electronic products. Finally, Chapter V demonstrates the applicability of behavioral ecology's *optimal foraging theory* to evaluate decisions related to 'feeding' or the processing (i.e., shredding or disassembly) of outflows from the electronic product community.

III. Assessing Community Structure and Function

3.1. Introduction

Due to growing negative and positive environmental, social, and economic impacts associated with consumer electronics production, use, and disposition, this research asserts that effective sustainability strategies must account for the interdependence of product consumption by considering an entire community of consumer electronics. The field of biological community ecology, which studies groups of organisms living and interacting in a defined habitat, offers a hopeful approach to modeling and managing groups of interacting consumer electronics. Additionally, a new methodology based on the field of community ecology answers a call in the industrial ecology literature for stronger connection to the fundamental source science (Templet 2004; Wells and Darby 2006; Mayer 2008; Jensen et al. 2011).

The purpose of this chapter is to demonstrate the utility of adapting a community ecology perspective for complex and rapidly changing groups of interconnected products so decision makers can better understand the mechanism driving the sustainability of electronic product community. This methodology provides a foundation on which environmental impacts (e.g., life cycle energy intensity or material flows) can be assessed for an entire product system, ensuring that quantified impacts reflect actual consumption and technology dynamics.

This chapter incorporates the relevant community ecology concepts that are translated into industrial equivalents in Chapter II into a community structure and function methodology. The methodology demonstrated in this research mirrors a process of how ecologists assess dynamic changes in biological community structure and function. Ecologists assess the *structure* of species composition, *functions* provided by these species, and resulting species interactions. Community structure is assessed using *diversity* indices, which measure the number and distribution of species present over time (Collier et al. 1973; Hairston 1989). More recently, ecologists have categorized species with similar functions into *functional groups* to describe the *functional diversity* of a community (Díaz and Cabido 2001; Hooper et al. 2005) and assess the degree to which species supply redundant functions (Walker 1992).

The novelty of using the community ecology perspective will lend insight to effective design, purchase, and life cycle management for communities of consumer electronics to avoid some of the pitfalls of 'per product' solutions described in Chapter I. This chapter also seeks to better understand similarities between natural and product communities and where such analogical methodologies must diverge**.** Ultimately, the knowledge from the community scale can contribute to comprehending stability and sustainability impacts at a larger scale. The results are then incorporated into other sections of the dissertation, thereby linking structural changes to ecosystem level flows.

3.2. Methodology

The application of the community ecology methods was to a typical group of consumer electronics consumed by an average U.S. household. The type of products included in this community was interconnected and responsible for supplying information, communication, and entertainment services desired by a household. Data were collected to characterize the representative community, a process that includes identifying species and classifying their functions. Finally, dynamic changes in community structure and function were analyzed based on empirical community ecology models.

3.2.1. Characterizing Community Structure

The first stage in implementing community ecology methods was evaluating the electronic product community's structure in terms of product species abundance, diversity, and attributes over time. Abundance is the number of each product species owned per household. Product species are characterized by attributes of *mobility* (i.e., stationary or mobile device) and *functionality* (i.e., product with single or multiple functions). Each type of common household electronic device was considered to be an individual 'species,' using product categorizations established by U.S. trade industry reports (CEMA 1998,1999; Roth and McKenney, 2007; Eskelsen et al. 2009; Urban et al. 2011), trade magazine articles (CEA 2008-2010), and reports on electronic waste by the U.S. EPA (2008, 2011).

Over 30 interrelated electronic products providing information, communication, and entertainment services for the average U.S. household were identified and then narrowed to 20 product species based on screening criteria (Table 2) that excluded products without sufficient publicly-available sales or household adoption data and/or products present at less than an average 0.05 devices per household.

Table 2 Household consumer electronic products included in the analysis

Product	Type of Data and Years Available	Data Sources	Notes
Blu-ray player	Sales units for 2008-2010, household penetration rates 2009-2010, and installed units for 2010	CEA 2009, 2010; Urban et al. 2011	d
Mobile phone - basic	Sales units for 1984-1995 and 2003-2008, installed units for 2006, and household penetration rate for 2010	CEA July/August 2010; Eskelsen et al. 2009; Roth and McKenney 2007, U.S. EPA 2008, 2011	b,d
Mobile phone – smartphone	Household penetration rates for 2008-2009 and sales units for 2003-2007 & 2010	CEA 2009, 2010; Eskelsen et al. 2009; Herbert 2008	
Computer – desktop	Sales units for 1980-2010, installed units for 2006 & 2010, and household penetration rates for 2008-2010	CEA 2009, July/August 2010; Roth and McKenney 2007; Urban et al. 2011, U.S. EPA 2008, 2011	a-d
Computer – laptop	Sales units 1989-2010, installed units for 2006 & 2010, and household penetration rate for 2008 & 2010	Eskelsen et al. 2009; Roth and McKenney 2007; Urban et al. 2011	c,d
Computer – netbook	Sales units (based on market share) 2008-2009, installed units for 2010	Baker 2008; Urban et al. 2011; Jeffries 2010	d
Digital camcorder	Sales units for 1996-2004 & 2010 and installed units for 2006 & 2010	CEA July/August 2010; Roth and McKenney 2007; Wilburn 2008; Urban et al. 2011	c,d
Digital camera	Sales units for 1995-2005, installed units for 2006 & 2010, and household penetration rates for 2008-2010	CEA 2009, CEA July/August 2010; Herbert 2008; Wilburn 2008; Roth and McKenney 2007; Urban et al. 2011	a-d

Product	Type of Data and Years Available	Data Sources	Notes
DVD player	Household penetration rates for 1998-2010 and installed units for 2006 & 2010	CEA 2009, July/August 2010; Eskelsen et al. 2009; Roth and McKenney 2007; Urban et al. 2011	a-d
E-reader	Sales units 2006, 2009-2010 and household penetration rate for 2010	CEA July/August 2010; Konig 2010; PBT Consulting 2012; Printed Electronics World 2011	
Gaming console	Installed units for 2006 & 2010, household penetration rates for 2004-2008 & 2010	Arendt 2007; Eskelsen et al. 2009; Urban et al. 2011; Grabstats.com, 2011	c,d
Monitor – CRT	Sales units 1998-2010, installed units for 2006, and household penetration rate for 2010	Roth and McKenney 2007; U.S. EPA 2008, 2011	c,d
Monitor – LCD	Sales units 1998-2010, installed units for 2006, and household penetration rate for 2010	Roth and McKenney 2007; CEA July/August 2010; U.S. EPA 2008, 2011	c,d
MP3 player	Installed units for 2006 & 2010, and household penetration rates for 2004-2008, 2010.	Eskelsen et al. 2009; CEA July/August 2010; Roth and McKenney 2007	c,d
Multi-functional and hardcopy printers	Sales units for 1980-2010, household penetration rates for 2008-2010, and installed units for 2006 & 2010	Herbert 2008; CEA 2009, July/August 2010; Roth and McKenney 2007; Urban et al. 2011; U.S. EPA 2008, 2011	a-d
Tablet	Sales units for 2010, expected sales 2011-2013, installed units for 2010, household penetration rate for 2010	CEA 2011, Chisholm, 2011; Indvik, 2011; Urban et al. 2011	d
TV – CRT	Installed units 2006 and sales units from 1980-2010	Roth and McKenney 2007; U.S. EPA 2008, 2011	c
TV – LCD	Sales units 1999-2010, Installed units for 2006, and household penetration rates 2008-2009	Herbert, 2008; CEA 2009, 2011, 2012; Roth and McKenney 2007; U.S. EPA 2008, 2011	c
TV- plasma	Sales units 1999-2010 and installed units for 2006	CEMA 2011; U.S. EPA 2008, 2011	c

Product	Type of Data and Years Available	Data Sources	Notes
VCR	Sales units for 1982, 1996-2006, U.S. penetration rates for 1980-2008, and installed units for 2010	Coplan 2006; Roth and McKenney 2007; Eskelsen et al. 2009; Urban et al. 2011	c,d
20	= Total number products included		

Notes: abbreviations in Table 2 are as follows: a) included in Top 10 Products list by CEA (2009), b) included in Top 10 Products list by CEA (July/August 2010), c) analyzed in an energy consumption report for Consumer Electronics Association by Roth and McKenney (2007), or d) analyzed in an energy consumption report for CEA by Urban et al. (2011).

As noted in Table S-1 in the appendices, automobile-related electronics and most analog (non-digital) products were excluded. Camcorder and camera data included only digital devices, but some analog products were included in this analysis because of high ownership concentrations (e.g., VCR) and/or because of conflation of analog and digital sales data (e.g., CRT television). Hardcopy printers, fax machines, scanners, and digital copiers were aggregated into a single product species (hard copy device) because the only available sales data combined the devices into one category (U.S. EPA 2008, 2011). While limiting the analysis to those products passing the screening criteria may not provide a complete inventory, the methodology can be easily adapted as more product data become available.

Product species *abundance* (n), or population size per average U.S. household, was computed by quantifying the total stock (Q) of each product type (i) owned in the U.S. in each year (t) and dividing by the number of U.S. households in that year (Equation 1):

$$n_{i,t} = \frac{Q_{i,t}}{x_t} \qquad 1$$

The number of U.S. households (x) was directly obtained from the U.S. Census Bureau (1990, 2000, 2005-2010). For a few products (DVD player, MP3 player, and gaming console), product abundance was directly available from published household penetration rates (Arendt 2007; Eskelsen et al. 2009; CEA 2009, 2010; Grabstats.com 2011). Otherwise, the total stock of products each year was determined using material flow analysis (MFA) methods that calculate the changes in stock over time using either: 1) known product sales and discard rates or 2) known product sales and lifespan distributions. More details on the MFA method and assumptions are provided in the supporting information (Tables S-2 to S-5).

In the first MFA method, stock (Q) for each product (i) in year (t) was calculated using data describing previous year's stock (Q_{t-1}) and current year unit sales (U_{sales}) and units discarded ($U_{discards}$), from published reports by the U.S. EPA (2008, 2011), as noted in Equation 2:

$$Q_{i,t} = Q_{i,t-1} + U_{sales,i,t} - U_{discards,i,t} \qquad 2$$

For products with no known discard rates, the second MFA method was applied, in which stock was back-calculated by first estimating yearly outflow units using annual sales data (Wilburn 2008; Eskelsen et al. 2009; CEA 2010; Indvik 2011; PBT Consulting 2011; Printed Electronics World 2011) and lifespan distribution models (e.g., Babbitt et al. 2009) as noted in Equation 3:

$$U_{discards,i,t} = \sum_n (U_{sales,i,t-n} * F_{i,n}) \qquad 3$$

For each product (i) and year (t), the number of obsolete units ($U_{discards}$) was determined by multiplying units sold (U_{sales}) in year (t-n) by the fraction (F_n) of those products that reached obsolescence after an n-year lifespan. Lifespan and sales data were obtained from MFA studies and lifespan distributions provided by the U.S. EPA (2008, 2011) and additional data sources (Tables S-2 to S-5).

The structure of the electronic product community was characterized using common ecological diversity indices. In ecology, diversity is attributed to richness (number of species present), evenness (how species' populations are distributed), or a combination thereof (Magurran 1988; Clark and Warwick 2001). Metrics used to quantify structural changes in the product community therefore included species richness (S_t), species abundance (n_t) (as described in the preceding section), Pielou's evenness index (J_t'), Simpson Dominance Index (λ_t), Brillouin Index ($H_{B,t}$), and Shannon Weiner Index (H'_t), which are described below.

Species richness (S_t) was determined by counting the number of electronic products present in the community per year (t). *Pielou's evenness index* (J_t'), was calculated as shown in Equation 4 and has values ranging between zero, which indicates an uneven community (few products with large populations), and one, which implies a uniformly even distribution of species' abundances. *Simpson dominance index* (λ_t) (Equation 5), also known as an index of "commonness," (Pielou 1975, 9) is the probability that any two individuals chosen randomly from the sample are from the same species, and is used to indicate if the community has one or a few dominant species (Pielou 1975; Krebs 2009). Simpson dominance is calculated based on the proportion of each species in the community (ρ_i), a function of number of individuals (n_i) per species divided by total number of individuals in the community (Pielou 1975; Krebs 2009). Total individuals (N_t) were a count of all products present in the community per year (t), (Equation 6). While Simpson dominance also varies from zero to one, the scale is opposite that of evenness: values closer to one are associated with groups dominated by one or a few species (Pielou 1975).

$$J_t' = \frac{H_t'}{ln\, S_t} = \frac{-\sum\left(\rho_{i,t} * ln\left(\rho_{i,t}\right)\right)}{ln\, S_t} \qquad 4$$

$$\lambda_t = \sum\left(\rho_{i,t}\right) = \sum\left(\frac{n_{i,t}}{N_t}\right)^2 \qquad 5$$

$$N_t = \sum n_{i,t} \qquad 6$$

Two diversity indices, which integrate concepts of richness and abundance (Magurran 1988; Clark and Warwick 2001), were computed. *Brillouin Index* ($H_{B,t}$, Equation 7) is commonly applied to communities where all members can be enumerated (Pielou 1975), as in this situation, while large communities requiring sampling are evaluated with the commonly applied *Shannon Weiner Index* (H_t', Equation 8).

$$H_{B,t} = \frac{\ln N!_t - \sum \ln n!_{i,t}}{N_t} \qquad 7$$

$$H_t' = -\sum\left(\rho_{i,t} * ln\left(\rho_{i,t}\right)\right) \qquad 8$$

Both diversity metrics are used here, due to their widespread use in ecological studies and as a means of determining robustness of results depending on indices selected. The analyses described above were computed using Microsoft Excel and ecological statistical software, Plymouth Routines in Multivariate Ecological Research (PRIMER) version 6 (Clark and Gorley 2006).

3.2.2. Characterizing Product Functions within the Community

The analysis of the electronic product community's structure, described above, was coupled with an assessment of functions resulting from that structure. To analyze functions in a manner consistent with ecological approaches, products were first organized into broad *functional groups* based on the main function the product was purchased to fulfill. Most electronic products can perform many functions to various degrees, and therefore each product was also characterized in terms of its total functions at a given time, based on descriptions provided in product manuals, technical reviews of 'typical models,' trade industry publications, or *Consumer Reports* publications. Figure 2 illustrates the assignment of functions: the inner circle identifies the five primary functional groups, while the outer circle reveals the bundle of all possible functions in an average U.S. household (functions are either present or absent depending on whether the product in consideration is owned and has that function at a given time). Thus, a 2005 laptop belonging to the data manipulation functional group also provided several additional functions that year, as noted by the shaded boxes, including interactively playing videos and passively viewing videos, images, and words. All functions per product and model year are provided in Tables S-6 to S-9 in the appendices.

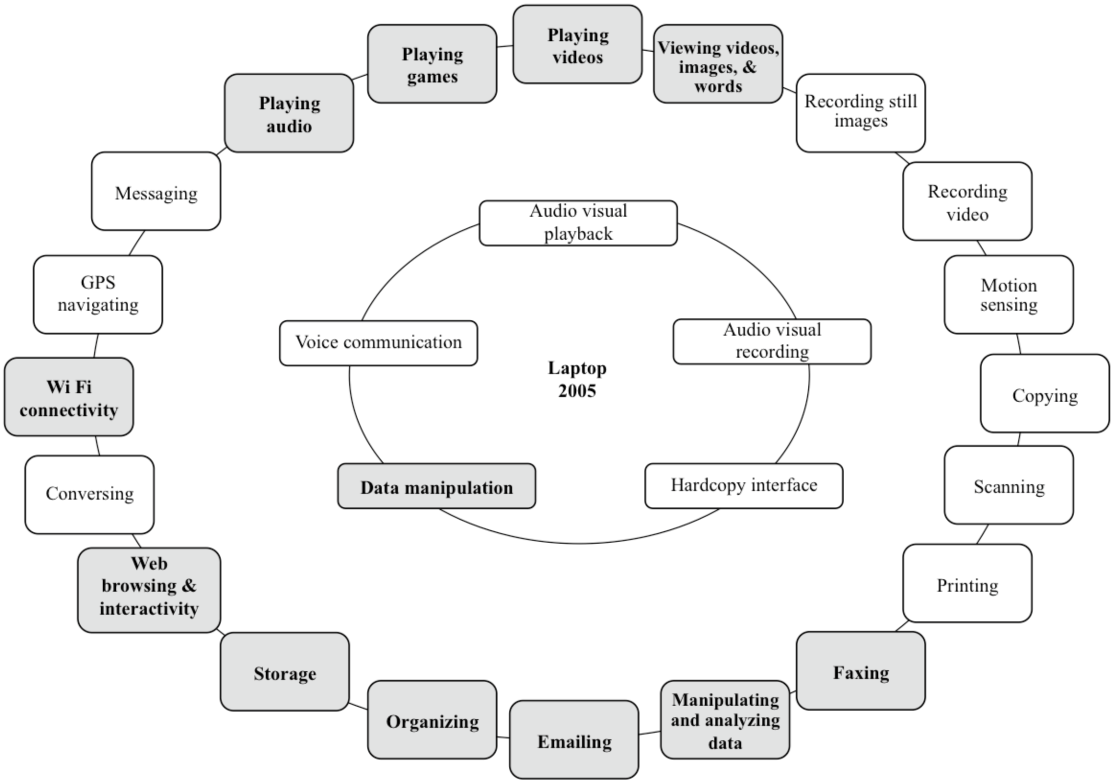


Figure 2 Classification of functions: inner circle represents the functional groups, or primary reason the device was purchased. The outer circle lists all possible functions provided by one or more products in the community. Shaded text boxes illustrate a laptop's functional group and available functions in 2005.

In ecological literature, the variety of functions provided by species is measured by 'functional richness,' a count of all unique functional groups (Díaz and Cabido 2001). Because the electronic product community had a small and static number of functional groups (five, see Figure 2), this metric was adapted to provide more useful information, by quantifying the *available* and *total functions* provided within the community. *Available functions* were determined on a binary basis: at a given time, did the function exist in any product within the community or not. Evaluation of function was built upon the abundance analysis, first determining which products existed in the community in year (t) and then determining which functions those product could theoretically provide at that time. Because available function is binary, each function is counted only once, even if more than one product possessed that function. *Total functions*, on the other hand, included all functions theoretically provided by the products in the community per year. For example, a household owning one smartphone and two basic mobile phones had one *available* conversing function, but three *total* conversing functions. The purpose of this distinction is to enable analysis of functional redundancy, assuming that functions provided by different products are of equal value to the household, an assumption that is revisited in the discussion. This research also categorized function within stationary versus mobile products and single versus multi-functional (having three or more functions) products, for three years in the data set (1990, 2000, and 2010).

The total function analysis described above was also extended to account for actual product consumption and functional redundancy, which is observed in natural communities when more than one species provides similar or equivalent functions. For the product community, a hypothetical 'consumption-weighted functional capacity' was calculated to determine the maximum potential bundle of functions provided by all the products owned by an average household (in 1990, 2000, and 2010). This analysis quantified *capacity per function* (C_f), which accounted for the abundance of each product species (n_i) and total functions that the product can theoretically provide. Total functions were determined with a binary factor (β), which reflected whether or not a function was available for a product in a particular year (Equation 9):

$$C_{f,t} = \sum_i \left(n_{i,t} * \beta_{i,f,t}\right) \qquad 9$$

For each product (i) and year (t), β equaled zero if the function did not exist or one if the function did exist in that specific product.

Because the entire household does not share each product in the electronic community, sensitivity analysis on the functional capacity was conducted. An average household in 2010 consisted of 2.58 members (U.S. Bureau of the Census 2010). However, the only products in 2010 that would be considered individually owned and had similar or greater abundances than the average of number of household members were devices included in the voice communication functional group (basic mobile and smartphone). To calculate the 'true' redundancy for a household in 2010, the functional capacity associated with all the smartphones and a portion of the basic mobile phones were subtracted from the original community's functional capacity. The true functional capacity analysis assumed that 1.03 smartphones and 1.55 basic mobile phones (2.58-1.03) were individually owned by members (2.58) of the household. Therefore, only a remaining 1.98 basic mobile phones (3.48 total basic mobile phones) contributed toward the community's new functional capacity.

Finally, a futuristic scenario was also calculated to begin to explore a household with 'minimal redundancy'. The minimal redundancy scenario, which was based on the concept of households sharing fewer, single function devices and individually owning a fewer number of multifunctional devices, is based on industry trends where patterns of functions are changing and shared by multiple products (NEEP 2013). For example, viewing video or television programming has shifted from solely using a traditional TV to multiple products such as smartphone or tablet (Barns 2014). In this scenario, devices assumed to fulfill a household's minimal functional capacity requirements included one laptop, LCD TV, gaming console, MP3 player, printer per household, and each individual member owning a smartphone and tablet. To calculate the minimal functional capacity, the binary factor ($\beta_{i,f,t}$) (whether the function existed or not in 2010) is multiplied by an abundance of one for each shared device and the binary factor ($\beta_{i,f,t}$) is multiplied by an abundance of 2.58 (average number of individuals in the household) for individually owned products. A list of product-specific binary factors and community-level binary factors are located in Tables S-10 to S-13 in the appendices.

3.3. Results and Discussion

3.3.1. Electronic Product Community Structure

The electronic product community size and structure evolved dramatically in the average U.S. household between 1990 and 2010 (Figure 3), in contrast to a relatively constant household size (2.29 members/household in 1990 and 2.58 in 2010; Table S-5). Products in this community were grouped by attributes of mobility and density. Mobility included either *stationary* products (only used in one location), such as a desktop computer, or *mobile* products (use batteries and can travel with the owner) like a mobile phone. *High-density* products had abundances greater than one per household, while *low-density* products had generally less than one device per household. In 1990, a few stationary products, like the CRT TV and VCR, dominated the community, but by 2010, the community shifted to reflect rapid adoption of small, mobile electronics like mobile phones and digital cameras. As shown in Figure 3c and 3d, stationary products undergoing technological innovations experienced significant growth, as seen for DVD players and LCD TVs, while mature stationary products, such as desktop computers, printers, VCRs, CRT monitors, and CRT TVs, stabilized or declined in abundance.

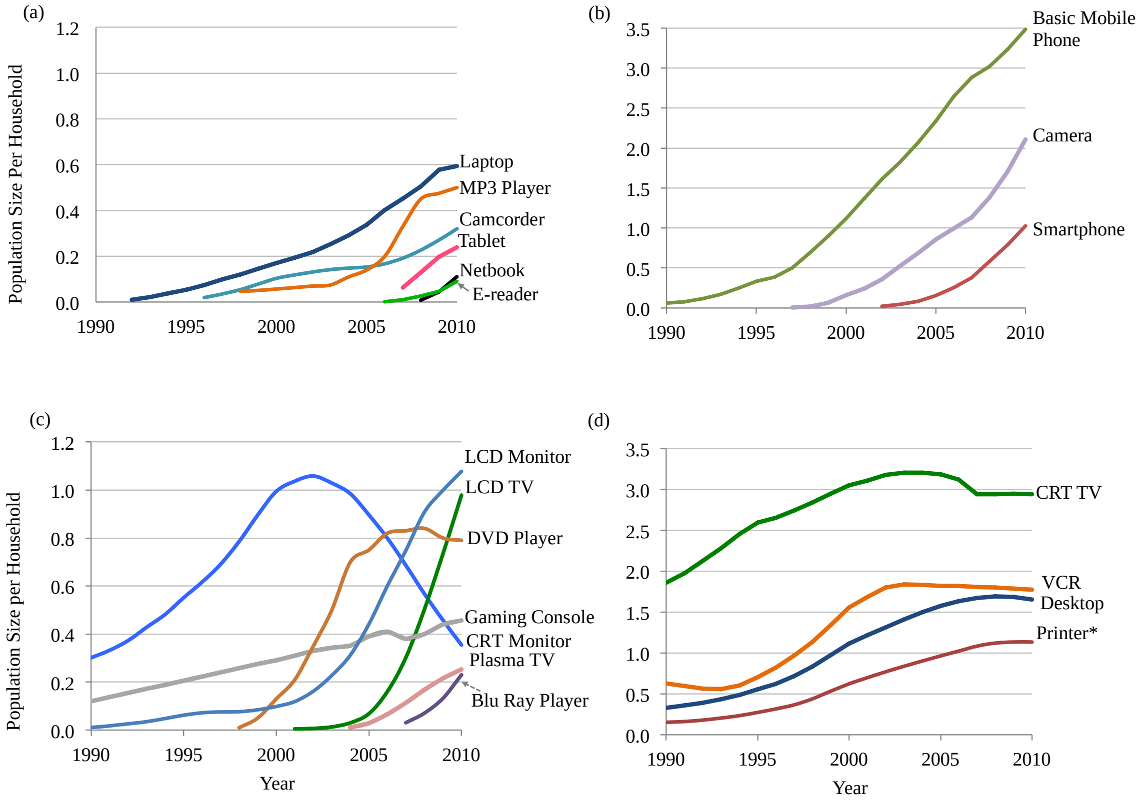


Figure 3 Dynamic changes in species abundance (number of products per household) from 1990-2000: a) mobile low-density, b) mobile high-density, c) stationary low-density, and d) stationary high-density. Note different scales for 'low density' and 'high density' products. Table S-2 to S-4 identifies all population sizes per product per year. *Printer category includes all hardcopy devices.

Ecological diversity metrics describing overall richness, evenness, and diversity of the electronic product community show a shift from an uneven community with low diversity to an increasingly diverse and even structure (Figure 4). Product richness increases 150% - from 8 to 20 products per household from 1990-2010. Trends from the Pielou evenness and Simpson dominance indices suggest that the community is initially uneven, where a few products like the CRT TV and desktop computer were dominant. But by 2010, products are more evenly distributed because of rapid consumption of new small mobile devices. Beyond 2010, this trend toward evenness will depend heavily on consumer preferences, potentially becoming uneven again if users converge on a small set of highly multi-functional devices. Increasing community diversity is confirmed with upward trends in both Shannon Weiner and Brillouin diversity indices. It is clear that the electronic product community has expanded both in terms of overall numbers and in complexity. However, to determine whether increasing diversity has fostered a greater degree of information and communication functionality per household, an analysis of the community's functional diversity is considered.

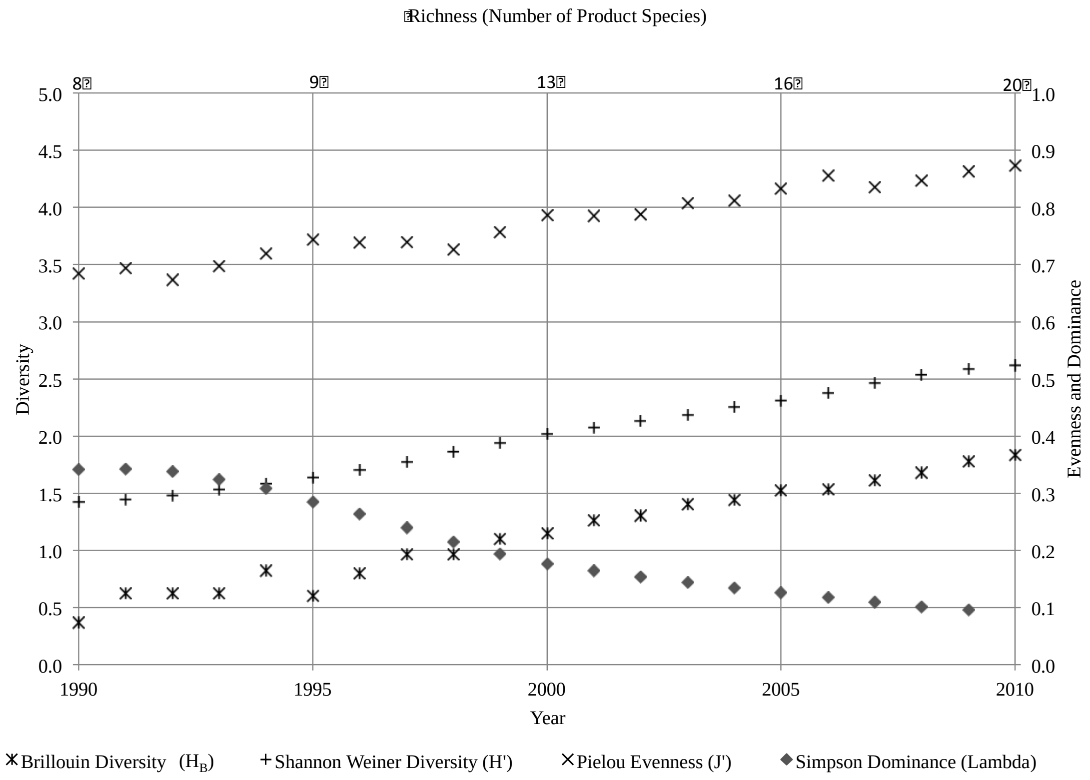


Figure 4 Ecological diversity metrics illustrate changes in the consumer electronic community structure from 1990-2010 (bottom x-axis), including diversity (left y-axis), evenness (right y-axis), and richness (top x-axis). Results are generated using PRIMER-E, version 6 (complete numerical results in Table S-14 in the appendix).

3.3.2. Electronic Product Community Functions

To address the relationship between structural and functional changes, the number and type of functions provided by each product and for the community as a whole are characterized. Community-level a*vailable* functions increased at a rate close to one new function per new product in the community (Figure 5a). At the product level, Figure 5b shows that the *total* functions provided by each product also rise over time, due to increasing multi-functionality, particularly for mobile products. Mobile products increase in functionality tenfold from 1990 to 2010 (Figure 5b) for two reasons: 1) new products enter the market with unique features and 2) existing product species evolve towards multi-functionality to keep up with consumer demand. Mobile products are almost exclusively single function in 1990, but 80% of all mobile products are multi-functional by 2000 and 100% by 2010. While increasing multi-functionality is an inevitable result of consumer demand and technological innovation, over time the product community has developed a high degree of functional redundancy.

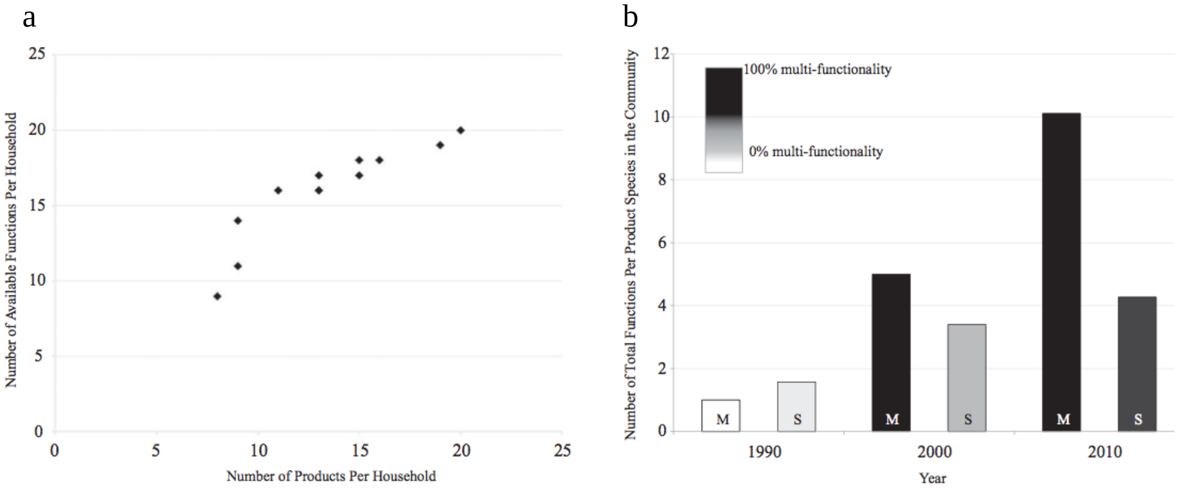


Figure 5 Changes in community-level functionality: a) compares number of available functions in the community to the number of products per household, and b) compares number of total functions per mobile (M) and stationary (S) product species and percentage of multi-functional (greater than three functions) product species in the community, 1990, 2000, 2010.

Functional redundancy was explored further through the *consumption-weighted functional capacity* analysis, which shows that the household's functional capacity has expanded unevenly (Figure 6), with significant increases in total functions for playing audio and games and recording video. Households have been purchasing more types of devices that can record video (digital camera, camcorder, mobile phone, smartphone, or tablet) and doing so at increasing rate (between 2000 and 2010 digital cameras increased from almost zero to over two per household). Moreover, after the year 2000, most functions, except for those related to hardcopy interface (i.e., printing, scanning, faxing, and copying), became theoretically redundant according to ecological perspectives, in that their total capacity exceeds their available capacity (one). Because functional redundancy depends on the species sampled, the estimate presented here is conservative, and would increase if certain products (hardcopy) are split into multiple groups or if analog devices (e.g., film cameras) were included as alternate means for providing information and communication services.

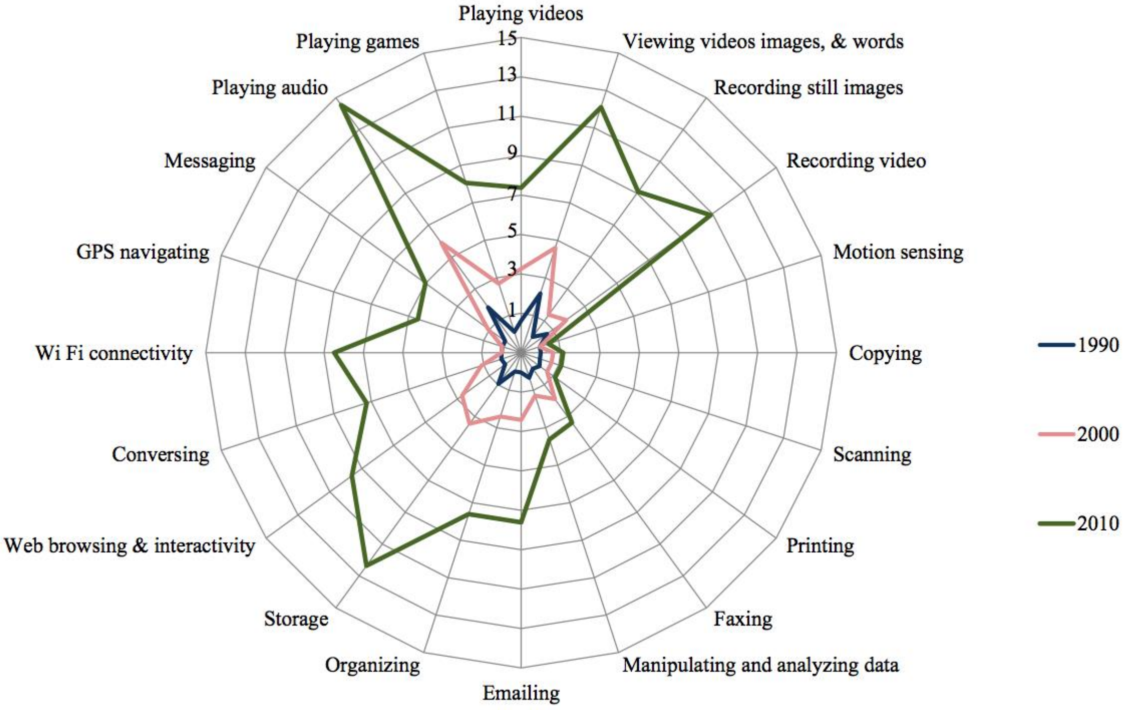


Figure 6 Hypothetical consumption-weighted functional capacity: 1990, 2000, 2010. Significant increases in functional capacity are observed across the community. By 2010, redundancy is observed in most functions, e.g., nine devices have 'recording video' functionality.

Because certain products, like a smartphone, are used by an individual rather than shared by all household members, an attempt is made to illustrate a realistic or 'true' functional capacity for the household. As noted in the methodology, individually owned products from the voice communication functional group are taken into account and only surplus functions from this functional group are included. As shown in Figure 7, an overall reduction in functional capacity for 2010 is seen in comparing the 'hypothetical' and 'true' scenarios. Reduction in functional redundancy, as noted in the 'true' scenario, is due to the exclusion of functions associated with individually owned, multi-functional devices that play audio, record video, interact with the internet, internet, store data, and provide communication functions such as emailing, messaging, and conversing.

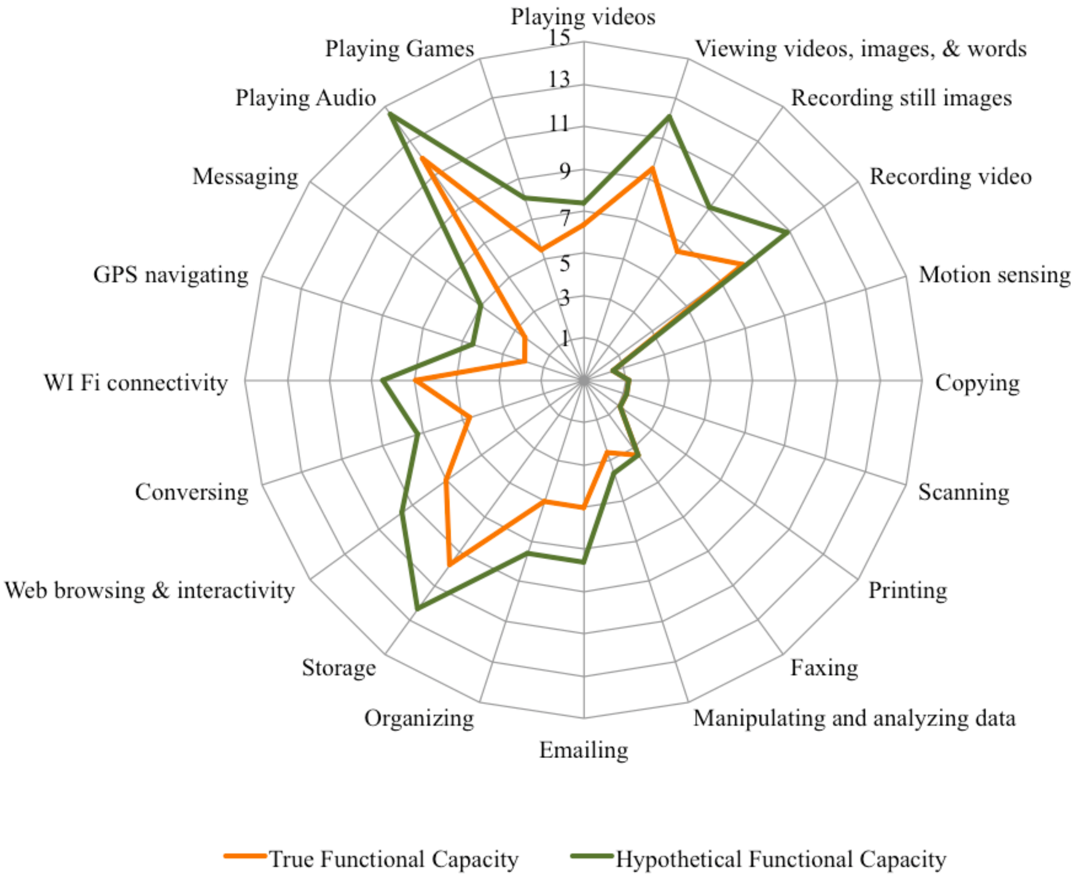


Figure 7 Comparison of true and hypothetical functional capacity: 2010. True functional capacity subtracts functions associated with the voice communication functional group (smart and basic mobile phones), so only the 'true' redundant functions in the community remain.

From an environmental perspective, functional redundancy may result in negative consequences, if demand for desired functions is met by increased consumption of a greater number of unique products. On the other hand, transitioning to adoption of fewer highly convergent, multi-functional electronic devices could potentially reduce material, energy, and waste impacts, although such a comparison would require a comprehensive life cycle study. However, a high degree of redundancy may actually complicate such a conversion. In natural communities, functional redundancy is believed to contribute to system resilience in the event of external perturbations (Díaz and Cabido 2001). If the same trend is true for electronic product communities, it will likely require significant intervention to "disrupt" the existing pattern of redundant product consumption. Future work can extend the results by adapting an ecological functional trait analysis to evaluate the quality levels at which consumers would accept each function as being fulfilled. While conducting a functional trait analysis is out of the scope of this work, potential environmental impact changes resulting from a shift in the community structure is explored in Chapter IV.

Designing functionally convergent products mirrors how biological species that share comparable habitats or environmental conditions may 'converge' to develop similar physical features or appearances, regardless of ancestry (Smith and Smith 2000). For example, modern sharks (fish), extinct ichthyosaurs (reptiles), and modern dolphins (mammals) all evolved over time to share a 'fish-like' form (Diamond and Cody 1985). Further examination of how products and functions have co-evolved within a functional group may provide insight to redesigning sustainable products and encouraging green consumer decisions.

Figure 8 looks in more depth at products classified in functional groups of 'voice communication' and 'data manipulation,' which have seen the greatest increases in functional capacity over time. In both cases, these product groups have transitioned from *specialists* with single or few functions to *generalists* that offer multiple (and redundant) functions. Both product groups undergo periods of technological progress, when the number of functions per species surges upwards, as well as periods of relative functional stability (Figure 8a and c). Furthermore, each new species introduced to the product community enters at roughly the same level of functionality as the existing products (again, no differentiation is made on the comparability of functions provided by different devices). Throughout the 20-year period, total functions provided by the data manipulation group increase from 2 to 45 functions, while the total number of species on the market quadruple. Over the same period, the voice communication group experiences a sharp increase in total functions, particularly after 2000. By 2010, a basic mobile phone offers nearly as many functions as a smartphone, and a smartphone has slightly more functions than a desktop or laptop computer. Consumer electronics are 'converging' physically into smaller, multi-functional mobile devices with parallel functions, regardless of original classification by functional group. For example, the tablet and smartphone are categorized under different functional groups, but share similar appearances and functions (e.g., the tablet entered the community in 2007 possessing 10 of the smartphone's 14 functions). In 2011, these products began to evolve into a hybrid species, the 'phablet,' (DesMarais 2013).

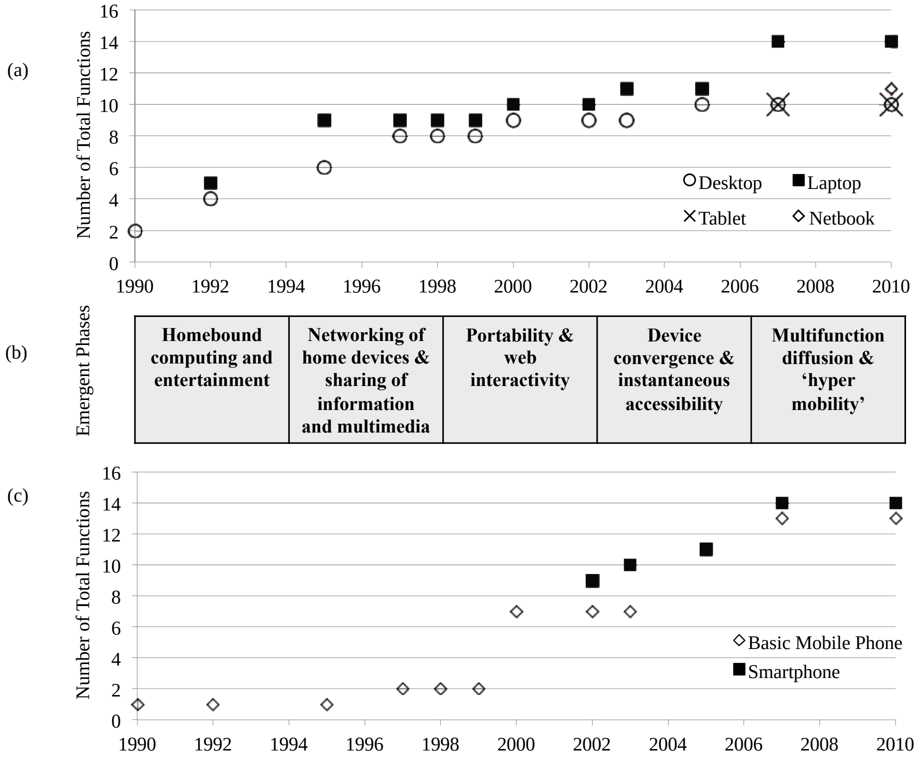


Figure 8 Trends in functional groups and emergent functional phases, 1990-2010: a) total functions per product and year for the data manipulation group, b) emergent functional phases associated with all functional groups, and c) total functions per product and year for the voice communication group.

The discussion of function to this point has centered on whether or not a specific product provides each well-defined function. In reality, however, some product attributes evolve and recombine over time, introducing 'emergent functions' that are not easily categorized (Figure 8b). For example, dematerialization of computing services into lightweight, multi-functional products like the tablet or e-reader could be classified as a new emergent function, such as ultra-portable data manipulation and visual playback. While it is impossible to enumerate all combinations, this research interpreted the community's evolution through emerging functional phases, considering observed functions and product attributes, like stationary versus mobile (Figure 8b). For example, the step increase in functions for the voice communication group after the year 2000 parallels the phase of portability and web interactivity. After the internet becomes the 'new normal' (Pew Research Center 2005, 59), product innovations are based on novel uses of the internet, like the demand for 'hyper mobility,' a term coined by Accenture (2012, 3) to describe constant connection to the web for productivity and entertainment.

As new functions emerge and products continue to converge, consideration of minimum redundancy may help prioritize high-use functions to be integrated into fewer, convergent devices to meet consumer demand. The 'minimal functional' capacity scenario (as shown in Figure 9) is consistent with an 'eco-sufficiency' strategy of living well while consuming less resources (Figge et al. 2014) and is portrayed as a futuristic, extreme 'digitally streamlined' household owning fewer, functionally convergent devices. The minimal functional capacity scenario reflects a significant decline in redundancy from the hypothetical consumption-weighted functional capacity, particularly related to the functions of recording still images and videos and playing audio, but an increased redundancy in manipulating data. The reduction in functional redundancy is realized by excluding single function and/or high-density devices (i.e., desktop, VCR, DVD player, monitors, plasma and CRT TVs, basic mobile phone, camera, and camcorder). While reductions in functional redundancy in the minimal functional capacity scenario appears similar to the true scenario, it is achieved with six rather than 20 devices. Consideration of minimal redundancy thus far suggests a change in consumption patterns could allow a household to retain a certain level of communication, entertainment and information services, but evaluating the subsequent environmental impact from fewer devices is critical.

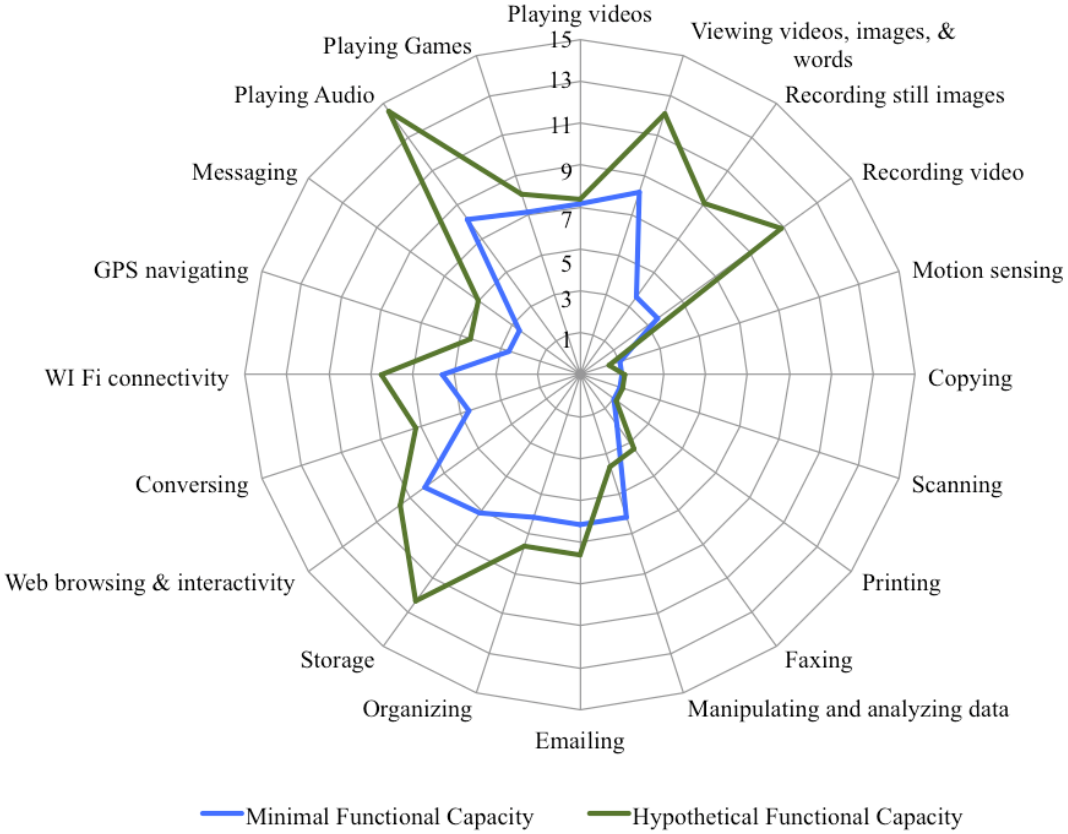


Figure 9 Comparison of minimal and hypothetical functional capacity: 2010. A minimal functional capacity scenario assumes that the household shares one LCD TV, laptop, printer, and gaming console (available function per product=1), as well as each individual owns a tablet and smartphone (functions weighted by 2.58 individuals per household).

While this research assumes that each device can provide services of comparable quality, in many cases functions are not actually equivalent. For example, the quality of pictures taken with a mobile phone may be inferior to those captured by a specialized digital camera. In some cases, the community may actually require more capacity to meet a minimum level of desired functionality. For example, in a family of four, the minimum ‘conversing’ capacity may be four, so each member can contact each other. Ecologists evaluate substitutability of functions by comparing trait values and frequency distributions across the range of resources used by a species (Petchey et al. 2004; Mason et al. 2005).

These types of analyses may provide potential opportunities to expand the community ecology approach in the future.

3.3.3. Comparison of Electronic Product and Natural Communities

The parallels between product and natural communities discussed so far, like functional redundancy and convergence, suggest that practical application of the community ecology concept may benefit from additional consideration of similarities and differences between biological systems and industrial analogs. Table 3 provides a foundation for this comparison, using common attributes of a natural community to inspire potential directions for study of an electronic product community evolving over time.

Table 3 Qualitative comparisons of general succession trends between natural and household electronics communities

	Natural Community		**Electronic Product Community**	
Stage	**Early or developing**	**Maturing**	**Early or Developing**	**Maturing***
Species Diversity (richness & evenness)	Low	High	Low	High
Niche Specialization	General or broad	Specialized or narrow	Specialized or single function	General or multi-function
Functional Redundancy	Low	High	Low	High
Species Size	Small	Large	Large	Small
Species Life Span	Short	Long	Long	Short
Complexity	Low	High	Low*	High*

Note: *Requires further investigation. Source: Odum (1969) and Collier et al. (1973).

Table 3 highlights points of similarities and divergence that may have the most relevance for understanding the environmental impacts of evolving electronic product communities. Natural communities in early phases of succession often begin with low species richness and evenness, and generally increase in diversity, biomass production, and functional redundancy as the community develops (Odum 1969). Similar to a natural system, the electronic product community has evolved into a diverse, functionally redundant, and evenly distributed structure. While natural communities typically transition to larger, longer lived species (Odum 1969), the product community structure has been evolving to smaller products that reach obsolescence at a growing rate, which leads to a growing waste stream comprised of products whose size may make disassembly and recycling difficult. Natural systems evolve towards complexity over time, which results in greater variability of resource consumption and types of metabolites (intermediates and wastes) generated, particularly as species partition into specialized ecological niches (Odum 1969). While this topic requires additional study for the electronic product community, the environmental implications of a complex, diversified electronic product system are likely to include a higher throughput of materials, increased energy consumption and waste flows, and a more diverse mix of resources required to produce and use these devices.

A major difference illustrated by Table 3 is in the relative role of specialists and generalists during a community's succession. The pioneer species that dominate early stages in natural communities are generalists that can more easily utilize limited resources or handle extreme conditions (Collier et al. 1973; Ricklefs and Miller 2000). For example, fast-growing annual plants initially dominate abandoned fields and produce biomass that enriches the soil, then are gradually replaced by a more diverse community of larger species such as herbaceous perennials, shrubs, and trees (Whittaker 1970; Ricklefs and Miller 2000). Alternatively, in the product community, early devices were introduced as single-function specialists that later transition into multi-functional generalists. Both systems move towards higher functional redundancy, but for different reasons: in the natural community multiple specialists have similar functions, whereas in the product community there are multiple generalists with overlapping functions, suggesting that more products are consumed than are needed to provide a desired function. These generalist products actually share several traits with invasive species, which can adapt and thrive in variable conditions (Townsend 2008). While invasive species have negative connotations for a natural community, they may actually represent a viable strategy for a more sustainable household electronics community. For example, if rapid product turnover due to consumer demand for the 'next best thing' is inevitable, then the ‘invasive’ product introduced can be designed with maximum functionality to replace multiple single or multi-functional products. A shift to a lower diversity structure dominated by a few multi-functional devices may actually reduce consumption of materials and energy, but this hypothesis requires investigation by complementary sustainability assessment, such as a community-level life cycle assessment (LCA) that is explored in Chapter IV.

3.4. Implications

New industrial ecology approaches based on community ecology can provide an effective link between sustainable consumption and production. Increasing trends in consumption, diversity, convergence, and functional redundancy reiterate the need to quantify sustainability impacts and design products on a *community* rather than ‘per product’ basis.

Ultimately, this chapter’s methodology and results can inform design and consumption of greener multi-functional products, thereby reducing overall household consumption impacts. Instigating a compositional regime shift without losing core community functionality requires parallel intervention strategies focusing on both production and consumption. Recent efforts to shift consumption patterns by solely concentrating on a single approach, such as green labels, have had little impact (Tukker et al. 2010). Focusing intervention strategies and innovations on curtailing redundancies and encouraging product and functional convergence may initially be problematic for manufacturers who want their devices to survive and compete in the market (Puri 2008). Nonetheless, adopting a community ecology perspective may help households begin to realize a ‘double dividend’ (Jackson 2005, 19) of being happier with less.

Just as laboratory models are used to elucidate larger-scale trends observed in field research (Odum 1969), the community-level structure and function analysis can provide a better understanding of the interactions underlying traditional ‘ecosystem-level’ industrial ecology models, like LCA. Thus, Chapter III’s structure data are incorporated into the methodology for Chapter IV, which establishes a linkage between community structural changes and ecosystem-level energy flows (i.e., annual energy demand). This linkage is achieved with a novel *consumption-weighted LCA methodology*.

IV. Linking Community Structure to Ecosystem-Level Energy Flows

4.1. Introduction

Greening the environmental performance of consumer electronics has been a major initiative for researchers and decision makers. Manufacturing innovations and voluntary product labeling have resulted in energy impact reductions for individual products (Brown 2002; Sanchez et al. 2008). As noted in Chapter III, U.S. households have been amassing a large and increasingly complex bundle of devices to fulfill information, communication, and entertainment functions (Ryen et al. 2014), which may be potentially offsetting environmental savings from efficiency gains. For example, while the average standby power for televisions (TVs), computers, and other related devices has declined since the 1990s with the introduction of Energy Star® standards (Roth and McKenney 2007), the overall volume of new products with standby modes has increased (Meier et al. 2008). The rebound effect has also been noted at the electronic component level, for computer microprocessors (Deng and Williams 2011). In order for efficiency improvements to result in reduced environmental impacts, technological innovations need to be greater than the consumption of the goods (Dahmus 2014).

Due to the complex relationship between consumption of electronic devices and technological progress, sustainability methods like LCA struggle with characterizing dynamic changes in environmental impacts. Of the wide body of literature quantifying energy impacts of various combinations and types of consumer electronics, all but a few (Hertwich and Roux 2011; Malmodin et al. 2010) compute life cycle impacts without consideration of consumption behavior and ownership patterns. For example, many LCAs focus on use phase at the household scale (Hendron and Eastment 2006; Porter et al. 2006; Peters et al. 2010; Bensch et al. 2010), state scale (Porter et al. 2006; McAllister and Farrell 2007), national scale (Rosen et al. 1999; Zogg and Alberino 1998; Kawamoto et al. 2002; Roth and McKenney 2007; Urban et al. 2011), or for a single product (Socolof et al. 2001; Williams 2004; Deng et al. 2011; Teehan and Kandlikar 2013) (see Table S-15 in the appendices). Thus, a need remains to link environmental analyses of manufacturing and use (impact per device) with evolving trends and interconnections in consumption (products owned at a given point in time).

Because electronics are usually purchased in groups to fulfill information, communication, and entertainment needs, LCA methods must consider the number and type of devices owned within this group, or ‘community.’ To this end, inspiration is drawn from the field of biological community ecology. An ecological community is a group of living organisms that persist and interact in a defined space and time (Whitaker 1970). As noted in Chapter III, organisms provide services or functions to the community and the overall ecosystem, such as nutrient cycling (Díaz and Cabido 2001) and facilitating response to external stressors (e.g., changes in resources, precipitation, or temperature) (Díaz and Cabido 2001; Ricklefs and Miller 2000). Fluctuations in the structure (number and distribution of organisms) and functions provided by the organisms in the community dictate resultant flows of inputs (e.g., energy from the sun or from nutrients) and outputs through the ecosystem (Ricklefs and Miller 2000). Similarly, household purchase and use of different numbers and types of electronic products also drive attendant inputs, like energy (e.g., electricity and fuel) and materials (e.g., plastics, glass, and metals) and resultant outputs (e.g., used components and electronic waste). Consequently, the field of community ecology offers a promising systematic approach to assessing a product community’s net environmental impact (Ryen et al. 2014).

As noted in Chapter 1, addressing household electronics as a community, or a ‘portfolio’ in the case of Williams (2011), builds on Levine’s product-centered approach (1999, 2003) and a small set of studies that focus on an ‘ensemble’ of energy generating systems (Gutowski et al. 2010; Kotaro et al. 2012), a ‘fleet’ of ferry vessels (Winebrake et al. 2005), a ‘fleet’ of fishing boats (as reviewed by Van Putten et al. 2012), a ‘fleet’ of automobiles (Field et al. 2000; Levine et al. 2007; Stasinopoulos 2011), and a group of mobile telephony (Michalakelis et al. 2010). These studies show that considering products as an interconnected group rather than on a ‘per product’ basis has led to more comprehensive pollution reduction strategies and policies (e.g., vehicle mileage standards, Winebrake et al. 2005). LCA applied at the household community scale is particularly relevant for products undergoing technology transitions (Levine et al. 2007), as impacts for emerging technologies are closely linked to consumption behavior (Guinée et al. 2010). Moreover, the household scale is used as unit of study in environmental behavior research because residents generally have more control over the household’s purchasing decisions, as compared to a larger scale (firm or nation), where only a few people have overall decision responsibility (Reid et al. 2010). Systematic understanding of impacts due to interactions of products within households can lead to more effective policies that encourage behavioral changes, reduce environmental impacts (Reid et al. 2010), and broaden the application and scope of LCA methodology (Guinée et al. 2010).

Therefore, the goal of this chapter is to develop and apply a new assessment approach that systematically characterizes dynamic changes in net environmental impacts for an evolving community of interrelated electronic products. By integrating Chapter III's results characterizing changes in the electronic product community's structure (number and type of products owned by an average U.S. household), this approach enables comparison of impact reduction strategies by evaluating changes in both production and consumption of the electronic products in a household. Ultimately, the community approach can be used to evaluate and encourage green design, manufacturing, and purchasing decisions through a better understanding of how evolving consumption patterns of interrelated products influence overall environmental impact.

4.2. Methodology

4.2.1. Objective and Scope

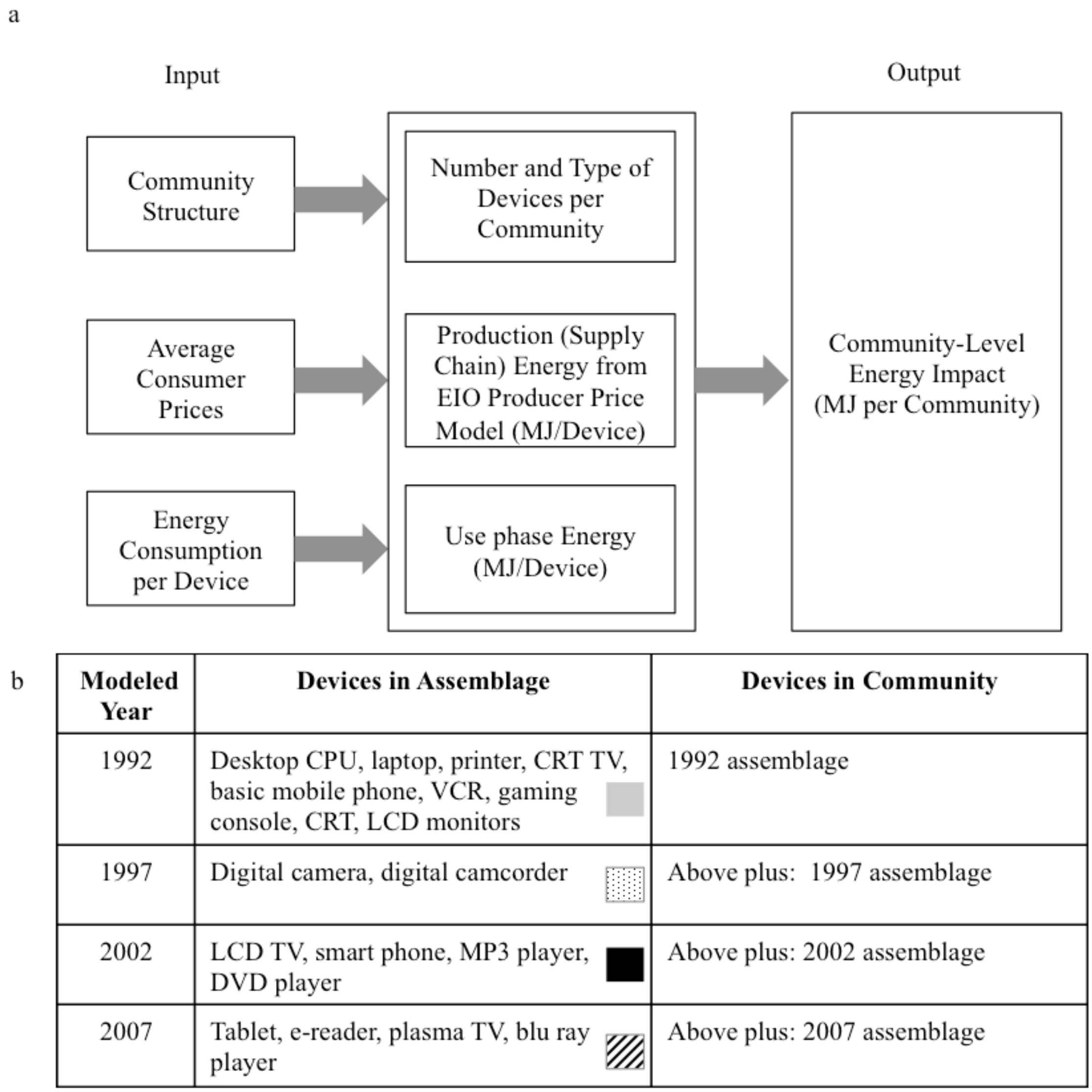
To quantify the electronic product community's net environmental impact, the *consumption-weighted LCA* approach was demonstrated for a 'community' of electronic products that provide information, communication, and entertainment services. The functional unit for this analysis was an average U.S. household for one year. The metric used to quantify environmental impact was annualized cumulative energy demand per household ($E_{household}$). While many environmental impacts result from production and consumption of consumer electronics, cumulative energy demand, which includes both direct (electricity consumed while using the device) and indirect (i.e., upstream fossil fuels) inputs, is a well established predictor of environmental impacts including, but not limited to the depletion of resources, acid rain, and release of greenhouse gas emissions (Kok et al. 2006; Huijbregts et al. 2006).

The community-level impact ($E_{household}$) (Figure 10a) was calculated as the product of community structure (number (n) of products (i) owned per average U.S. household) and the annualized energy demand ($E_{i,t}$) (in MJ) per product (i) per household for the modeled years (t) (Equation 10).

$$E_{household,t} = \sum_i (E_{i,t} * n_{i,t}) \quad (10)$$

The annualized energy demand ($E_{i,t}$) was determined by a hybrid LCA approach following Hertwich and Roux (2011), which included the product's upstream manufacturing supply chain (material extraction, manufacturing, and transportation) and the product's use. The scope excluded end of life (EOL), because many studies have noted that only a small fraction of life cycle energy occurs at the EOL stage (Williams 2002, 2004; Deng et al. 2011; Hertwich and Roux 2011). Estimation of manufacturing and use energy relied on obtaining transparent and publicly available data. Specifically, manufacturing energy was estimated via the online Economic Input-Output Life Cycle Assessment (EIO-LCA) tool by Carnegie Mellon University (CMU)'s Green Design Institute (2008). As a result, the dynamic analysis focused on years for which EIO-LCA data were available (1992, 1997, 2002) reasonably extrapolated (2007). Analyzing the 2007 model year was essential for capturing the effect of newer devices (plasma TVs, tablets, and e-readers) on the overall energy impact.

The number of products per household ($n_{i,t}$) was determined in a previous study (Ryen et al. 2014), which first categorized consumer electronic products based on industry classifications and then estimated the number of each product per household between 1990-2010 using a material flow approach (see Table S-16 for the 19 devices included in the scope). While products are introduced continuously to U.S. households, the EIO-LCA data only provides snapshots of specified years for which data are available. For example, the 1997 electronic product community was comprised of products from the previous EIO year's analysis (e.g., CRT TV, 1992) plus devices between 1992-1997 (e.g., the digital camera and camcorder) (Figure 10b). Additionally, products were grouped into assemblages based on timing of their first appearance in U.S. households and the closest subsequent EIO-covered year (Figure 10b). For example, the '1992 assemblage' only consisted of devices introduced by and before 1992 (e.g., CRT TV and desktop computer), while the '1997 assemblage' was comprised of devices introduced after 1992, but through 1997 (e.g., the digital camera and camcorder). Throughout this paper, the groupings within the community are color coded consistently.



Modeled Year	Devices in Assemblage	Devices in Community
1992	Desktop CPU, laptop, printer, CRT TV, basic mobile phone, VCR, gaming console, CRT, LCD monitors ░	1992 assemblage
1997	Digital camera, digital camcorder ⬚	Above plus: 1997 assemblage
2002	LCD TV, smart phone, MP3 player, DVD player ■	Above plus: 2002 assemblage
2007	Tablet, e-reader, plasma TV, blu ray player ▨	Above plus: 2007 assemblage

Figure 10 Consumption-weighted LCA methodology and scope: a) inputs and outputs used in the community-level analysis and b) type of devices comprising the electronic product community per modeled year. The community in each modeled year is divided into groups of products or assemblages (see color coding). Product assemblages are based on the year devices were introduced into the community.

4.2.2. Hybrid LCA Methodology

As discussed above, the hybrid LCA methodology computed the annualized energy demand per device ($E_{i,t}$) as the summation of manufacturing energy ($E_{p,i,t}$) (estimated via

EIO-LCA) and use phase energy ($E_{u,i,t}$) (estimated via product-level process data) for each device (i) and modeled year (t) (Equation 11).

$$E_{i,t} = \sum_i (E_{p,i,t} + E_{u,i,t}) \qquad 11$$

Using EIO-LCA does have potential to introduce error due to aggregation of data to the sector level or to assumptions that products were produced in the U.S. (Hendrickson et al. 2006). However, its benefits, such as reduced cut-off error and quick and inexpensive nature have promoted its use as an environmental policy tool (Hendrickson et al. 2006; Finnevden et al. 2009). While conducting individual process-based LCA on all 19 devices in the electronic product community would be an ideal and thorough measurement of environmental impacts, the effort would have enormous financial and time constraints. Thus, the approach used here was to demonstrate the benefit of the consumption-weighted LCA approach using a hybrid method, which can easily be extended in the future as product-specific data become available.

In terms of geographic scope, the U.S. IO sector data was initially closely aligned with the production of consumer electronics because manufacturing was largely domestic before 2001 (Duan et al. 2009; EIA 1991; McCormack 2009). According to the Consumer Electronics Industry (1995), many consumer electronics were still produced in the U.S. as late as 1994, including half the number of television sets sold domestically. However, the transition to overseas production necessitated consideration of global supply chains, modeled here with China-based IO energy data from Chang et al. (2011) as described in Table S-17 in the appendices. A sensitivity analysis comparing U.S.- and China-based manufacturing energy was based on available years in the Chinese data set (2002 and 2007, Chang et al. 2011).

4.2.3 Calculation of Manufacturing Energy

Manufacturing phase energy was estimated by first classifying each electronic product into appropriate U.S. Bureau of Economic Administration (U.S. BEA) IO sectors and then determining the average producer prices for each device as an input to the EIO-LCA model. The net annualized manufacturing energy (E_p) (in MJ) for each device (i) was a product of the IO sector energy (e) (in \$/MJ) from the 1992, 1997, and 2002 producer price EIO models (and extrapolated for 2007) and the average producer price (p_p) (in \$) for year (t), divided by the average service life of the product (l) (Equation 12).

$$E_{p,i,t} = \frac{p_{p,i,t} * e_{i,t}}{l_i} \qquad 12$$

Energy per IO sector for 2007 was projected using linear extrapolation of existing aggregated IO sector level energy per nominal input dollar from the 1992, 1997, and 2002 IO sector data points, an approach enabled by the relatively small year-to-year variability in the stable U.S. manufacturing sector (as shown in Figure 11 below and Tables S-18 to S-19 in the appendices). Future work linking environmental impact vectors with the recently released 2007 IO data using CMU's EIO LCA methodology will provide a more accurate measure of environmental impacts.

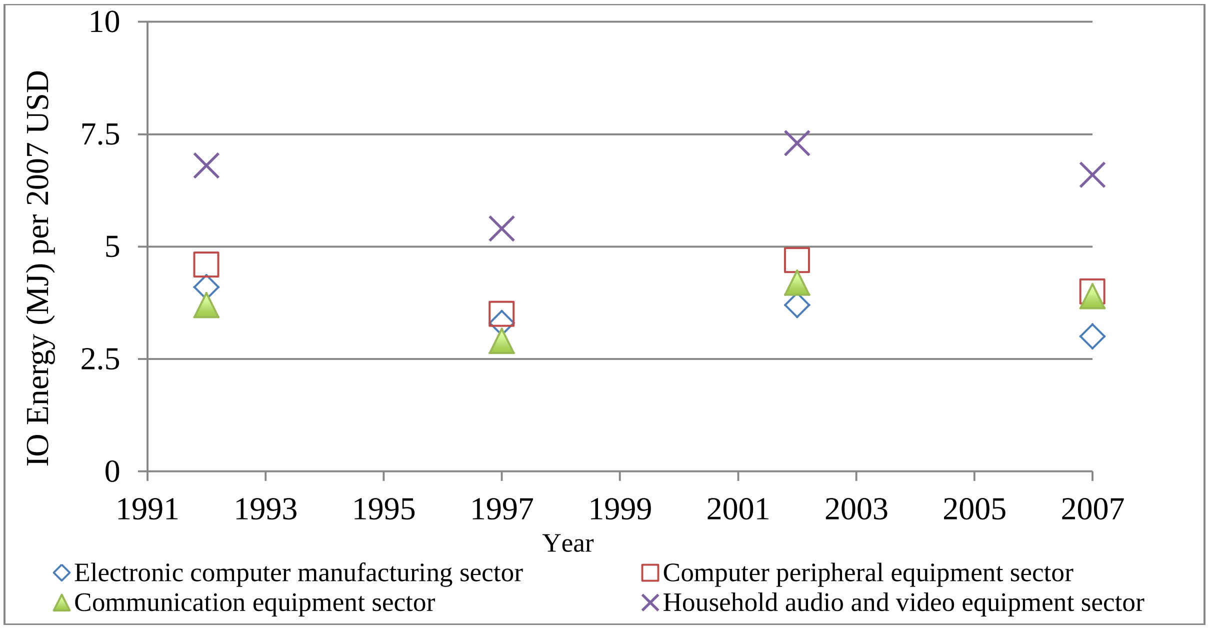


Figure 11 Temporal changes in IO sector energy (MJ) per constant U.S. dollar (2007). 2007 IO values are estimated based on 1992, 1997, and 2002 IO sector data points.

Product price is a key input to the EIO-LCA model, here determined in two steps: 1) collecting average consumer prices for each product in the community for every modeled year, and 2) converting these consumer prices to producer prices for use as inputs to the producer price model (Table S-20 in the appendices and Table 4 below). Average consumer prices were collected from a consistent set of publicly available trade publications and commercial sources, such as the Consumer Electronics Manufacturing Association (1998), review articles (e.g., Cheng 2007; Ballou 1992), or *Consumer Reports* (1992-1993, 1995, 1997-2002, 2004-2010) (See Table S-20 for a complete listing). While electronic devices are available with variable customizations and sizes (e.g., screen sizes for televisions and monitors), a single model size was generally used for all years analyzed, and average prices reflected typical product models and configurations. In a few cases where consumer prices were not available for the modeled years, average consumer prices adjacent to the modeled year were adjusted using the U.S. Bureau of Labor Statistics (BLS) producer price index (PPI) (2013) for the specified IO sectors or for a few cases (gaming consoles and printers) the consumer price index (2013). Producer prices were converted from consumer prices using the ratio of producer to consumer price values found in the U.S. BEA IO Bridge Tables to Personal Consumption Expenditures for each modeled year (1992, 1997, 2002, 2007) (See Tables S-21 to S-24 in the appendices for assumptions and details related to manufacturing input values). A summary of producer prices used as inputs for the consumption-weighted model is shown in Table 4.

Table 4 Summary of average producer prices

	Device	1992	1997	2002	2007
1992	CRT TV	$399	$259	$305	$312
	VCR	$257	$121	$63	$51
	Desktop CPU	$803	$1,207	$509	$355
	CRT monitor	$838	$490	$157	$86
	Printer	$230	$249	$114	$118
	Gaming console	$127	$91	$96	$226
	Basic mobile phone	$202	$73	$75	$37
	LCD monitor	$1,710	$1,277	$284	$144
	Laptop	$1,305	$1,538	$1,390	$460
1997	Camcorder	na	$582	$744	$260
	Camera	na	$358	$275	$188
2002	DVD player	na	na	$173	$48
	MP3	na	na	$153	$108
	Smartphone	na	na	$312	$243
	LCD TV	na	na	$1,415	$307
2007	Plasma TV	na	na	na	$674
	Blu-Ray player	na	na	na	$148
	Tablet	na	na	na	$1,197
	E-reader	na	na	na	$287

Notes: Average producer prices are organized per year devices introduced into the electronic product community. If a product is not included the community in a specified year (e.g., plasma TV in 1992), the price is listed as 'na.' Prices are in nominal dollars (not adjusted to significant figures).

Product lifespan is also a required input, whereby total manufacturing energy can be equally divided by the average service life to determine an annualized energy impact for each modeled year. We recognize that the issues surrounding product lifespan definition and resultant contribution to uncertainty and variability to life cycle energy impacts have been widely discussed (Babbitt et al. 2009; Teehan and Kandlikar 2012; Arushanyan et al. 2013). Here, the lifespan in consideration is the time in use during the device's average first life (l_i). In some cases with limited delineation of use, storage, and reuse lifespans (printer, TVs, camera, camcorder, and VCR, DVD, blu-ray, and MP3 players), the total available lifespan was applied. The selection of each product's lifespan from available sources was first based on primary data on consumer behavior, such as from consumer surveys (e.g., Williams 2008 and NIES 2013). In cases where this information was not available, lifespans were based on product studies, technical reports, or assumptions in peer-reviewed publications (Figure 12).

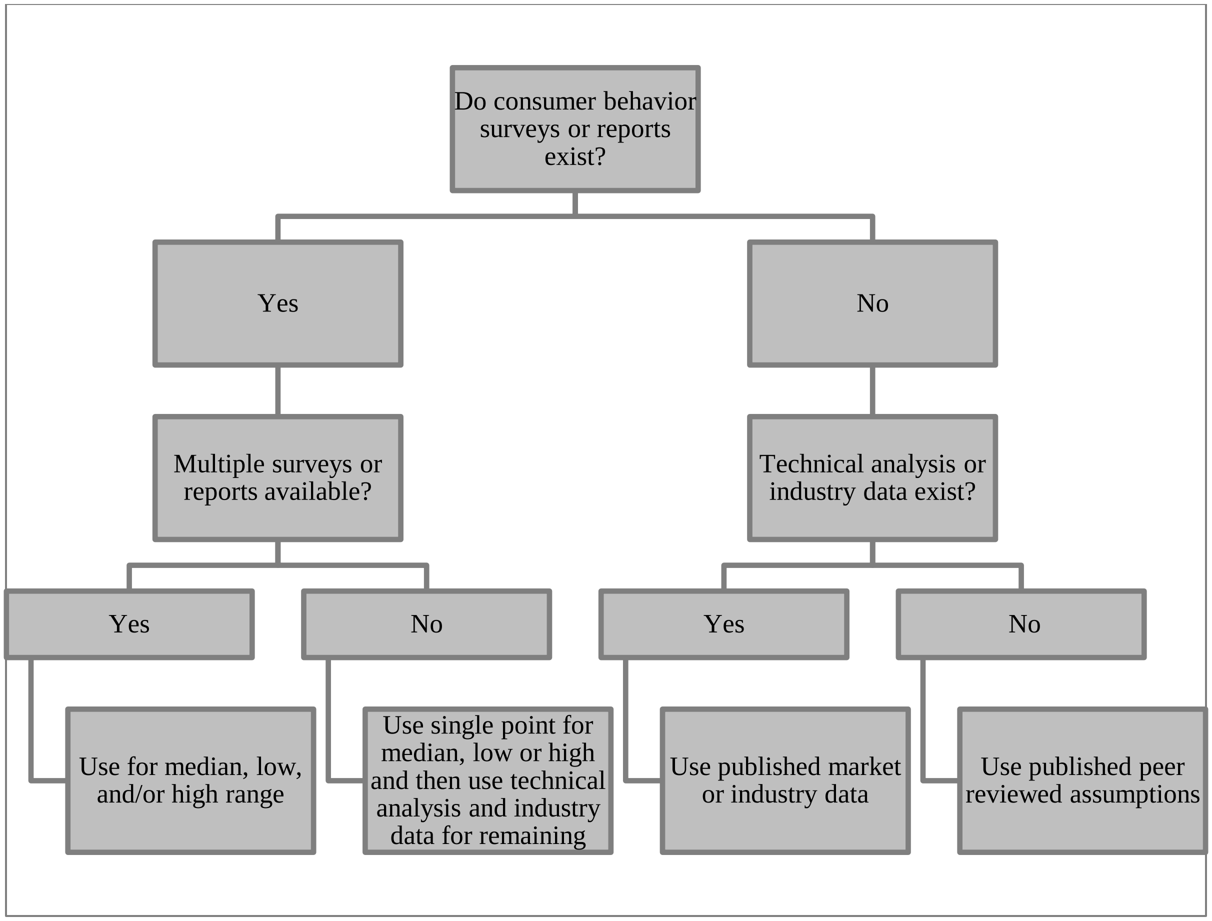


Figure 12 Decision tree diagram used to select the baseline lifespan for each product. The selection of lifespan was first based on using data points that most reflected the way people used products such as survey data or product studies. The baseline consumption-weighted LCA analysis is based on the median lifespan.

Except for products with limited data points (MP3 player), the baseline LCA analysis was based on the median of all lifespan values compiled (Table 5). In a few cases where lifespan data were limited, but products had closely related functions or forms (e.g., basic and smart mobile phones, or tablets and e-readers), the same lifespan was assumed for both. As shown in Table 5, to capture the range of uncertainty associated with varying lifespans, a sensitivity analysis using low, median and high data was conducted.

Table 5 Summary of lifespan data

	Proposed Lifespans (years)			Alternative Lifespans and Sources		
Product	**Baseline**	**Low**	**High**	**Lifespan (years)**	**Sources**	**Notes**
Desktop CPU	4.1	2.9	5.5	5.5	Williams 2008	Replacement interval
				4	Choi et al. 2006	CPU only, made in 2001 and used in Korea
				6	Eugster 2007	First life (China, 2000-2005); assumption
				4.4	Yao et al. 2010	First life for established regions; assumption
				3-6	Teehan and Kandlikar 2012	Noted as acceptable range
				5.5	Babbitt et al. 2009	First life + storage for university computer purchased in 2000
				6.6	Oguchi et al. 2008	2003; includes storage & multiple uses
				6	Duan et al. 2009	No year or additional information
				2.9	Deng et al. 2011	Replacement interval of any computer based on household survey
				4.1	NIES 2013	First life for “PC”-any computer based on 2001 survey of Japanese households

Product	Baseline	Low	High	Lifespan (years)	Sources	Notes
Desktop CPU				4 (low), 6 (average), 8 (high)	Zogg and Alberino 1998	Range of lifespans reported.
				5 (average)	Zogg and Alberino 1998	Part of range life lifespans, but used 5 as an average
Laptop	4.1	2.9	5	4.4	Williams 2008	Replacement interval
				2.9	Deng et al. 2011 (based on Williams and Hatanaka, 2005)	Replacement interval of any computer based on household survey
				5	Eugster 2007	First life (China, 2000-2005), assumption
				3	DesAutels and Berthon 2011	Assumption-no information
				2-3	National Safety Council (NSC 1999)	First life
				7.4	Oguchi et al. 2008	2003; included storage & multiple uses
				4.1	NIES 2013	First life for “PC”- any computer based on 2001 survey of Japanese households

Product	Baseline	Low	High	Lifespan (years)	Sources	Notes
Tablet	3	2	4	1-2	Moberg et al. 2010	Moberg et al.2010 first uses one year and then 2 years as a sensitivity analysis.
				3	Arushanyan & Moberg 2012; Crane et al. 2010	Arushanyan and Moberg 2012 assumed 3-year lifespan. Crane et al. 2010 used a 3-year lifespan from Apple for their analysis.
				4	Kozak 2003; Crane et al. 2010	Kozak 2003 lifespan based on 4-year college. Crane et al. 2010 noted 4 years as a technical life.
E-reader	3	2	4		Same as tablet	
CRT monitor	4.1	2.9	5.5	6	Eugster 2007	First life (China, 2000-2005)
				4	NSC 1999; Socolof et al. 2001; Roth et la. 2002	First life-business
				4	Kawamoto et al. 2001	IRS deprecation guidelines
				9	US EPA 2011	Average life (total)
				7	US EPA 2011	Residential. Assumed used 7 years before entering storage

Product	Baseline	Low	High	Lifespan (years)	Sources	Notes
LCD monitor	4.1	2.9	5.5	6	Eugster 2007	First life (China, 2000-2005), assumption
				4	Socolof et al. 2001	First life- used same assumption on first life as the CRT
				9	U.S. EPA 2011	Average life (total)
				7	U.S. EPA 2011	Residential; assumed used 7 years before entering storage
Printer	6	7.1	8.8	8.8	U.S. EPA 2011; NIES 2013	Average total lifespan, 2004
				7	U.S. EPA 2011	Residential/Life before entering storage
				7.1	NIES 2013 (also noted in Oguchi et al. 2008)	Includes multiple lives/storage, based on household survey 2003
				6	Kawamoto et al. 2002 and Koomey et al. 1995	IRS depreciation guideline
Basic mobile phone	2.5	1.5	3	2.5	Williams 2008	Replacement interval (combined smart and basic mobile phones)
				3	Eugster 2007	First life China/not say if smart or basic mobile phone
				1.5	Bhui et al. 2004; Fishbein 2002; EPA 2004; Neira et al. 2006	Economic life (and opportunity to renew before 2 year contract)

Product	Baseline	Low	High	Lifespan (years)	Sources	Notes
Smart-phone	2.5	1.5	3		Same as basic mobile phone	
CRT TV	11	7.7	12	7.7	Williams 2008	Replacement interval
				12	Oguchi et al. 2008	2003; included storage, multiple uses
				10	Eugster 2007	First life (China, 2000-2005)
				10-12 (used average of 11)	Zogg and Alberino 1998	na
				11	Huber 1997	na
				11	U.S. EPA 2011	Life before entering storage
LCD TV	6.4	5	9	6.4	Williams 2008	Replacement interval (combined LCD and plasma TVs)
				9	U.S. EPA 2011	First life/Life before entering storage
				7.2	Oguchi et al.2008	Year/type of lifespan not clear
				5	Eugster 2007	First life (China, 2000-2005)

Product	Baseline	Low	High	Lifespan (years)	Sources	Notes
Plasma TV	6.4	5	9	6.4	Williams 2008	Replacement interval (combined LCD and plasma TVs)
				9	U.S. EPA 2011	First life/Life before entering storage
				7.4	Oguchi et al. 2008	Year/type of lifespan not clear
				5	Eugster 2007	First life (China, 2000-2005)
VCR	6.8	5.4	11	5.4	Williams 2008	Replacement interval (combined with DVD player)
				11	Zogg and Alberino 1998	No information
				6.8	NIES 2013	2003 survey of Japanese households; duration first life-no storage
DVD player	5.4	4.3	7.4	5.4	Williams 2008	Replacement interval (combined with VCR)
				7.2	Oguchi et al.2008	Multiple uses, includes storage; 2003
				4.3	NIES 2013	No storage, first life; 2004; based on survey of Japanese households
Blu-ray player	5.4	4.3	7.4		Assumed to be the same as DVD player	

Product	Baseline	Low	High	Lifespan (years)	Sources	Notes
Cam-corder	6.6	4.2	7.2	4.2	Williams 2008	Replacement interval (combined camera and camcorder)
				7.2	Oguchi et al. 2008	Multiple uses and storage/year unknown
				6.6	NIES database	First life, no storage; based on 2004 survey of Japanese households
Camera	4.2	2.8	6.8	4.2	Williams 2008	Replacement interval (combined camera and camcorder)
				6.8	Oguchi et al. 2008	Multiple uses and storage/year unknown
				2.8	NIES 2013	No storage, first life; 2004; based on survey of Japanese households
Gaming console	4.2	4	5	5	Snow 2012, Loftus 2013	Business cycle
				4.2	Williams 2008	Replacement interval
				4	Huber 1997	No information
MP3 player	3.6	3.6	4.9	4.9	Oguchi et al. 2008	Multiple uses and storage/year unknown
				3.6	Williams 2008	Replacement interval

4.2.4 Calculation of Operational Energy

The use phase energy phase was derived from each product's average energy consumption per power mode and time spent in each mode for typical models as reported in trade industry reports (e.g., Roth and McKenney 2007; Urban et al. 2011) and governmental reports (e.g., Zogg and Alberino 1998; Bensch et al. 2010). For modeled years where these data were not available, energy consumption and usage per mode or unit energy consumption (UEC) data were extrapolated from adjacent years. A full description of data, extrapolation, and sources is available in the appendices (Section 7.2.8, Tables S-25 to S-45). The average UEC (kWh per year) per product was converted to cumulative energy demand based on a factor of 11.3 MJ cumulative energy demand per kWh of electricity generated (U.S. EPA 2006; Keolian and Lewis 1997) to account for upstream energy inputs, inefficiencies, and transmission losses.

When a household owned multiple devices of the same type (observed for TVs and desktop computers), the products' usage was assumed to vary depending on whether they were the primary device in use or secondary devices used less frequently. Distinctions in use phase energy for primary and secondary products are described in the appendices and followed reported usage patterns in technical and trade publications (Rosen et al. 1999; Ostendorp 2005; Roth and McKenney 2007; Urban et al. 2011). For example, in 2007, an average U.S. household owned 3.35 TVs, which included plasma, LCD, and CRT models. In this case, it was assumed that if a household had a plasma TV (0.11 per household) or LCD TV (0.30 per household), they would automatically be considered "primary" televisions, likely purchased and used for the main household TV viewing. The remaining households (1.0-0.11-0.30 = 0.59) would have used 0.59 CRTs per household as primary viewing devices and any remaining CRT TVs (2.94-0.59 = 2.35 per household) would be considered using secondary usage patterns. The appendices provide a sample calculation depicting the division of use phase energy for primary and secondary TVs and desktop computers (Section 2.7.2) and a summary of use phase energy values used as model inputs is shown in Table 6.

Table 6 Average annual unit energy consumption (UEC) (kWh/year) input values

	Device	**1992**	**1997**	**2002**	**2007**
1992	CRT TV (Primary)	152	171	192	214
	CRT TV (Secondary)	105	118	137	147
	VCR	69	57	53	46
	Desktop (Primary)	50	46	89	218
	Desktop (Secondary)	na	na	74	173
	CRT monitor	99	106	113	121
	Printer	31	30	28	27
	Gaming console	24	22	44	65
	Basic mobile phone	10	7	5	3
	LCD monitor	74	68	68	65
	Laptop	28	29	46	73
1997	Camcorder	na	3	3	3
	Camera	na	5	5	6
2002	DVD player	na	na	43	25
	MP3 player	na	na	6	5
	Smartphone	na	na	5	4
	LCD TV (Primary)	na	na	142	229
2007	Plasma (Primary)	na	na	na	568
	Blu-ray player	na	na	na	29
	Tablet	na	na	na	7
	E-reader	na	na	na	12

Note: UEC values per device are organized by the year introduced into the community. If a product is not included the community in a specified year (e.g., plasma TV in 1992), the price is listed as ‘na.’

4.2.5 Defining Intervention Strategies and Future Consumption Scenario Analysis

To further demonstrate the utility of the consumption-weighted LCA approach, the method was used to analyze the extent to which common intervention strategies (e.g., green production and use behaviors) and/or radical changes in the community structure can reduce the net impact.

Two common production-oriented strategies were considered: increase energy efficiency during use by 10% and/or extend product lifespan by 10%. A 10% energy efficiency improvement per device is consistent with conservative estimates by U.S. EPA Energy Star® program, which suggested that building occupants could achieve at least 10% in energy savings through education and behavior changes (2012), like unplugging devices not in use, using smart power strips to further reduce standby energy (U.S. EPA 2012; U.S. DOE 2013; NEEP 2013), or implementing common denominator strategies (efficiency standards for chargers) (Porter et al. 2006). Extending lifespan has been recommended as another key strategy to manage life cycle impacts of products with short innovation cycles (e.g., laptops and desktops) (Williams 2004; Deng et al. 2011; Cooper 2005). Product lifetime extension could be achieved with more durable materials, enhanced maintenance services, or product labeling (Cooper 2005; Cox et al. 2013). Descriptions of scenarios and devices included in each are noted in Table 7 below.

Table 7 Descriptions of green intervention strategies and devices included

Sensitivity Analysis		Description	Type of Devices	Rationale
1.	Energy efficiency	Reduce each product's use phase energy by 10%, no change in consumption	All devices included in the baseline.	U.S. EPA 2012, 2014 EPEAT 2014
2.	Lifetime extension	Extend the lifespan of each product by 10%, no change in consumption	All devices included in the baseline.	Williams 2004 Deng et al. 2011
Scenario Analysis		**Description**	**Type of Devices**	**Rationale**
3.	Smart communication & image capturing	Reduce consumption of older devices. Maximize functionality with multifunctional, 'convergent' devices, by focusing on devices providing voice communication functionality	Desktop, laptop, tablet, printer, CRT monitor, smartphone, CRT TV, LCD TV, plasma TV, VCR, DVD player, blu-ray player, and gaming console	Ryen et al. 2014 Figge et al. 2014
4.	Mobile data processing & browsing	Reduce consumption of older devices. Maximize functionality with multifunctional, 'convergent' devices, by focusing on devices on devices that provide data analysis and manipulation functionality	Laptop, tablet, printer, basic mobile phone, smartphone, CRT TV, LCD TV, plasma TV, VCR, DVD player, blu-ray player, camera, camcorder, and gaming console	See #3
5.	On demand video viewing	Reduce consumption of older devices. Maximize functionality with multifunctional, 'convergent' devices, by focusing on devices that provide data analysis and manipulation functionality on audio video playback and recording viewing functionality	Laptop, tablet, printer, basic mobile phone, smartphone, LCD TV, blu-ray player, camera, camcorder, and gaming console	See #3

Scenario Analysis		Description	Type of Devices	Rationale
6.	Digital streamlined	Fewer digital (mostly multifunctional) devices meet the household's total functional needs	Laptop, tablet, printer, smartphone, LCD TV, and gaming console	Jackson 2005 NEEP 2013 Ryen et al. 2014 Figge et al. 2014
7.	Digital streamlined + energy efficiency	#6 plus, reduce each product included in the digital streamlined scenario use phase energy by 10%	All devices included in the digital streamlined scenario	See #6
8.	Digital Streamlined + Lifespan Extension	#6, plus, extend lifespan of each product included in the digital streamlined scenario by 10%	All devices included in the digital streamlined scenario	See #6

Note: The *consumption-weighted LCA* methodology is tested with different sensitivity and scenario analyses to illustrate changes in energy impacts for common strategies (improving each product's energy efficiency without changing consumption) or enhanced green strategies (digital streamlined) in which changes of consumption occur, or digital streamlined + strategies (combination of digital streamlined and energy efficiency and a combination of digital streamlined and lifespan extension).

To assess potential changes in the net energy impact due to shifts in consumption, multiple scenarios were developed to reflect the ongoing emergence of small, mobile devices and the potential for design and purchase of fewer, functionally convergent devices, as suggested in Ryen et al.(2014). Functionally convergent or hybrid devices that provide multiple functions have been gaining momentum in the market, as seen by blending the following: phone and tablet ('phablet') (NEEP 2013; DesMarais 2013; Venture Beat 2014), high resolution camera and smartphone (e.g., Nokia Lumia 1020) (CNET 2013), and smart TV, gaming console, and desktop computer (Hachman 2014). Future consumption scenarios consisted of three test cases that represented a potential shift in consumption away from many single- or few-function products towards minimizing the total number of highly multi-functional products, specifically for categories of devices used in 1) voice communication (e.g., phone calls), 2) data manipulation (e.g., word processing, surfing the internet), and 3) combined audio visual playback/recording functionality (e.g., recording or watching movies or music). An extreme test case, the 'digital streamlined' scenario, was based on maximum deployment of six functionally convergent devices (see Table 7 for additional information).

Percent savings (S) from the baseline net energy (E_B) values on a 'per product' (pp) and 'per community' (pc) basis for conventional and converging device scenarios was calculated as shown in Equations 13 to 14:

$$S_{pp,i} = (E_{B,pp,i} – E_{EE,pp,i})/ E_{B,pp,i} \tag{13}$$

$$S_{pc,i} = ((E_{B,pc,i} – E_{EE,pc,i})/ E_{B,pc,i} \tag{14}$$

The per product savings for device ($S_{pp,i}$) was calculated as the 2007 baseline energy ($E_{B,pp,i}$) on a 'per product' level for device (i) minus energy from an intervention strategy such as energy efficiency ($E_{EE,pp,i}$) divided by the baseline energy for that product ($E_{B,pp,i}$). Savings that took consumption into account for each individual product is shown in equation 14. The 'per community' saving (S_{pc}) for each individual device (i) was the difference between the baseline 2007 community level energy ($E_{B,pc,i}$) and energy from an intervention strategy such as energy efficiency ($E_{EE,pc,i}$) divided by the baseline energy for that product $E_{B,pc,i}$.

Calculating savings by considering the community as a *whole* (S_C) on a per product and 'per community' basis was also calculated as shown in Equations 15-16:

$$S_{C,pp} = (E_{B,C,pp} – E_{EE,C,pp})/ E_{B,C,pp} \tag{15}$$

$$S_{C,pc} = ((E_{B,C,pc} – E_{EE,C,pc})/ E_{B,C,pc} \tag{16}$$

The percent savings for the entire community on a 'per product' basis ($S_{C,pp}$) (i.e., one of each product is owned) was difference between the baseline 2007 net energy for the community on a 'per product' level ($E_{B,C,pp}$) and the net energy for the community using an intervention strategy such as energy efficiency ($E_{EE,C,pp}$), all divided by the baseline net community on the per product level ($E_{B,C,pp,}$). The 'per community' savings for the entire community was calculated as the difference between the baseline 2007 community level energy ($E_{B,C,pc}$) and the net energy after applying an intervention strategy such as energy efficiency ($E_{EE,C,pc}$), all divided by the baseline energy for that product $E_{B,C,pc}$).

4.3. Results and Discussion

4.3.1. Model Results

The net annualized energy impact for electronics purchased and used by an average U.S. household is presented for all products, assessed independently, or ‘per product’ (Figure 13a) and on a consumption-weighted basis for the entire household, or ‘per community’ (Figure 13b) (see also Table S-46). If products are accounted for independently (i.e., the impact of producing one of each product is summed for all products in the household for a modeled year), the net impact appears to increase over time (Figure 13a), corresponding to the introduction of new products into the household. When net impact is disaggregated into assemblages, stable (1992 assemblage) or declining (1997 and 2002 groupings) trends are observed, which arise from a relatively flat manufacturing intensity over time (MJ/$ in the EIO model), level or declining prices ($/product, suggesting manufacturing improvements), and/or increasing product use phase efficiencies.

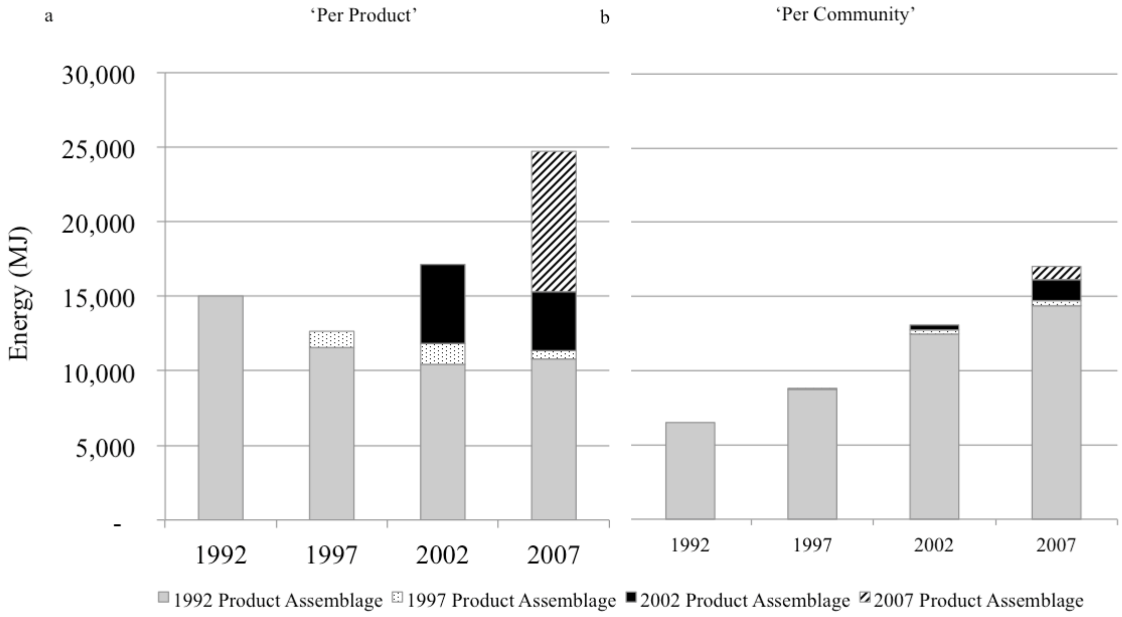


Figure 13 Dynamic changes in net annualized energy impact. Data within each community modeled year is aggregated by assemblages or the year devices are introduced into the community (indicated by shadings), and compared on a ‘per product’ (a) and ‘per community’ basis (b).

When accounting for actual consumption of each product, the community's net annualized energy impact also increases over time (Figure 13b), but not due to the purchase of newly introduced products (e.g., plasma and LCD TVs), as these devices have very low ownership rates in the time period analyzed. Instead, the increase is almost completely attributed to increasing accumulation of earlier products that have become essential components of a household's social, communication, and entertainment activities (Figure 13b). For example, households in 2007 owned an average of 3 CRT TVs. The resulting net impact of the electronic product community is significant; equivalent to nearly 30% of the average annual fuel consumed by an average passenger vehicle in 2007 (U.S. BTS 2014) (see Table S-47 in the appendices). While energy services like transportation and climate-control garner far more policy attention than consumer electronics, they are actually delivered by a community of far fewer different products (e.g., automobile and gas furnace).

When the net impact for the electronic product community is partitioned, the products responsible for the greatest impact vary significantly depending on if a 'per product' (Figure 14a) or 'per community' (Figure 14b) approach is used. For example, the plasma TV, as one of the highest contributors to the aggregate impact (Figure 14a), appears to be a prime candidate for environmental improvement. While such energy gains would certainly not be a detriment, they may make little to no difference for the community as a whole, because ownership of plasma TV devices is low during this time period. Instead, the CRT TV and desktop computer are the main contributors to the entire household impact (Figure 14b). Not only does their ownership expand in this time period (close to 40 percent for a CRT TV and a three-fold increase for the desktop computer), their active usage (hours per year) increases (20 percent for the CRT TV and an 11-fold increase for the desktop computer), overshadowing any power mode energy efficiencies occurring at the same time (Table S-25 and S-33. Going beyond 2007, these products are certainly being replaced with newer technology (e.g., LCD TVs, laptops, or tablets), but the analysis demonstrates that prioritization for environmental improvement must account for actual consumption, which may lag the adoption.

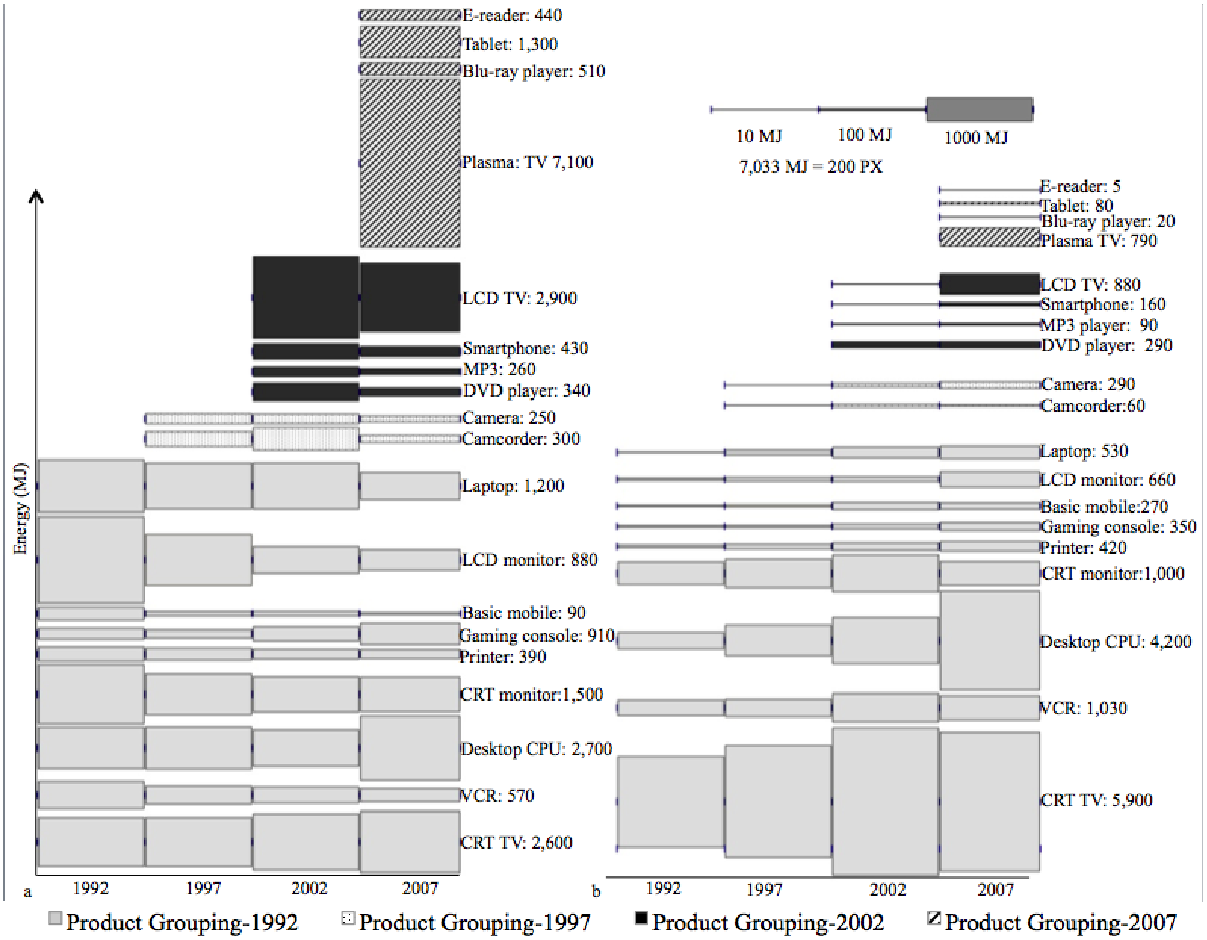


Figure 14 Partitioning the net annualized energy impact on a ‘per product’ (a) and consumption-weighted ‘per community’ (b) basis. Devices are shaded to indicate the assemblages or year introduced into the community. Numerical results at right of each figure are for 2007. Each product’s net impact (in MJ) is represented thickness or number of pixels (PX).

4.3.2 Sensitivity and Intervention Strategy Analysis

4.3.2.1 Sensitivity to Manufacturing IO Data

Because manufacturing of consumer electronics has shifted overseas, it is also important to understand changes in the household-level impact with IO-sector energy data based on Asian manufacturing processes. When comparing Asian-based IO manufacturing energy, the consumption-weighted (‘per community’) impact remains relatively constant from 2002 to 2007 (Figure 15), but is 1.5 times the U.S. community-level energy impact in 2007 (see Table 8). While on a ‘per product’ basis, the percent manufacturing contribution to the net impact decreases between 2002 and 2007 when using U.S.- and Asian-based IO manufacturing energy, the percent contribution of Asian-based manufacturing in 2007 is more than doubled that of the U.S. (Table 8 below and Table S-48 and S-49 in the appendices). There are several regional differences that contribute to this finding, but a primary distinction is that the contributing U.S. sectors have already gone through periods of growth, innovation, and now, stability, where relatively little further improvements are observed in the sector-specific energy intensity (MJ/$) over the time period in study.

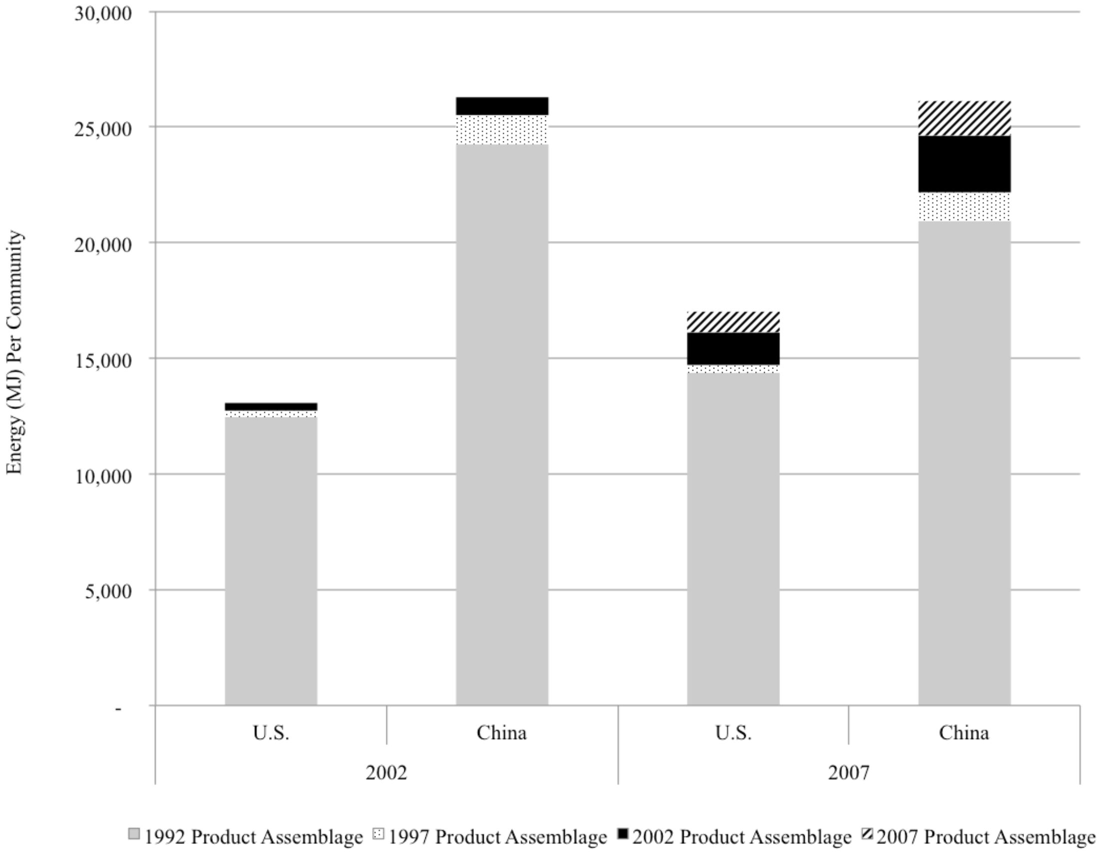


Figure 15 Comparison of net annualized energy impact on a consumption-weighted basis for the electronic product community using U.S.- and Asian-based manufacturing energy: 2002 and 2007. The color-coding identifies the year in which the product assemblages or groups of devices are introduced into the community.

On the other hand, China's electronic device manufacturing sectors are still experiencing production efficiency gains that outpace increasing consumption trends, illustrated by the decreasing contribution of the 1992 product grouping. However, consumption changes still dominate for some products, particularly the LCD TVs and smartphones introduced in 2002, which increased by 10- and 38-fold in net energy impact for the household from 2002 to 2007 (Table 8). In this case, increasing ownership (in addition to use phase energy consumption for the LCD TV) surpassed the manufacturing efficiency gains. In general though, if consumption trends continue as is, the future net energy impact for an average U.S. household consuming products produced in Asia will likely show similar trends as Figure 13b, once these sectors stabilize manufacturing energy intensity. Since the sensitivity analysis to manufacturing energy is based on average U.S. consumer prices, future work using global producer prices would refine the community-level impact.

Table 8 Net Annualized energy impact ('per community') with U.S.- and China-based manufacturing energy

		2002		**2007**	
	Device	**U.S.**	**China**	**U.S.**	**China**
1992	CRT TV	6,300	8,400	**2007**	7,010
	CRT TV	6,300	8,400	5900	70,10
	VCR	1,200	1,600	1,030	1,200
	Desktop	2,000	6,200	4,200	6,600
	CRT monitor	1,600	2,600	1,000	1,200
	Printer	320	710	420	750
	Gaming console	200	390	350	690
	Basic mobile phone	320	1500	270	990
	LCD monitor	190	480	660	1,070
	Laptop	430	2,400	530	1,400
1997	Camcorder	130	480	60	160
	Camera	150	770	290	1,080
2002	DVD player	260	530	290	380
	MP3 player	30	100	90	220
	Smartphone	10	80	170	790
	LCD TV	20	60	880	1,100
2007	Plasma TV	-	-	790	950
	Blu-Ray player	-	-	20	30
	Tablet	-	-	80	500
	E-reader	-	-	5	20
Total		13,100	26,300	17,020	26,100
Percent manufacturing (per product contribution)		44%	79%	22%	61%

Note: Devices are organized by year introduced into the community and adjusted to two significant figures (except for the totals that are shown in 3 significant figures). Totals may not sum due to rounding approximation. The percent contribution from manufacturing energy (on a ‘per product’ basis) is noted in the last row.

4.3.2.2 Evaluation of Intervention Strategies

This research thus far has demonstrated the utility of the consumption-weighted LCA methodology to illustrate the rising energy impact for a community of consumer electronics owned by an average U.S. household. It stands to reason that this methodology can also be applied to determine the effectiveness of common intervention strategies (energy efficiency and lifetime extension), as well as more radical changes to the community’s overall structure.

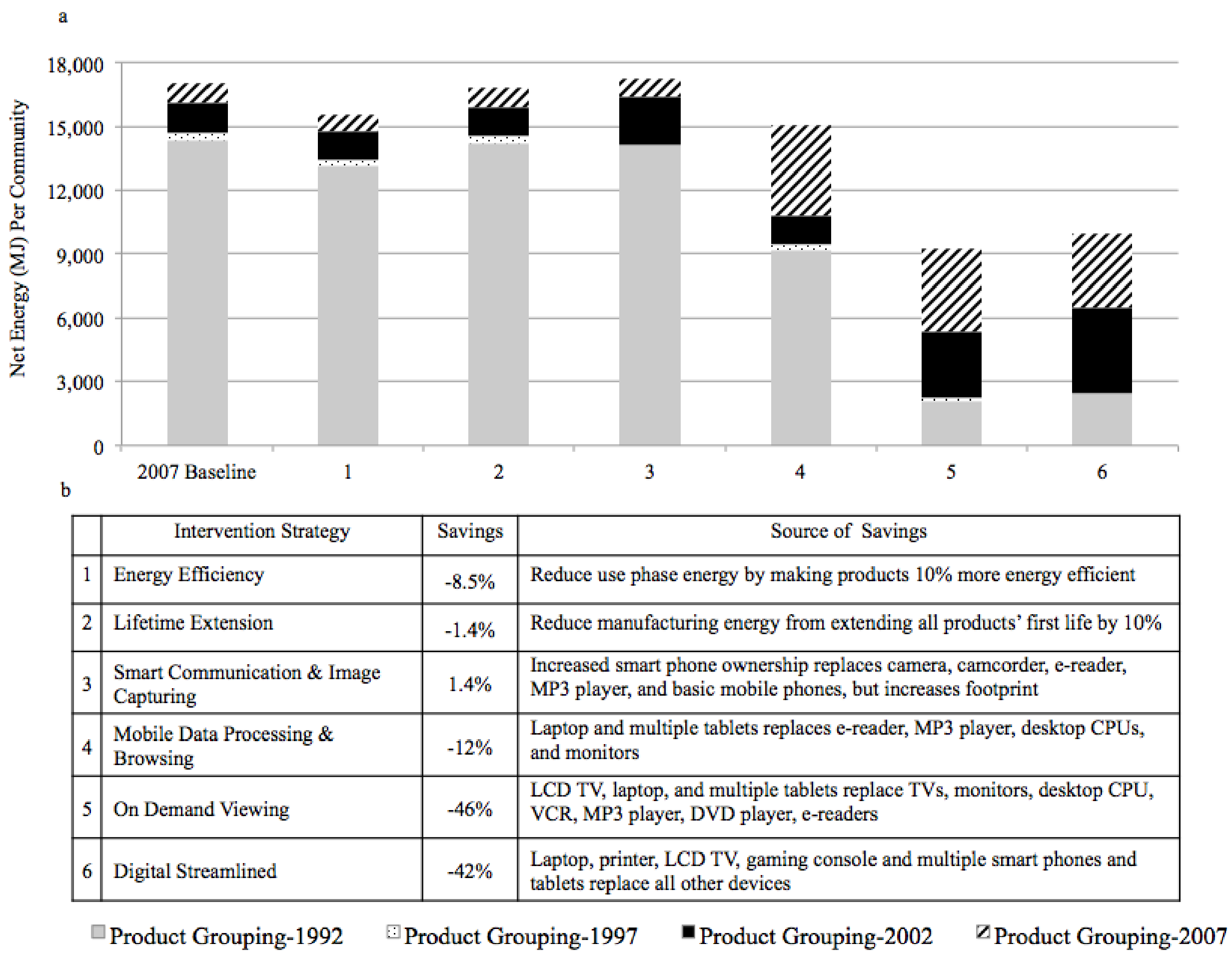
When considering energy efficiency and lifespan extension, these strategies show promise on a ‘per product’ basis, but actually yield incremental energy reductions for the product community after accounting for consumption. For example, a 10% reduction in use phase energy can lead to as much as a 9% decrease in energy impact per product for the CRT TV, VCR, desktop computer, and plasma TV, all of which have high use phase contributions to their total life cycle impact. Similarly, a 10% increase in lifespan creates 6-8% decrease in energy impact per product for the camcorder, camera, smartphone, MP3 player, e-reader, and tablet, which have high manufacturing phase impacts (See Table S-9). However, these benefits are diminished when consumption is taken into consideration, as many of the products with high individual improvements are actually owned at low rates within the community. Impacts per individual product (examined on a ‘per product’ and ‘per community’ basis) resulting from the conventional strategies are shown in Table 9 below, as well as Table S-50 in the appendices.

Table 9 Percent savings from baseline net energy annualized impact for the green intervention strategies

		Energy Efficiency		**Lifespan Extension**	
		PP	**PC**	**PP**	**PC**
1992	CRT TV	-9.3%	-3.1%	-0.7%	-0.3%
	VCR	-9.1%	-0.6%	-0.8%	-0.05%
	Desktop	-9.0%	-2.2%	-0.9%	-0.2%
	CRT Monitor	-9.4%	-0.6%	-0.5%	-0.03%
	Printer	-7.9%	-0.2%	-1.9%	-0.05%
	Gaming console	-8.1%	-0.2%	-1.7%	-0.03%
	Basic mobile phone	-3.5%	-0.05%	-5.9%	-0.1%
	LCD Monitor	-8.3%	-0.3%	-1.5%	-0.06%
	Laptop	-7.0%	-0.2%	-2.7%	-0.1%
1997	Camcorder	-1.1%	-0.004%	-8.1%	-0.03%
	Camera	-2.6%	-0.04%	-6.7%	-0.1%
2002	DVD player	-8.2%	-0.14%	-1.6%	-0.03%
	MP3	-2.0%	-0.01%	-7.2%	-0.04%
	Smartphone	-1.0%	-0.01%	-8.2%	-0.08%
	LCD TV	-8.9%	-0.5%	-1.0%	-0.05%
2007	Plasma TV	-9.0%	-0.4%	-0.9%	-0.04%
	Blu-Ray Player	-6.3%	-0.01%	-3.4%	-0.003%
	Tablet	-0.6%	-0.003%	-8.5%	-0.04%
	E-reader	-3.1%	-0.001%	-6.3%	-0.002%
	Total	-7.8%	-8.5%	-2.0%	-1.4%

Note: The top five ranking products that contribute to savings (or increases in footprint) on per product (PP) or per community (PC) base are shaded in gray.

When considering the community *as a whole*, improving operational efficiency as a strategy (Figure 16a, strategy 1) results in community-level savings of 8.5% compared to the 2007 baseline (Figure 16a and 16b and Table S-50 in the appendices). However, to achieve this savings would require every product in the community to reach efficiency improvements of at least 10%, which could be difficult to achieve due to rapid changes in consumer preferences and shortened innovation cycles. In contrast, the conventional strategy of extending product lifespan (Figure 16a, strategy 2) yields incremental improvements (1.4%) for the entire community as shown in Figure 16b.



	Intervention Strategy	Savings	Source of Savings
1	Energy Efficiency	-8.5%	Reduce use phase energy by making products 10% more energy efficient
2	Lifetime Extension	-1.4%	Reduce manufacturing energy from extending all products' first life by 10%
3	Smart Communication & Image Capturing	1.4%	Increased smart phone ownership replaces camera, camcorder, e-reader, MP3 player, and basic mobile phones, but increases footprint
4	Mobile Data Processing & Browsing	-12%	Laptop and multiple tablets replaces e-reader, MP3 player, desktop CPUs, and monitors
5	On Demand Viewing	-46%	LCD TV, laptop, and multiple tablets replace TVs, monitors, desktop CPU, VCR, MP3 player, DVD player, e-readers
6	Digital Streamlined	-42%	Laptop, printer, LCD TV, gaming console and multiple smart phones and tablets replace all other devices

Figure 16 Comparison of baseline 2007 and resultant changes from conventional interventional strategies and future converging scenarios. For each strategy (a), shadings identify assemblages of products or years are introduced into the community. Resultant savings (negative percentages) or increases in the footprint (positive percentages) for each strategy are denoted on a 'per community' basis (b).

A sensitivity analysis on using low and high lifespans data points (Figure 17 and Table S-54 in the appendices) indicates a reduced net impact for the community as a whole by extending all products' lifespans on both a 'per product' and 'per community' basis. However, benefit of a reduced net impact diminishes over time due to the increasing consumption of more mobile products (mobile phones) with short lifespans and low adoption of newer stationary products (LCD TVs), which have long lifespans.

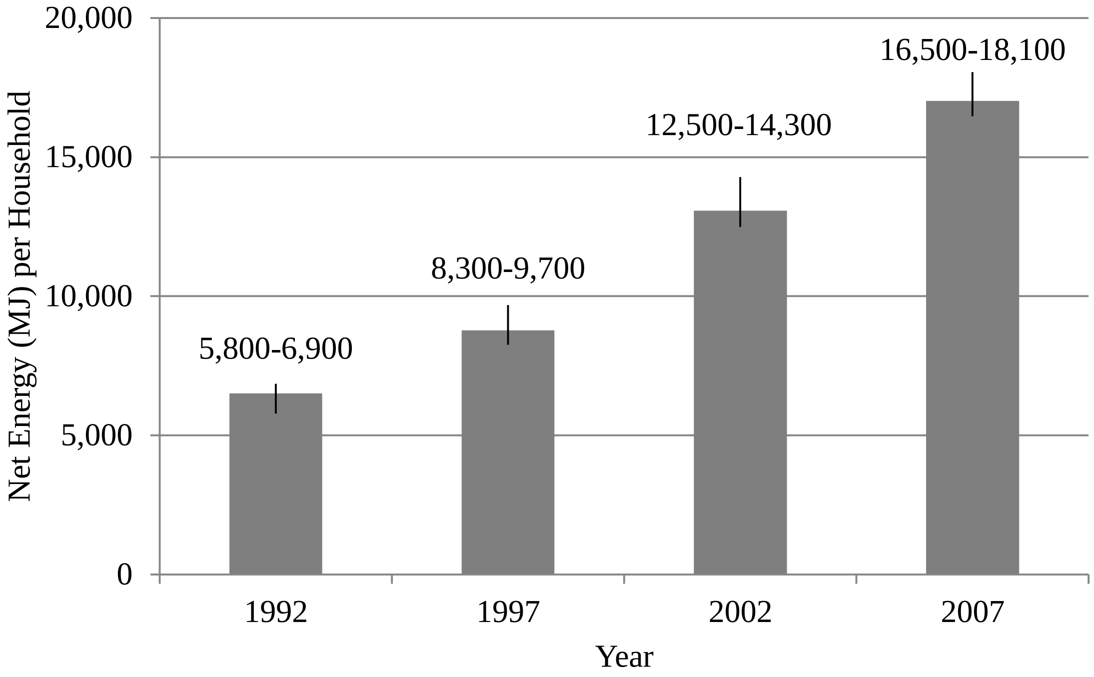


Figure 17 Range of net energy impact with high and low lifespans, on a 'per community' basis. This figure bounds the uncertainty associated with using variable product lifespan definitions on a per community basis. Error bars represent the range of net energy (MJ) from applying high lifespan data points to low lifespan data points.

In addition to conventional strategies, the consumption-weighted approach can quantify how potential future changes in product ownership associated with device convergence may ultimately influence overall net energy impact (See Figure 16 and Tables S-51 to S-53 in the appendices). In most cases, the model is very sensitive to fundamental changes in the community structure, such as if tablets were to largely replace desktop computers, monitors, e-readers, and MP3 players for providing mobile data processing and browsing functionality to consumers (Figure 16, strategy 4). Certain multifunctional products (e.g., tablet), like natural invasive species, could hypothetically disrupt the electronic product community by changing consumption patterns and reducing overall energy impacts (Ryen et al.2014). In the 'digital streamlined' scenario, as few as six types of products, each albeit owned at higher concentrations, could theoretically provide all required information, communication, and entertainment services used in a household (Ryen et al. 2014), which would result in a significant reduction in the net annualized energy impact for the entire community (Figure 16b, strategy 6). A majority of these savings is due to eliminating highly concentrated legacy products such as the CRT TV, desktop computer, CRT monitor, and VCR, which contribute over 70% of the 2007 baseline community-level impact. In the new consumption scenario, the highest impact products would then be the tablet and LCD TV. Then, appropriate product-level intervention strategy can be applied to maximize further improvements. For example, mobile devices with short lifespans (tablet) would likely benefit from a lifespan extension strategy and high-energy use devices (LCD TV) would benefit with an operational efficiency strategy (see Tables S-50 in the appendices).

Encouraging the design and ownership of functionally convergent devices as an energy reduction strategy for the electronic product community is consistent with current industry trends (NEEP 2013). For example, as digital content on the cloud increases, consumers are expected to "favor lighter, faster and fewer devices" (A.T. Kearny 2010, p.6), resulting in multi-functional devices prevailing over single function products (e.g., e-readers) as a content delivery system. Since consumers identify price and feature variety as purchasing decisions over energy efficiency (NEEP 2013), designing a fewer number of functionally convergent devices may be the catalyst to disrupt the 'unsustainable' community, significantly reduce overall energy impact, and move households onto a sustainable path that integrates both consumption and production improvement strategies.

4.3.2.3 Uncertainty

The authors recognize uncertainty is associated with the EIO LCA model and its inputs. While the EIO LCA model represents the average impact for an industry based on similarly produced devices, the impact can vary for products within the sector (Hendrickson et al. 2006). Finding dynamic use phase energy for 19 products was a challenge, there is more uncertainty associated with some products (smartphones, tablets, e-readers) than others due to limited data available in the literature. In addition, because prices are critical inputs and environmental impact is assumed to be linear to changes in sector economic activities (Hendrickson et al. 2006). However, uncertainties may arise from prices not actually reflecting the average annual U.S. or global price per good, or from the linearity assumed by the EIO LCA model. As noted previously, the uncertainty resulting from variable product lifespan definitions is bounded for a 'per community' analysis (assuming U.S.-based manufacturing energy) in Figure 17.

Uncertainty is also associated with the Asian-based manufacturing data. One contributing factor may be the aggregation of sectors in the U.S. and China EIO models. China-based IO manufacturing data is based on 42 sectors for 2002 and 135 sectors for 2007 (Chang et al. 2011), in comparison to the U.S. 2002 model, which is based on 428 sectors (CMU 2008). Other sources of uncertainty may be attributed to using of a U.S. rather than a global price, different mixture of fuel sources used to produce electricity in each country, or to the less efficient coal-based energy production plants in China.

4.4 Implications

As these results suggest, we can no longer ignore product communities when designing, producing, and consuming green devices. The consumption-weighted LCA methodology presented here is able to capture dynamic changes in the net environmental impact (annualized energy demand) for both production and consumption of an interrelated group or ‘community’ of consumer electronics in an average U.S. household. This approach is important since consumer electronics are experiencing rapid changes in consumption patterns and functional preferences (Barns 2014). Considering products as a community answers a call for LCA to broaden its scale, address rebound, behavior, and price effects, while balancing the need for a simplified assessment tool (Hertwich 2005; Guinée et al. 2010). The consumption-weighted results are also more relevant for design, production, and policy changes, which must target products that are high impact in their own right (‘per product’) as well as those whose net contribution becomes significant due to high ownership rate (‘per community’). Applying the most suitable conventional strategy for each product can then maximize additional improvements. The consumption-weighted LCA methodology can therefore assist governmental and industry decision makers as they propose and implement future policies, standards, and legislation to manage life cycle impacts for groups of emerging computing technologies. Just as Chapters III and IV successfully demonstrated how to adapt and apply the biological ecology concept of community ecology to a group of consumer electronics owned by an average U.S. household, Chapter V seeks to adapt the concept of foraging to characterize how e-waste processing business select how to handle or process waste product outflows from electronic product community.

V. Evaluating Foraging Decisions

5.1. Introduction

Due in part to the increasing consumption of products, technological progress, and evolving composition of the community structure, the outflow from the electronic product community has resulted in an increasing amount and diverse mix of obsolete devices ('e-waste'). As a result, the products pose promising business opportunities from the recovery of valuable materials and components, as well as potential concerns of negative impacts to human health and the environment if managed informally (Widmer 2005; Williams 2011). These opposing situations is attributed to products containing: 1) toxic substances (e.g., mercury, lead), 2) abundant, low value materials (i.e., plastic from computer casing), and 3) low volume, high value material (precious metals found in printed circuit boards) (Widmer et al. 2005; Robinson 2008). Therefore, efficient recovery of materials and components is important to companies built around the collection and processing (i.e., recycling, reselling, and final disposition) of e-waste because certain components such as a system board contain a small concentration of valuable precious metals such as silver, platinum, and gold (Park and Fray 2009).

Sustainable management of obsolete electronics in the U.S. centers on the e-waste processing business (aka recycler). The role of a responsible e-waste processing business is to collect discarded products and conduct a variety of EOL management strategies (i.e., recycling, reselling, and final disposition) that follow a 'patchwork' of product-oriented, state-level regulations (e.g., NYS Electronic Equipment Recycling and Reuse Act) (Nnorom and Osibanjo 2008; Kahhat et al. 2008; Hickle 2014). In the U.S., e-waste processing strategies have been primarily fixated on improving operational economics due to the lack of unifying federal guidelines (Nnorom and Osibanjo 2008; Kahhat et al. 2008; Hickle 2014) and a historical focus on 'free market' thinking (Kahhat et al. 2008).

The increasingly diverse waste stream resulting from the electronic product community impacts a variety of decisions for the e-waste processing business: where to site facilities, which processing activity to employ for each product, and what collection strategies to use to obtain products for processing (i.e., drop off at the facility, actively search for discarded products from businesses or institutions, or utilize decentralized drop off sites).

A spectrum of EOL processing activities is leveraged to earn profits, including: 1) triage (sorting and testing), 2) data destruction, 3) refurbishment, reuse, and resale, 4) demanufacturing into subassemblies and components (including resale of these items), 5) depollution, material separation, and mechanical processing of similar and mixed materials, and 6) refining/smelting of metals (GEC 2009). Most facilities engage in some form of demanufacturing or manual disassembly to isolate and sell components for a higher commodity scrap value (GEC 2009). However, labor costs and uncertainties associated with locating and accessing high value components is a challenge. Another common strategy, mechanical processing or shredding of the products and components, is associated with high fixed costs from the equipment, but lower overall operational costs. While shredding may be perceived as a more cost effective strategy compared to disassembly, variable material recovery efficiencies may yield lower overall value in comparison to the disassembly process. However, uncertainties related to changes in a product's material composition, the type and location of hazardous materials and/or new materials, and accessibility to high valued components due to limited bill of material data and evolving consumer preferences (GEC 2009) also challenge e-waste processing business decisions.

While voluntary design standards (EPEAT) are being devised to encourage efficient material recovery via disassembly, there is concern that only a small proportion of products may be suitable (GEC 2009). As noted in Chapter IV, smaller, mobile products with short lifespans are being introduced and adopted into the electronic product community. In addition, a European trend towards using automatic shredding processes (GEC 2009) suggests that disassembly may not be the appropriate strategy to process the electronic product community's outflows. In light of the changing electronic product community structure (Ryen et al. 2014), the literature has yet to answer following questions with quantitative data: Does it make economic sense to disassemble electronics, and consequently, should we design products for disassembly?

To help answer these questions, we look to ecological systems, in particular how animals forage or search for and process food. The behaviors employed by animals to search for and handle food (e.g., activities associated with capturing and consuming prey) and the extrinsic factors affecting these behaviors (e.g., weather, tides, or predators) are part of the ecological concept of optimal foraging theory (Pyke et al. 1977). Animals engaging in foraging have problems and choices: where to search for prey, what prey to eat, whether or not to pursue the prey, and when to leave the area where the prey is found (Perry and Pianka 1997; Stephens and Krebs 1986). For example, while foraging, gray squirrels choose between searching for and handling high quality, low abundance nuts or for highly abundant, low value nuts (Lewis 1980). Foraging has been widely studied by ecologists because feeding is critical to species' survival and reproduction (Pyke et al. 2007) and ultimately influences ecosystem level services and processes (O'Brien et al. 1990).

Therefore, optimal foraging theory may provide a source of models and methodologies to systematically quantify e-waste processing decisions. Traditionally, optimization models from the disassembly planning and operations research literature have primarily centered on the disassembly sequence of electronic device components to maximize profit (Lambert 2002), minimizing environmental impact for a given profit or cost (Hula et al. 2003), maximizing profit from component disassembly and bulk recycling (e.g., shredding) (Spengler 2003; Sodhi and Reimer 2001), minimizing costs (Deng and Shao 2009), or selecting an optimal disassembly sequence (Gupta et al. 2004). The disassembly planning and operations literature, however, appears to lack an underlying comprehensive framework to determine the quantities and/or characteristics of products to be selected for each processing strategy. The lack of a comprehensive quantitative tool has been affirmed by observations at e-waste processing businesses, in which employees still rely on heuristic information such as product color or age as a basis for selecting processing strategies (Sunnking 2010). Limited operations research has applied foraging models such as optimal facility siting based on honeybee behavior (Vera et al. 2010) or bacteria foraging behavior (Tabatabei and Vahidi 2011), as well as product disassembly analyses based on a complex ecological genetic algorithm (Hula et al. 2005) and self-guiding ant behavior (Tripathi et al. 2009). However, these studies fail to fully discuss or understand the connections and differences between applying ecological foraging concepts and models to industrial systems. Furthermore, it also appears that the operations research has not yet applied foraging models to e-waste processing decisions. Since ecologists began modeling foraging behavior with simple foraging models such as the optimal diet model (Charnov 1976a, 1976b), it stands to reason that e-waste processing decision models should begin with simple rather than complex optimal foraging theory models.

5.2.Methodology

5.2.1. Goal, Scope, and Overview

The purpose of this research was to demonstrate the applicability of biological ecology's optimal foraging theory models as an alternative means to analyze EOL processing decisions for an increasingly diverse e-waste stream. To achieve this goal, a novel e-*waste foraging model*, which was based on the classic optimal diet model (Charnov 1976a, 1976b; Krebs 1980; Stephens and Krebs 1986), was developed and compared to a conventional profit maximization model. Just as ecological models are used in an attempt to understand mechanisms driving feeding decisions in natural systems (Stephens and Krebs 1986), this research was the first step towards building a holistic framework to help quantify the type of products and components that should be disassembled or shredded and identify other factors (e.g., scrap component values or recovery efficiencies) that would influence processing decisions. By providing a systematic framework rooted in ecological models, this research also tackled a need for the field of industrial ecology to become more grounded in the source science of ecology (Templet 2004; Wells and Darby 2006; Mayer 2008; Jensen et al. 2011).

First, a relevant foraging model from ecology was identified after reviewing the traits and strategies associated with ecological organisms. Then the foraging model concepts and parameters were adapted from its biological basis into terminology germane to the electronics waste recycling industry. Next, the e-waste foraging model and its operations research counterpart, a conventional profit maximization model, were parameterized with data from the test cases. The 2008 Elitebook 6930 notebook and 2008 iPhone 3G were selected as test cases because these products were part of functional groups that have undergone rapid changes in functional capacity and consumption (Ryen et al. 2014 as noted also in Chapter III). Conventional profit maximization model results were compared to the e-waste foraging model results to identify similarities and differences between each model. Sensitivity analyses were conducted on both models' parameters to understand how certain inputs influenced processing decisions at the component level and to test the robustness of the models. For the profit maximization model, a futuristic scenario analysis explored how a completely modular design would impact decisions.

5.2.2. Foraging Model Selection

Before determining which ecological model would be applicable to the electronic waste processing business, first one must understand the traits and feeding strategies of natural organisms.

5.2.2.1. Comparison of Traits and Strategies Used by Natural Foragers

In ecology, predators would generally leverage three different types of foraging modes: sit and wait (e.g., lion waiting and then suddenly moving to attack or ambush the prey), widely ranging (e.g., ungulate actively moving or searching for grass to chew), or a combination of both. A predator using both strategies (saltatory) would be observed to have 'stop and go' patterns related to its movements and distance (O'Brien et al. 1990). Foraging modes are influenced by the predator's characteristics (e.g., size, energy requirements, or range size) and prey traits (e.g., mobility, type, or size) (Pianka 1973; O'Brien et al. 1990; Evans and O'Brien 1988; Pough et al. 2009). Different organisms within species, such as the extant lizard species, have been observed to employ a range of foraging modes and behaviors. For example, Iguanian lizards 'sit and wait' for prey, in contrast to Autarchoglossan lizards that actively search for prey. As a result, both lizard species have evolved to use different chewing or processing activities to handle the prey (McBrayer and Reilly 2002). Scavengers in Bialowieza Primal Forest have been observed to use different foraging strategies while adapting to changing extrinsic factors such as temperature, snow coverage, and tree coverage (protection from other predators) (Selva et al. 2005).

In addition to having different foraging modes, organisms have been observed to handle (i.e., process and consume) prey differently. For example, the octopus (*O. minus)* was observed to conduct extensive handling activities (e.g., drilling) in order to access and consume prey protected by shells (e.g., gastropods or bivalves) (McQuaid 1994; Cortez et al. 1998). Grazing species (e.g., mammalian herbivores) were observed to consume every bite of food as each bite was encountered (Spalinger and Hobbs 1992). Semi-sessile or stationary species, bivalves (e.g., mussels, oysters, and scallops), have evolved to utilize an efficient filtering mechanism to consume a large amount of phytoplankton and other suspended particulate matter it would come into contact with and then discharge undigested organic and inorganic material as waste (e.g., faeces) (Zhou et al. 2006).

To understand how foraging models could be applied to the processing of e-waste, ecological foraging modes and organism traits were compared to the e-waste processing business and then translated into industrial equivalents. To begin, it was assumed that the predator was the e-waste processing business (i.e., e-waste forager) and prey were the obsolete devices from the electronic product community. E-waste processing business, like their ecological counterparts, engage in a range of foraging modes and handling activities. For example, an e-waste forager could actively search for and travel to decentralized collection programs and/or to other companies and institutions to pick up obsolete products to be processed back at the facility. In addition, the e-waste forager could 'sit and wait' for customers to drop off obsolete products at the facility. Similar natural organisms, the e-waste forager would handle or process products with different techniques (e.g., disassembly or shredding) to access valuable components and materials within the products. In addition, just as a grazer or filter feeder would consume each bite of food, the e-waste forager in the model would process every product it encounters since manufacturers are required to provide free recycling in New York State (NYS) for certain products (e.g., mobile phones, computers, and televisions) per the NYS Electronic Equipment Recycling and Reuse Act and NYS Wireless Recycling Act (NYS DEC 2014).

5.2.2.2. Selection of an Ecological Foraging Model

Choosing an ecological foraging modeling was therefore a challenge due to the range of modes and strategies used by the e-waste processing business and difficulty in finding one type of predator with similar traits and foraging behaviors. Beginning with Emlen (1966) and MacArthur and Pianka (1966), a variety of foraging theories and models have been developed to understand the feeding decisions of ecological species. For example, central foraging theory (Ydenberg and Schmid-Hembel 1994; Olssom et al. 2008) has studied how birds locate and bring back food. The classic grazing model, developed by Spalinger and Hobbs (1992), was originally developed to understand the relationship between plant abundance and short term diet of grazing species, but has also explored the influence of bite size and site selection (Milne 1991) and regulation of nutrients (e.g., Simpson et al. 2004). Lehman (1976) modeled the influence of filtering and ingestion rates on the foraging behavior of the stationary, filter-feeding zoo plantkton species. However, all these foraging models appeared to stem from the classic optimal diet model.

A simple optimal diet model (e.g., Charnov 1976a), which was based on the Holling disc equation (1959) and sought to identify the optimal set and rank of prey types. This model assumed that animals maximized their energy intake during the foraging period to maintain fitness (Pyke et al. 1977; Schoener 1971) and made feeding decisions based on this assumption, without considering other factors such as the risk of predation (Krebs 1980; Charnov 1976a). This supposition was devised because the amount of time allocated to foraging was assumed to be fixed and optimal fitness occurred when the maximum amount of energy was gained (Pyke et al. 1977; Stephens and Krebs 1986). Other models have referred to species as a 'time minimizer' or having a fixed energy requirement. Minimizing time spent foraging would then allow for time to be spent on other activities such as mating or hiding from predators (Schoener 1971; Pyke et al. 1977; Stephens and Krebs 1986).

Because of the variety of ecological models available and lack of a parallel natural organism, the ecological optimal diet model was deemed as an appropriate starting point for quantifying e-waste processing decisions. The classic ecological optimal diet model maximized the net rate of energy intake (E_n/T), which consisted of the energy (E) expended while searching and handling prey per feeding period (T). The set feeding period (T) included time to search (T_S) and handle the prey (T_H), as shown in Equation 17:

$$\frac{E_n}{T} = \frac{E}{T_S + T_H} \qquad 17$$

Energy (E) would include the calories or biomass gained from consuming prey and the costs associated with searching for and handling prey. Early ecological studies assumed that prey with the highest profitability or energy content per unit of searching and handling time (E_n/T) would be selected (Emlen 1966; MacArthur and Pianka 1966; Charnov 1976a, 1976b).

5.2.3. Model Adaptation into Industrial Equivalents

After identifying the relevant ecological model, the parameters associated with Equation 17 were first translated into the e-waste equivalents as shown in Table 10. As noted previously, the models explored in this research assumed that the predator was the e-waste processing business (i.e., e-waste forager) and prey were the obsolete devices from the electronic product community. While the e-waste forager could potentially use a range of foraging modes, the model assumed that products were dropped off at the facility and therefore, employed a 'wait and see' strategy. Following the optimal diet model from ecology, the e-waste foraging model aimed to maximize energy (E_i) per unit of feeding time (T_i), which was translated as net profit ($) per second of time spent on processing each component (i) by shredding and disassembly.

Table 10 Translation of ecological model parameters into e-waste equivalents

Parameter	Ecological	E-waste
En/T	Net calories (or biomass) per foraging time unit (joules (or mass) per second)	Net profit gained per time unit spent processing ($ per second)
E_n	Net energy gained (joules or mass) while foraging	Net profit ($) in 2008 USD
T	Total time (seconds, minutes, or hours) spent foraging (searching and handling prey)	Total time (seconds) spent foraging (searching and handling) component (i) and product (j)
E_i	Energy gained (joules or mass) per unit of prey (i)	Total revenue or value ($) gained from disassembling or shredding each component (i)
$C_{S,i,}$	'Costs' or energy expended (joules or mass) while searching and locating prey (i)	Total costs ($) of searching, collecting, and managing each component (i)
$C_{H,i}$	'Cost' or energy expended (joules or mass) while subduing and handing prey (i)	Total costs ($) expended while processing each component (i) via shredding or disassembling
$T_{S,i}$	Time expended (seconds, minutes, or hours) while searching for prey (i)	Time (seconds) expended to search for products; assumed to be zero because products were dropped off
$T_{H,i}$	Time expended (seconds, minutes, or hours) while handling prey	Time (seconds) to shred products or disassemble each product to the component level

The e-waste equivalent parameters were then used to build the e-waste foraging model and conventional profit maximization model.

5.2.3.1. E-waste Foraging Model

The e-waste foraging model adapted the classic optimal diet model (E_n/T) as shown in Equation 18, and constraints were represented by Equations 19-23:

$$\forall_{i,j}$$

$$Max\ {}^{E_n}/_{T} = \sum_{i,j}\left(Q_{s,i} * \left(\frac{E_{s,i}-C_{s,i}-C_{S,s,i}}{T_{s,i}+T_{S,i}}\right)\right) + \left(Q_{d,i} * \left(\frac{E_{d,i}-C_{d,i}-C_{S,d,i}}{T_{d,i}+T_{S,i}}\right)\right) \qquad 18$$

$$Q_{s,j} + Q_{d,j} = q_j \qquad 19$$

$$q_j = 1 \qquad 20$$

$$Q_{s,i,j} \leq 1 \qquad 21$$

$$Q_{d,i,j} \leq 1 \qquad 22$$

$$T_S = 0 \qquad 23$$

For all products (j) and components (i), the net profit (E_n) per unit of EOL processing time (T) maximized the sum of revenues (E) for each strategy (i.e., shredding (s) or disassembling (d)), handling costs (C_d or C_s), and search costs (C_S) divided by the time needed to search for (T_S) and complete each EOL processing strategy (T_d or T_s). The model was assumed that the quantity of each product (j) (i.e., laptop and smartphone) available (q_j) for processing was one per product and the e-waste forager had to process all products. For each product (j), the model selected the number of components to be shredded ($Q_{s,i}$) or disassembled ($Q_{d,i}$). The time to search (T_S) for products was assumed to be zero since products were dropped off at the facility. This model began with a simple analysis of two products with quantities of one each, but could be adjusted to address a larger range and number of products and components. Because this is an exploratory model, no constraints were placed on the facility's processing capacity, time, or profit. The set feeding period (T) consisted of the total time spent on disassembling (T_d) and shredding (T_s) all the components. Without establishing these constraints, the e-waste foraging model could not predict or analyze if the e-waste forager was an energy maximizing or time minimizing species. However, just as early ecologists assumed animals conducted foraging activities efficiently to maximize fitness (Charnov 1976a), it was assumed that the e-waste forager would maximize its energy intake rate.

5.2.3.2.Conventional Profit Maximization Model

A conventional profit maximization model was developed with the same parameters as the e-waste foraging model in order to compare how both models optimized e-waste processing decisions. The profit maximization model is shown in Equation 24 and constraints in Equations 25-28:

$$\forall_{i,j}$$

$$Max\ E_n = \sum_{i,j}\big(Q_{s,i} * (E_{s,i} - C_{s,i} - C_{S,s,i})\big) + \big(Q_{d,i} * (E_{d,i} - C_{d,i} - C_{S,d,i})\big) \tag{24}$$

$$Q_{s,j} + Q_{d,j} = q_j \tag{25}$$

$$q_j = 1 \tag{26}$$

$$Q_{s,i,j} \leq 1 \tag{27}$$

$$Q_{d,i,j} \leq 1 \tag{28}$$

For all products (j) and components (i), the net profit (E_n) maximized the sum of revenues (E) for each strategy, handling costs (C_d or C_s), and search costs (C_S). The constraints were similar to the e-waste foraging model. However, the handling time parameters (T, T_d, T_s) were not included in this model. Disassembly time, as discussed in the next section, was integrated into the handling costs parameter.

Both the e-waste foraging and conventional profit maximization models sought to quantify the following overarching question: should products be shredded or disassembled. As shown in Figure 18, an e-waste forager's decision was based on inputs such as the number and type of products (and components) available for processing and the revenues and cost parameters associated with each processing strategy. Both models generated a net profit associated with the facility's processing decisions.

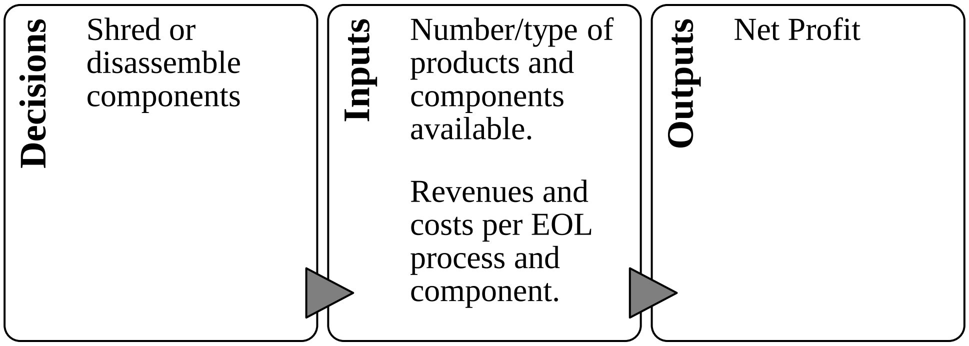


Figure 18 Overview of model decisions, inputs, and outputs

The both models made similar assumptions as the classic ecological foraging models each product was encountered one at a time, each product/component recognizable, and there were no other no predators (Stephens and Krebs 1986). In contrast to the classic model assumptions described in Hirvonen and Ranta (1996), the cost of handling (i.e., shredding or disassembling) was different rather than assumed to be the same, and products were not encountered randomly. Energy was also measured in dollars rather than calories or mass, as typically measured by ecologists.

5.2.4. Parameterization of the Models

The next step was to identify the data needed to parameterize the e-waste foraging and conventional profit maximization model inputs. A diagram detailing the model decision variables, inputs, and output is shown in Figure 19.

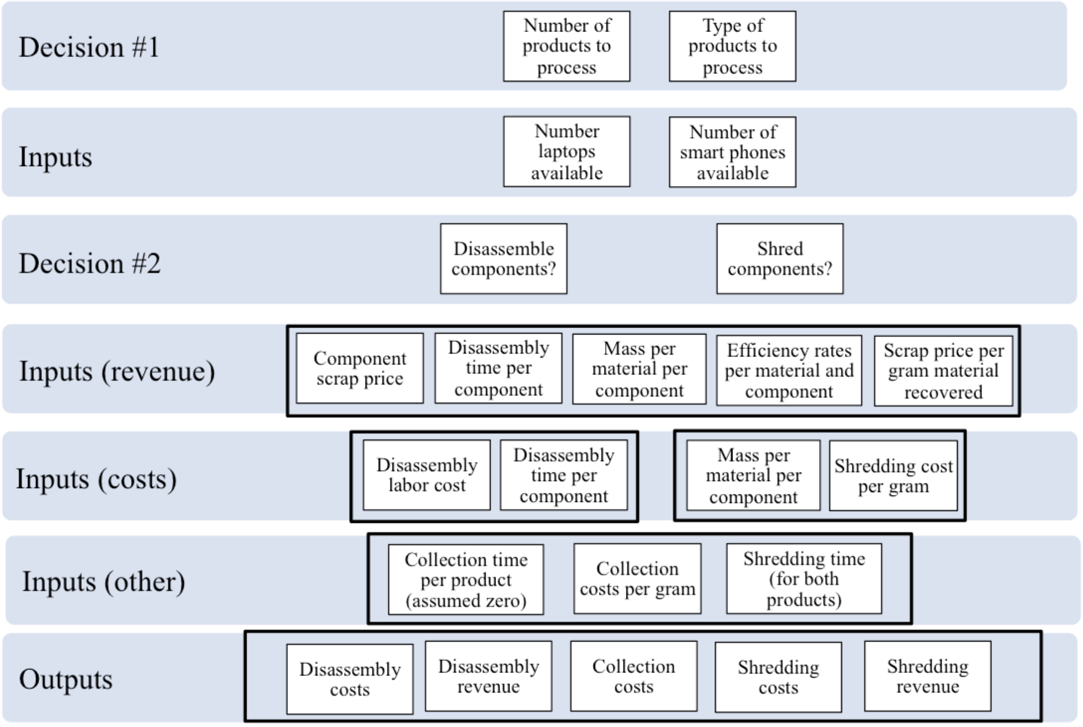


Figure 19 Detail of model parameters and decision variables

5.2.4.1. Disassembly parameters

Disassembly revenues were calculated as the product of the decision (number of components selected for disassembly, 1 or 0), efficiency rate per component, component mass (grams), and scrap component price ($ per gram). The efficiency rate of disassembling each component was assumed to be 100%. The component mass parameter for each product was derived directly from a disassembly conducted in the laboratory and the resultant bills of materials (RIT 2010; 2013). Component masses (Table 11), while within a range found in the literature (see appendix for more information), might not reflect an average of all laptops and smartphones purchased and used in 2008. Future work could address the uncertainty associated material masses used in this model with a range of component mass values. As noted in the appendix, the distribution of precious metals, ferrous, base metals, plastics, and other materials found in PCBs and lithium ion batteries were based on percentages based on the literature (Goosey et al. 2003; Cui and Zhang 2008; Paulino et al. 2008) and used in a proprietary report for Intel Company (RIT 2010). Determining a distribution of materials for these components was necessary since these components contain small quantities of high valued materials (e.g., gold) that may potentially impact EOL processing decisions. For this analysis, it was assumed that the system board and processor had the same material distribution as the smaller PCB components. Furthermore, due to limited information on the material composition of SIM cards found in smartphones, it was assumed that 60% of the component was PVC plastic and 40% was the PCB chip. A sensitivity analysis on PCB chip mass (including system boards, processor and SIM card) was conducted to see if a reduction in the size would influence decision changes. This sensitivity was initiated to address uncertainty of the materials, as well as the increasing adoption of smaller devices (as noted in the convergence of devices in Chapter III). In this sensitivity analysis, it was assumed that mass for each PCB component was reduced by 10%. Component scrap prices were based on spot 2014 prices from scrap industry website sites (Didion Orf Recycling 2014; Gold Chip Buyer 2014; Boardsort.com 2014; Rockaway Recycling 2014; Recycling E-Scrap 2014; Scrap Monster 2014) that were adjusted to 2008 dollars using the U.S. Bureau of Labor Statistics inflation calculator (2014). Except for the SIM card and laptop display, which had single scrap component price data points, an average of several data points were used to calculate the base case scrap component prices. An average PCB scrap price was applied to the small PCB components. A listing of component mass and average scrap prices used as model disassembly inputs is noted in Table 11:

Table 11 Disassembly revenue input variables

Component	Mass (grams)	Average scrap price (2008$)
Laptop		
LIB	240	$3.1 x 10^{-3}$
Battery PCB	3.0	$2.0 x 10^{-3}$
Hard Drive	130	$1.0 x 10^{-3}$
Hard Drive PCB	12	$2.0 x 10^{-3}$
Optical Drive	160	$2.0 x 10^{-4}$
Optical Drive PCBs	19	$2.0 x 10^{-3}$
Memory - other	7.0	$0
Memory PCB	10	$0.02
RTC Battery	3.0	$3.1 x 10^{-3}$
Display	504	$2.0 x 10^{-3}$
Display PCB	27	$2.0 x 10^{-3}$
Audio PCBs	46	$2.0 x 10^{-3}$
Blue tooth & other	59	$0
Fan and Heat Sink	72	$2.0 x 10^{-3}$
System Board PCB	204	$0.01
System board assembly - other	1.0	$0
Processor PCB	6.0	0.074647664
Housing	780	$0
Housing PCBs	30	$2.0 x 10^{-3}$
Wires	32	$1.0 x 10^{-3}$
Smartphone		
SIM card	0.30	$0.04
LCD Assembly	51	$0
System board PCB	14	$0.02
System board assembly - other	8.0	0
LIB	20	$3.0 x 10^{-3}$
LIB PCB	1.0	$2.0 x 10^{-3}$
Back Casing	38	0

Notes: This table identified the average scrap components prices, which were calculated from spot 2014 prices and then converted into 2008 dollars. Components without a scrap price were listed as zero. Data was adjusted to two significant figures.

To address the uncertainty associated with spot scrap component prices not reflecting the annual price variability, the sensitivity analysis compared low and high scrap component prices. The SIM card and laptop display assumed a 10% increase and decrease from the base case price in the sensitivity analysis since only one data point was available. For a listing data points and sources used to calculate disassembly revenue parameters, see the appendices.

The cost of disassembling each device was computed as the product of labor costs in 2008 ($) per hour and the cumulative time (seconds) to disassemble each component within the device. Labor costs were taken directly from the NYS Department of Labor stated 2008 minimum wage (PPI 2014), but a range of costs (10% lower and higher than the base case) were explored in the sensitivity analysis. Disassembly time for the laptop components were based on the timed disassembly of the laptop (RIT 2010) in the laboratory. Average disassembly times for a smartphone were calculated from the timed disassembly of a smartphone (RIT 2013) in the laboratory and disassembly time values taken from online videos (AppleiPodParts.com 2014; pdasmartdot.com 2014; DirectFix.com 2014). In cases that PCBs were integrated with other components (e.g., hard drive or optical drive), it was assumed that the PCB disassembly time was 10% of the total disassembly time for that component. Both the profit maximization and e-waste foraging models assumed that disassembly time was cumulative for each component because disassembling each product was a sequential process. Uncertainty associated with the disassembly times was explored in a sensitivity analysis and in a scenario analysis (as described in section 5.2.5). Sources of base data points used to calculate the average disassembly time per component are noted in the appendix. Cumulative disassembly times for each product that were used as model inputs are shown in Table 12.

Table 12 Cumulative disassembly time per component

Component	Cumulative Disassembly Time (seconds)
Laptop	
LIB	3.2
Battery PCB	3.6
Hard Drive	31
Hard Drive PCB	34
Optical Drive	61
Optical Drive PCBs	73
Memory - other	80
Memory PCB	96
RTC Battery	120
Display	600
Display PCB	601
Audio PCBs	640
Blue tooth & other	960
Fan and Heat Sink	1,000
System Board PCB	1,010
System board assembly - other	1,050
Processor PCB	1,060
Housing	1,300
Housing PCBs	1,300
Wires	1,600
Smartphone	
SIM card	6.3
LCD Assembly	67
System board PCB	73
System board assembly - other	130
LIB	140
LIB PCB	150
Back Casing	310

Note: This table identified cumulative disassembly times for components within the laptop and smartphone. Because values were adjusted to two significant figures, some data points could be slightly off, and in some cases, could appear similar to other components (housing and housing PCB). Individual component disassembly times are noted in the appendices.

5.2.4.2. Shredding parameters

Shredding revenue per component was calculated as the product of the decision (number of components to shred, 1 or 0), 2008 scrap prices per material ($), mass of materials (grams) found in each component, and the recovery efficiency rate for each material. The material mass input parameter for each component and product was the same as described above, originating from a disassembly conducted in the laboratory and resultant bills of materials (RIT 2010; 2013). The base case recovery efficiency rates per material (Table 13) were calculated from an average of data points found in the literature (Hagelüken 2007; Rigamonti et al. 2009; Xie et al. 2009; Umicore 2009; Electrometals Technologies Limited 2010; Xu et al. 2008; Neira et al.2006; Williams 2006; Cui and Zhang 2008; Ruhrberg 2006; Kamberović et al. 2009; Yu et al.2009; Reuter et al.2006; Reck and Gordon 2008; ITRI 2009; Scott et al. 1997; siliconinvestor.com 2008; Petrie 2007; USGS 2004; Umicore 2009; Zheng et al. 2009; Qu et al.2006). Due to limited information, material recovery efficiency data points included all types of processing, not just mechanical shredding. Uncertainty linked to material recovery efficiency values was explored in the sensitivity analysis with the minimum and maximum data points.

Materials scrap prices (in 2008 USD) were used directly from scrap industry websites (Kitco 2011; Scrap Metal Prices 2011; Scrapindex.com 2011; Ides.com 2014), and government publications (USGS 2005-2011). The exception was glass and plastics, which were based on spot 2009 (Scrapindex.com 2011) and 2013 prices (Ides.com 2014) and then adjusted to 2008 dollars using the U.S. BLS inflation calculator (2014). The analysis assumed that lithium would be recycled as a concrete additive, so the slag concrete additive price was used rather than scrap or primary lithium prices (USGS 2006, 2011) and used virgin 2008 prices for magnesium (USGS 2005, 2009). See Table 13 below for listing of base case input variables used to calculate shredding revenue.

Table 13 Shredding revenue input variables

Material	Mass (gram)	Average Recovery Efficiency Rate (%)	2008 Average Scrap Price ($ per gram)
Ferrous	350	99%	$\$3.5 \times 10^{-4}$
Li	21	95%	$\$1.8 \times 10^{-5}$
Co	60	99%	$0.03
Cu	90	99%	$0.01
Al	440	98%	$\$7.6 \times 10^{-4}$
Ni	3.5	80%	$\$2.0 \times 10^{-3}$
Sn	14	85%	$\$3.6 \times 10^{-3}$
Ag	8.0×10^{-1}	95%	$0.48
Au	1.5×10^{-1}	99%	$29
Pd	2.0×10^{-2}	98%	$12
Mg	340	0	$0.01
Hg	3.0×10^{-3}	0	0
Brass	2.5	0	$\$2.9 \times 10^{-3}$
PC	50	92%	$\$1.1 \times 10^{-3}$
PC-ABS	69	92%	$\$1.0 \times 10^{-3}$
PVC	1.8×10^{-1}	92%	$\$1.0 \times 10^{-3}$
Plexiglass	12	84%	$\$3.7 \times 10^{-4}$
Plastics (mixed)	380	92%	$\$1.4 \times 10^{-3}$
Glass	190	100%	$\$3.8 \times 10^{-6}$
Non-recoverable materials	450	0	0

Note: This table summarized the total material mass, average recovery efficiency input parameters per material, and scrap prices per material. Input values were adjusted to two significant figures.

Similar to the disassembly revenue parameters, inputs associated with shredding revenue were a source of uncertainty. For example, while many websites and publications provided ‘average’ prices, the prices might not actually reflect an average of price variability over the year. While this concern was not addressed in this analysis, future work could explore a range of material prices (percent higher and lower than the base case values).

The cost to shred each component was calculated as the decision to shred each particular component (0 or 1), mass per component (grams), and cost to shred each component ($ per gram). The average shredding cost was calculated from data points found in the literature (Neira et al. 2006; Fredholm 2008; Gregory and Kirchain 2008; CIWMB 2007; Brown-West 2010) and from the estimated cost of operating an Eidal Model 62x41 low-speed/high-torque shredder in 2008 (Worldwide Recycling Equipment Sales LLC, 2011). Shredding cost data points adjacent to the modeled year were adjusted to 2008 dollars where needed. The costs used from the literature may include other processing activities besides shredding and were from different U.S. regions. To address this uncertainty, minimum and maximum shredding cost values that used to calculate the base case parameter was analyzed in the sensitivity analysis. See the appendices for a summary of the sources of data used to calculate base case shredding cost values.

This analysis assumed that the components would either be disassembled or shredded. The base case shredding time was used as an input the e-waste foraging model, not the conventional profit maximization model. Shredding time was assumed to be a constant sum for both products (31 seconds), regardless of component selected, and was calculated by dividing the total products' mass by the stated shredding capacity (mass per minute) for commercial e-waste shredding equipment (i.e., Allegeny 12HD 7.5 model). Model specifications indicated a shredding capacity of 35 hard drives per minute (http://www.alleghenyshredders.com 2014), which was converted into grams per second by multiplying the average mass of a hard drive and 60 seconds per minute. Uncertainty associated with shredding time is explored in the sensitivity analysis. Future work could explore additional shredding time data points to reduce the associated uncertainty with shredding time.

5.2.4.3. Searching (Collection) parameters

The cost of collecting or searching for each device, regardless of EOL process, was based on an average of data points found in the literature (Fredholm 2006; Gregory and Kirchain 2008; CIWMB 2007) and adjusted to 2008 values. Search cost data points included the weighted average cost of a California pick up program (CIWMB 2007), weighted average cost of a California drop off program (CIWMB 2007), management and oversight costs for a program Maine (Gregory and Kirchain 2008; Fredholm 2006), average collection cost for a program in Maryland (Gregory and Kirchain 2008), and the weighted average of total recovery costs for a program in California (CIWMB 2007). Total recovery costs for the California program included labor, transportation, multiple types of programs (e.g., drop off and pickup), and additional costs such as, but not limited to supplies, fuels, taxes, and overhead. Fixed costs (e.g., building rent, capital equipment, and salaries) were not included in the California data point (CIWMB 2007). Due to the wide range of programs and locations, uncertainty was inherent to the search cost parameter. Therefore, minimum and maximum search cost data points, which were used to calculate the base case parameter, were explored in the sensitivity analysis. Similar to how Schoener (1971) excluded search time because a predator searches for food simultaneously, the e-waste foraging model assumed products were dropped off at the facility and assumed the time to search for and transport products to the facility was zero.

5.2.5. Model Implementation and Sensitivity/Scenario Analysis

After parameterizing the models with data, the conventional profit maximization model was first run using What'sBest!® 10.0.3.2 software on a Dell Optiplex 9010 with an Intel 2 Core processor. The results were compared to the e-waste foraging model, which was also run using the same software and computer. Both models identified the net profit (E_n) for the facility and optimal EOL strategy for each component. The e-waste foraging model also identified the optimal net profit per time unit spent on EOL processing (E_n/T). A list of parameters used in each model is shown in Table 14:

Table 14 List of parameters used in models

Parameter	Conventional Profit Maximization	E-waste Foraging
Handling Revenue – disassembly	✓	✓
Handling Revenue – shredding	✓	✓
Handling Cost – disassembly	✓	✓
Handling Cost – shredding	✓	✓
Search (collection) costs	✓	✓
Search (collection) time	✓	✓
Handling time - disassembly		✓
Handling time - shredding		✓

Note: This table identified the parameters used in both the conventional profit maximization model and the new e-waste foraging model. The parameter of handling time is only used in the e-waste foraging model.

Because many factors could potentially affect an e-waste forager’s processing decisions, a sensitivity analysis was performed to test the robustness of the models, address the uncertainty associated with certain model parameters, and illustrate the range of parameter values that influenced decision changes at the component level. To achieve this goal, model parameters (as discussed earlier) such as material recovery efficiency rates, labor costs, scrap component prices, shredding costs, search costs, disassembly time, and PCB component mass were changed and re-run using What'sBest!®.

In addition to testing the model's sensitivity to parameter changes, a scenario analysis investigated how processing decisions would change if the e-waste forager could access each component individually. The futurist modularity scenario assumed that disassembly times for each component were separate rather than cumulative and was implemented for the profit maximization model only. The modularity scenario was based on the Green Electronics Council recommendation to develop design for EOL standards (2009) that encouraged disassembly as a means to obtain higher recovery values. This scenario was also based on a new modularity design for smaller devices such as the Google © 'gray phone' (Rosenblatt 2014). While the modular phone was designed to enable customization of smartphones (Rosenblatt 2014), this design would also allow the e-waste forager to access each component individually.

5.3 Results and Discussion

5.3.1. Model Results

A globally optimal solution is found for the base case profit maximization model using a linear program. The profit maximization model runs very quickly (within seconds). Using model parameters, as summarized in Table 15, the conventional profit maximization model results in a decision to shred all components and dissemble only the laptop hard drive. The base case net profit is $6.42, which is primarily attributed to the laptop shredding revenue.

Table 15 Conventional profit maximization model outputs

	Laptop	**Smartphone**
Shredding revenue ($ per product)	$7.60	$0.39
Disassembly revenue ($ per product)	$0.16	$0
Shredding cost ($ per product)	$0.91	$0.10
Disassembly cost ($ per product)	$0.06	$0
Search cost ($ per product)	$0.66	$0.10
Profit ($ per product)	$6.10	$0.30
Total mass recovered from Shredding and disassembly (grams)	1,460	102

Note: Values are adjusted to two significant figures, except for the total mass recovered values, which were adjusted to three significant figures. Model outputs are in 2008 dollars (except total mass) and may not sum due to rounding approximation.

The decision to select the hard drive only also includes the time it takes to disassemble the previous component (i.e., battery). Although the battery has to be taken out first in this model, it is ‘shredded’ along with the other components. In reality, batteries are sent to another facility for processing. Due to the way the profit maximization and e-waste foraging models have been set up, when a component is selected for disassembly, it doesn’t require any previous component(s) to be selected for disassembly. This research recognizes that the both models may require additional adjustment, but are a first step towards developing a more robust decision making tool. Future work will ensure that additional constraints and complexity are in place to mirror how an e-waste processing facility makes decisions at the component level.

In comparison to the *conventional profit maximization model*, a feasible solution is found for the base case e-*waste foraging model* using a *non-linear* program. A feasible solution means that there are other possible solutions and/or additional constraints are needed in order for the model to identify an optimal solution. The model also runs quickly (within seconds). Using model outputs as summarized in Table 16, the e-waste foraging model results in a base case decision to shred all components.

Table 16 E-waste foraging model outputs

	Laptop	**Smartphone**
Shredding revenue ($ per product)	$7.70	$0.40
Disassembly revenue ($ per product)	$0	$0
Shredding cost ($ per product)	$0.91	$0.10
Disassembly cost ($ per product)	$0	$0
Search cost ($ per product)	$0.66	$0.10
Profit ($ per product)	$6.10	$0.30
Total mass recovered from sand disassembly (grams)	1,440	102

Note: Values are adjusted to two significant figures, except for the total mass recovered values, which were adjusted to three significant figures. Model outputs are in 2008 dollars (except total mass) and may not sum due to rounding approximation.

The base case e-waste foraging model results in an optimal net energy (profit) per unit of processing time (E_n/t) of $0.42 per second and net profit of $6.37. Similar to the profit maximization model, the e-waste foraging model optimal net profit is primarily attributed to the laptop shredding revenue. In *both* models, 56% of laptop shredding revenue is attributed to the system board and lithium ion battery, while 49% of smartphone revenues are associated with the system board. From a materials perspective, 51% of total shredding revenue (for both models) is from gold, which is found in the PCB chips, systems boards, and processors and only accounts for a 0.01% of total product mass. Ferrous metals account for 19% of total shredding revenue and 15% of total product mass.

The conventional profit maximization model confirms the e-waste foraging model since both have similar net profits and total quantities of material recovered. Since both model base case decisions result in the selection of nearly all components being shredded, the models suggest that under this set of assumptions and constraints, the laptop and smartphone should not be designed for disassembly. Moreover, the results of both models reflect the trend of using automatic shredding processes in Europe (GEC 2009). Interestingly, the base case model decisions contrast observations of computer disassembly at an e-waste processing business, but corroborate the choice to send mobile phones out for material processing (Sunnking 2010; 2013). Similar to the ecological prediction of choosing more profitable prey, the e-waste foraging model (and the conventional profit maximization model) indicates that the strategy to shred all products is more profitable than the disassembly strategy. The e-waste forager's preference for one strategy is probably due to E_n being based on dollars rather than mass (grams) like ecological counterparts. Favoring one processing strategy contrasts how a natural species such as the *octopus vulgaris* selects handling activities depending on the prey size (McQuaid 1994). A sensitivity analysis is conducted on the model parameters in order to understand range of conditions would encourage an e-waste forager to adjust its decision.

5.3.2. Sensitivity and Scenario Analysis Results

5.3.2.1.Profit Maximization Model

The conventional profit maximization model decision is sensitive to changes in scrap value, labor costs, shredding costs, and disassembly time. As noted in the appendices, reducing labor costs by 20% (from a policy change) and increasing scrap value by 24% (possibly due to a material scarcity situation) results in the model to disassemble another component (SIM card). Significantly increasing shredding costs (by 220%) also results adding another component (display) to disassemble. However, the decision to disassemble one additional component results in small changes to the net profit. The model is not sensitive to a 10% reduction in PCB component mass or material recovery rates, which makes sense since most components (including all PCB components are already being shredded.

As shown in Figure 20, the conventional profit maximization model is particularly sensitive to changes in labor costs, which is due to the assumption that the e-waste foraging encountering each component sequentially. For example, as labor costs decrease (i.e., base case to 50% reduction per component scenarios) leads to an increasing number of components selected for disassembly (one to four). Thus, this result illustrates a potential ranking of components that may be appropriate disassembly, similar to how ecologists model how predators rank selection of prey by profitability. Therefore, if disassembly was important to decision makers, enacting a policy or grant subsidizing labor costs would encourage e-waste foragers to disassemble additional components. In these cases, efforts can be focused on ensuring certain components (i.e., hard drive and display for the laptop and the

SIM card and system board for the smartphone) are designed for EOL processing with snap clips or designing components to be removed by generic disassembly tool kits.

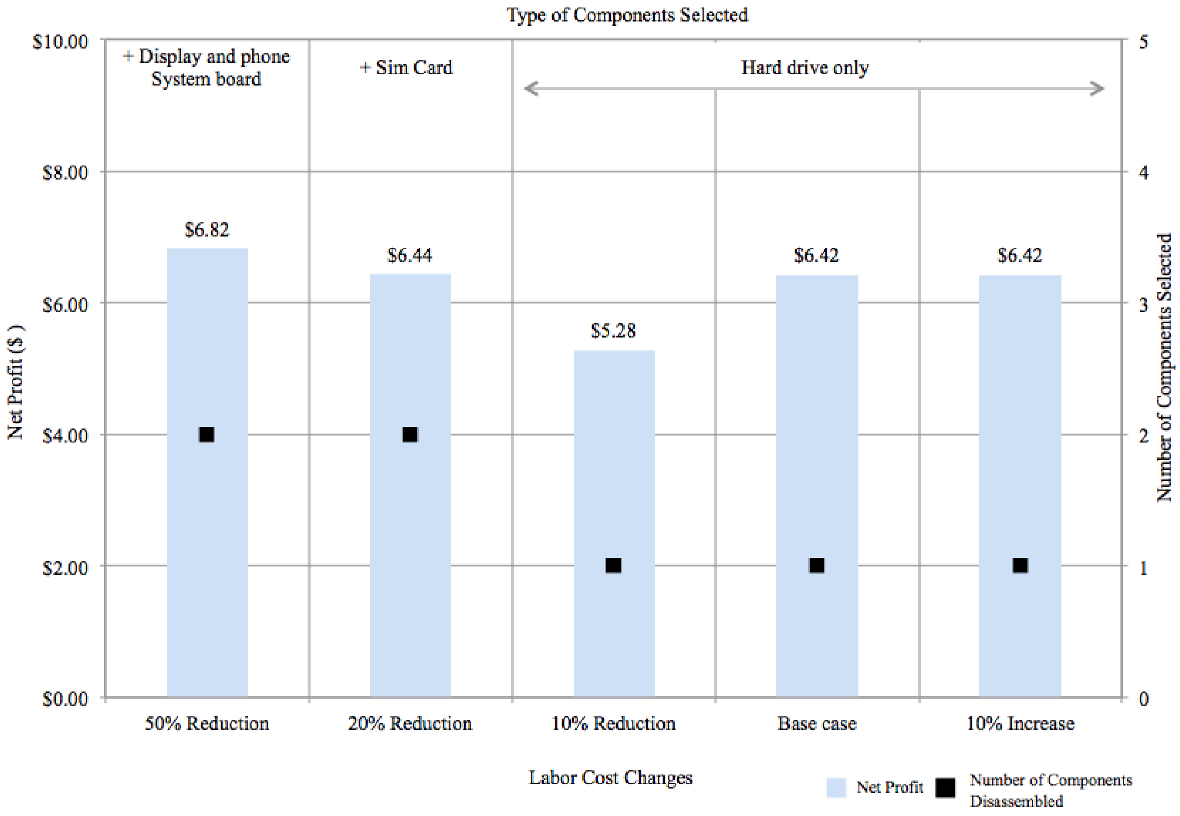


Figure 20 Relationship between changes in net profit, number of components selected, and labor costs. The primary X axis represents changes in labor costs data points from 50% decrease from the base case to a 10 percent increase from the base case. The secondary X axis identfies the type of component(s) selected. For instance, the base case only selects the hard drive for disasembly, but reducing labor costs by 50% results in four components being selected for disasembly: hard drive, display, SIM card, and system board (smart phone).

The ability to access each component individually, as suggested in the futuristic modularity scenario, results in an increased net profit and more components selected for disassembly. The conventional profit maximization model applies the futuristic scenario and finds a globally optimal linear solution. The net profit is $6.84 ($6.47 per laptop and $0.37 per smartphone), which is six percent greater than conventional profit maximization base case result. Four components are selected for disassembly in the futuristic modularity scenario: hard drive, memory PCB, processor, and smartphone system board. As shown in the appendix, this scenario is more sensitive to most parameters, except search costs. Model sensitivity is probably influenced by the distinct rather than cumulative component disassembly times. The sensitivity analysis indicates that additional components are selected for disassembly with high shredding costs, low labor costs, minimal recovery rates, and high scrap value. A voluntary design standard or product innovation encouraging modular designs (e.g., Google © 'gray phone') appears to have positive implications to the e-waste processing business.

5.3.2.2.E-waste Foraging Model

Unlike the conventional profit maximization and modularity scenario, the e-waste foraging model appears to be fairly insensitive to changes in model parameters. Interestingly, the e-waste foraging model appears insensitive to changes in shredding time (see the appendix). Increasing shredding time ten fold did not affect a change in the e-waste model's decision and still resulted in a feasible solution. Most parameter changes result in 'feasible solutions' to shred all components. As shown in the appendices, high and low labor costs and high component scrap prices result in locally optimal solutions, but the model decision to shred all components remains the same.

Since the model decisions and revenue is associated with shredding, further investigation of material recovery efficiency rate, shredding costs, and disassembly time is warranted. When comparing the net profit (E_n) and net profit per unit of time (E_n/T) metrics in the e-waste foraging model, the foraging metric appears to remain stable as material recovery efficiency rates increases (Figure 21a) and shredding costs decrease (Figure 21b). This stability may be due to nature of the metric (net profit divided by total processing time). As expected, net profit increases with material recovery efficiency rates (Figure 21a) and decreases with shredding costs (Figure 21b). The material recovery efficiency rate may be the ecological equivalent of a digestion constraint (Edouard et al. 2010) or protein content (Cheung et al. 2006). Similar to how ecological models study the digestibility of protein and other nutrients and its impact on E_n/T (Edouard et al. 2010; Simpson et al. 2004), future work could integrate a grazing model (Spalinger and Hobbs 1992) and investigate the relationship between material recovery, net profit, and component processing decisions. While not shown in the base case or sensitivity analysis of this research, an e-waste foraging may adjust feeding behaviors (switch from shredding to disassembling components) like mammalian herbivores adapt feeding behaviors to include a complementary set of nutrients to maximize energy intake (Stephens and Krebs 1986; Edouard et al. 2010).

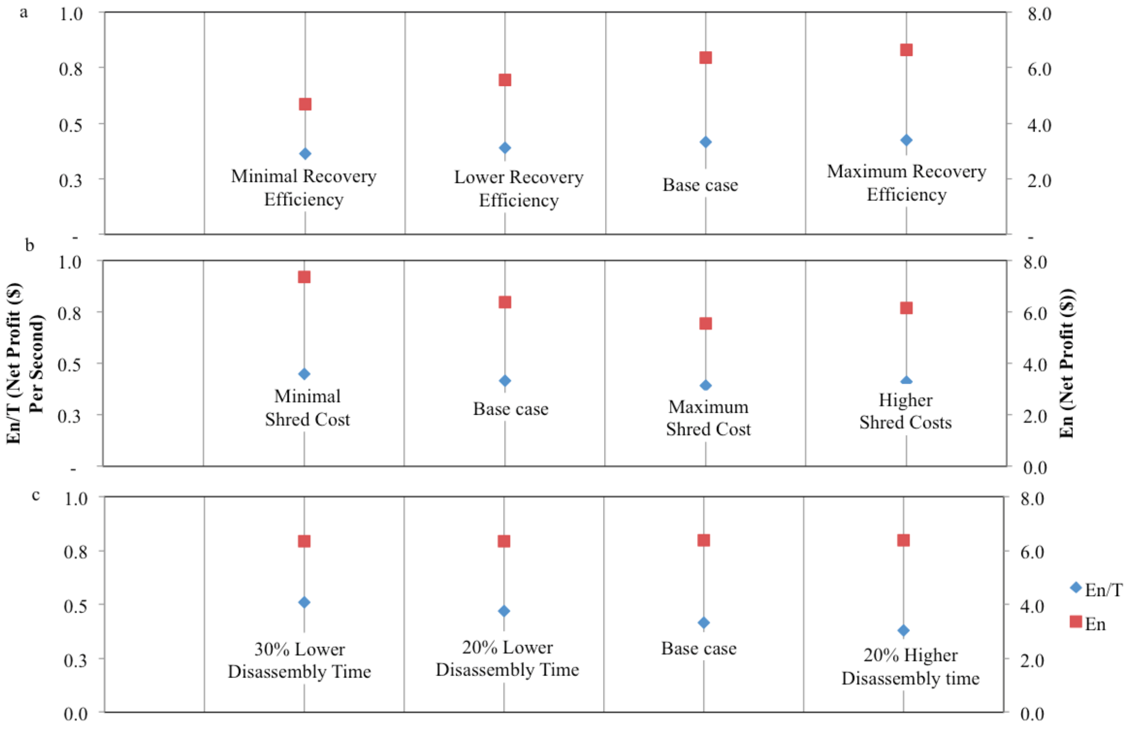


Figure 21 Comparing E_n/T and E_n in comparison to ranges of data points related to: a) material recovery efficiency rates, b) shredding costs, and c) disassembly times. Descriptions of the sensitivity analyses are noted in Table 17. Net profit appears to decrease with increases in shredding costs and increase with increases in material recovery efficiency rates, in comparison to the relatively stable En/T trend (Figure 21a and 21b). On the other hand, net profit remains relatively stable while En/t illustrates a decreasing trend with higher disassembly time scenarios (Figure 21b).

On the other hand, net profit remains relatively stable and E_n/T illustrates a decreasing trend with increasing disassembly time (Figure 21c). Even if the current e-waste foraging model decision doesn't change in the sensitivity analysis, it suggests that increasing modularity (via lower disassembly time) may positively impact the e-waste forager. Descriptions of the material recovery efficiency, shredding cost, and disassembly time sensitivity analyses illustrated in Figure 21 are defined in Table 17.

Table 17 Description of sensitivity analyses

Name	Description
Base case	Use average data point value for parameters
Minimal recovery efficiency	Use minimum recovery efficiency data points
Maximum recovery efficiency	Use maximum recovery efficiency data points
Lower recovery efficiency	Reduce each recovery efficiency data point by 10% for each recoverable material
Minimal shredding costs	Use minimum shredding cost data points
Maximum shredding costs	Use maximum shredding cost data points
Higher shredding costs	Increase shredding costs 50% higher than base case
20% lower disassembly time	Decrease base case disassembly time for each component by 20%
30% lower disassembly time	Decrease base case disassembly time for each component by 30%
20% higher disassembly time	Increase base case disassembly time for each component by 20%

Note: the sensitivity analyses described in this table are used in Figure 21.

5.3.4 Uncertainty

As noted in the methodology, many input variables used in the e-waste foraging and profit maximization models are surrounded by uncertainty. While running sensitivity analyses on model parameters can reduce uncertainty to some degree, the primary contributors appear to stem from the model itself, material composition, and shredding time.

As noted earlier, the e-waste foraging model's inability to reach an optimal solution is probably due to the need for additional constraints. This may be achieved with disassembly and shredding capacity constraints, as well as a set foraging time (constraint of one day). Then the limited time could be allocated between shredding and disassembly activities. If disassembling products to the component level is highly desired by decision makers, then an expanded foraging model may be able to identify the range of parameter changes encourage decisions changes. In addition, the constraints may allow an analysis on whether or not the e-waste forager behaves as a time minimizing or energy maximizing species.

If shredding is the potential future of e-waste processing, as suggested by both models' base case results, future work expanding this research can reduce uncertainty by using enhanced material composition data, especially for high valued components (e.g., PCB, processor, system board, and SIM card). It is unlikely that the PCBs, processor, and system board components have the same material composition. Understanding of the materials within these high valued components is an important part of developing a solid decision making tool. While a sensitivity analysis on materials was not initially explored in this analysis, a range of materials could be tested using the results of research conducted by Kasulaitis et al. (2014, in the review process). The suggestion to develop publically available bills of materials for all products by the Green Electronics Council (2009) may provide the added benefit of bounding the models' uncertainty, as well as minimizing e-waste foragers' challenge of managing a diverse and shifting e-waste stream.

Finally, shredding time is another likely source of uncertainty. The way the current models are set up, shredding time is only part of the e-waste foraging model and the base case value is from one data point. If shredding costs are a function of time and additional shredding time data points are available, then the model may become more sensitive to changes in shredding time. Finally, if the models are arranged such that the shredding time includes the time to disassemble a component, then the decision may change from shredding all components to dissembling a portfolio of components.

5.4 Implications

The classic optimal diet foraging model demonstrates that e-waste processing decisions can be modeled similar to how ecologists model foraging decisions of natural species. While the profit maximization and e-waste foraging models developed in this research are simple and may require additional constraints, the base case results suggest it is not sensible to design all products for disassembly. However, the sensitivity analysis from the profit maximization model indicates a potential spectrum of parameters that may affect e-waste processing decisions for each component. While the e-waste foraging model was applied to the processing of electronic waste from traditional products, it could also be applied to other product waste streams (e.g., health care appliances) or emerging waste streams such as electronics found in non-traditional products (‘wearables’) or from 3-printing.

Because no single ecological species mimics the e-waste forager, future work could develop a more comprehensive model reflecting the e-waste forager’s strategies and traits by integrating multiple models such as the grazing model (Spalinger and Hobbs 1992) and central foraging theory (Ydenberg and Schmid-Hembel 1994). As the composition of the material and product e-waste stream changes due to shifts in the electronic product community structure, a comprehensive model may help e-waste forager quantify decisions and identify how to adapt processes while maximizing net profit.

Many other opportunities are available to further this research. For example, integrating central place foraging with optimal facility siting and logistics planning and geographic information systems tools can explore how to optimize the collection and transport of diverse products and materials within the e-waste forager’s range. In addition, dynamic and stochastic ecological information models (Stephens and Krebs 1986; Hirvonen and Ranta 1995) may show how changes in the materials within devices affect decisions Finally, future work maximizing net profit in terms of MJ (rather than dollars) per unit of time spent processing may result in a different set of decisions, which could provide the policy justification to support disassembly even if the economic models indicate otherwise.

The e-waste foraging model is the first step towards developing a set of practical tools for e-waste processing businesses and product designers. The shift towards smaller devices and/or components being embedded in non-traditional devices in the electronic product community will have consequences on the waste product and materials flows. Thus, even after adding additional constraints, the changing community structure may affirm the models’ decision to shred all components. Models decisions may also remain the same (but profits may vary) if the electronic product community structure changes towards designing and adopting products with highly abundant, low value materials (plastics) found in casings. Rather than creating products without considering EOL implications, a robust e-waste foraging model may provide the necessary information to ensure sustainable EOL management and bridge the gap that currently exists between product designers and e-waste processing businesses.

VI. Conclusions

This dissertation demonstrates the utility of adapting ecological concepts of community ecology and optimal foraging theory to understand how a group or 'community' of consumer electronic products' structure, functions, interactions, and resultant ecosystem impact flows have evolved over time. This research has illustrated how one product community parallels and diverges from natural communities, but the methodologies in Chapter III, IV, and V based on community ecology and optimal foraging theory can be applied to other product groupings. Examples of other pluralistic product groupings include household appliances, traditional clothing, food consumption, renewable energy portfolios, or municipal solid wastes, as well as the upcoming rise in computing technologies embedded in non-traditional products (e.g., clothing and other 'wearable' electronics) or products developed from 3D printing. Chapter II and III demonstrate that a household is a suitable functional unit for groups of interconnected products (Guinée et al. 2010) undergoing an innovation transition (Levine et al. 2007).

As noted in Chapters III and IV, the evolving electronic product community's increasing structural diversity and high functional redundancy is linked to an increasing net annualized energy impact on a community-level. The electronic product community's estimated impact is significant, equivalent to nearly 30% of the average fuel consumed by a passenger vehicle in 2007. Can households reduce its environmental footprint while preserving the features we demand from the beloved electronic devices? The consumption-weighted LCA demonstrates that consuming a smaller group of multi-functional devices can potentially yield significant improvements. While diversity is perceived to be important for industrial system survival and functioning (Jensen et al. 2011), this may not be the case for the electronic product community, where a shift to a lower diversity structure could potentially lead to energy impact reductions. However, application of intervention strategies to further reduce impacts will need to consider the changing rank of higher impact species, as key contributing products shift from stationary, legacy devices (e.g., CRT TV) to mobile devices with shorter lives (i.e., tablet) and stationary, longer lasting devices (i.e. LCD TV). Designing and encouraging the ownership of fewer multifunctional devices mirrors recently recommended "big pivot" (p. 60) strategies to help companies be resilient in a world facing increasing material scarcity while accepting the need for an overall reduced environmental footprint (Winston 2014).

Not only does comparing natural community empirical foraging systems with the electronic product community analysis provide insight on the type of products that should be designed for different EOL strategies and range of factors affecting processing decisions, it may lend insight on design standards that encourage sustainable EOL management. The base case results of a simple model based on optimal foraging theory in Chapter V suggests that not all products should be designed for disassembly (i.e., laptop and smartphone). Thus, standards encouraging modularity or material labeling may be ineffective as the community shifts towards mobile, multifunctional devices and have repercussions on a facility's profit and selection of processing strategies. The consumption-weighted LCA methodology and e-waste foraging model can therefore assist governmental and industry decision makers as they propose and implement future design innovations, policies, standards, and legislation to manage emerging computing technology life cycle impacts. Development of future regulations and standards for the electronic product community should consider a fleet-based approach, as developed for the automobile and trucking industry.

Future analyses can link structural changes to other environmental implications and can determine vulnerability to external perturbations (material scarcity, energy availability, or product regulations). For example, while the consumption-weighted LCA methodology is focused on energy, it can be expanded upon to illustrate changes in other ecosystem level flows including GHG emissions, material input flows, and EOL product and waste output flows. The environmental implications of a complex, diversified electronic product system are likely to include a higher throughput of materials, increased energy consumption and waste flows, and a more diverse mix of resources required to produce and use these devices.

Considering consumer electronics a community may enable us to achieve more benefits (increased functionality and environmental improvements) with less. To provide guidance on how to move beyond the single product perspective, future work exploring the strength of interactions between products in the community will help identify which highly demanded functions should be incorporated into future convergent devices. In ecology, interactions between species influence community structure and functions (Wootton and Emmerson 2005). By integrating Chapter III's results with an ecological functional trait analysis to identify highly demanded functions, the new functionally convergent devices can be evaluated with the consumption-weighted LCA approach from Chapter IV. Moreover, in contrast to a natural community, we can count (rather than estimate) species in a product community. Thus, the results may actually lend to insight for ecologists as they continue to study the influence of biodiversity and interactions on ecological system functions while further bolstering industrial ecology's connection to the source science.

VII. Appendix

7.1 Chapter III Supplemental Tables

Tables S-1 to S-14 are associated with the structure and function analysis in Chapter III. Table S-1 describes devices that were considered, but excluded in Chapter III's analysis.

Table S-1 Household Consumer Electronic Products and Data Sources Considered, But Excluded From Analysis

	Product	Type of Data and Years Available	Source(s)	Notes	Exclusion Reason
Computer-related devices	Docking station	Household penetration rates for 2009-2010 and installed units for 2010	CEA 2009; July/August 2010; Urban et al. 2011	b	i
	External storage device	Household penetration rates for 2008-2009	Herbert 2008; CEA 2009	b	i
	Modem	Installed units for 2006 and 2010	Roth and McKenney 2007; Urban et al. 2011	a,b	i
	Pair of speakers	Household penetration rates for 2009-2010	CEA 2009; July/August 2010		i
	Wireless hub/router	Household penetration rates 2009-2010	CEA 2009; July/August 2010	a,b	i
Entertainment-related devices	Gaming device - portable	Household penetration rate for 2008	Eskelsen et al. 2009		i
Television-related devices	Set top box - satellite	Installed units for 2006 and 2010	Roth and McKenney 2007; Urban et al. 2011	a,b	i
	Set top box - cable	Installed units for 2006 and 2010	Roth and McKenney 2007; Urban et al. 2011	a,b	i
	Stand alone - DVR	Installed units for 2010, household penetration rates 2004-2008	Eskelsen et al. 2009; Urban et al. 2011	b	i
	TV - projection	Sales units 1984-2010 and installed units for 2006 & 2010	Roth and McKenney 2007; Urban et al. 2011; U.S. EPA 2008, 2011	a,b	ii
	11	**= Total number of excluded products**			

Note:

a. Analyzed in an energy consumption report for Consumer Electronics Association by Roth and McKenney (2007).

b. Analyzed in an energy consumption report for Consumer Electronics Association by Urban et al. (2011).

Reasons for exclusions:
i. Product does not have sufficient sales unit data to calculate household penetration rate
ii. Product has low ownership penetration

Tables S-2 to S-4 identifies abundance or number of each product owned in the community from 1990-2010, but organized by each functional group.

Table S-2 Number of Products Owned Per Household-Year for the Data Manipulation Functional Group

	Desktop	Laptop	Tablet	Netbook
1990	0.33	0	0	0
1991	0.36	0	0	0
1992	0.40	0.01	0	0
1993	0.44	0.02	0	0
1994	0.49	0.04	0	0
1995	0.56	0.05	0	0
1996	0.63	0.08	0	0
1997	0.72	0.10	0	0
1998	0.84	0.12	0	0
1999	0.98	0.14	0	0
2000	1.11	0.17	0	0
2001	1.21	0.19	0	0
2002	1.31	0.22	0	0
2003	1.41	0.25	0	0
2004	1.50	0.29	0	0
2005	1.57	0.34	0	0
2006	1.63	0.40	0	0
2007	1.67	0.45	0.06	0
2008	1.69	0.50	0.13	0.01
2009	1.69	0.58	0.20	0.05
2010	1.65	0.59	0.24	0.11

Note: *Laptop* and *desktop* stock was based on the U.S. EPA (2008, 2011) published material flow analysis reports. Laptop sales were adjusted to separate out netbooks and tablets sales units. Netbook sales data was estimated from U.S. EPA (2008, 2011) laptop sales data and market share information from Jeffries (2010) and Baker (2008). Tablet sales data was from Indvik (2012). *Netbook* and *tablet* stock was determined by calculating material flow analyses using a normal lifespan distribution methodology (Babbitt et al. 2009). Netbook and tablet lifespan was assumed to be same as e-reader: 4.0 years (Kozak 2003) and standard deviation of 2.4 years (Oguchi et al. 2008).

Table S-3 Number of Products Owned Per Household-Year for the Audio Visual Playback Functional Group

	E-reader	LCD Monitor	CRT Monitor	CRT TV	Plasma TV	LCD TV	DVD	VCR	Blu-Ray	MP3 Player	Gaming Console
1990	0	0.01	0.30	1.85	0	0	0	0.63	0	0	0.12
1991	0	0.02	0.33	2.00	0	0	0	0.60	0	0	0.14
1992	0	0.03	0.37	2.15	0	0	0	0.57	0	0	0.15
1993	0	0.04	0.43	2.30	0	0	0	0.56	0	0	0.17
1994	0	0.05	0.48	2.47	0	0	0	0.60	0	0	0.19
1995	0	0.06	0.55	2.59	0	0	0	0.70	0	0	0.21
1996	0	0.07	0.62	2.70	0	0	0	0.83	0	0	0.22
1997	0	0.08	0.69	2.78	0	0	0	0.98	0	0	0.24
1998	0	0.08	0.79	2.86	0	0	0.01	1.14	0	0.05	0.26
1999	0	0.08	0.90	2.96	0	0	0.05	1.35	0	0.05	0.28
2000	0	0.10	0.99	3.05	0	0	0.13	1.56	0	0.06	0.29
2001	0	0.12	1.04	3.09	0	0.01	0.21	1.68	0	0.06	0.31
2002	0	0.16	1.06	3.17	0	0.01	0.35	1.79	0	0.07	0.33
2003	0	0.23	1.03	3.20	0	0.01	0.50	1.83	0	0.07	0.34
2004	0	0.31	0.98	3.22	0.01	0.03	0.70	1.84	0	0.11	0.35
2005	0	0.44	0.90	3.18	0.03	0.07	0.75	1.82	0	0.14	0.39
2006	0	0.60	0.80	3.12	0.07	0.16	0.82	1.82	0	0.20	0.41
2007	0.01	0.75	0.69	2.94	0.11	0.30	0.83	1.81	0.03	0.33	0.38
2008	0.03	0.91	0.57	2.94	0.17	0.50	0.84	1.80	0.07	0.45	0.40
2009	0.05	1.00	0.46	2.95	0.22	0.73	0.80	1.79	0.13	0.48	0.44
2010	0.09	1.08	0.35	2.94	0.25	0.98	0.79	1.77	0.23	0.50	0.46

Note: For the *e-reader*, sales units were from PBT consulting (2011). Stock was based on a calculated material flow analysis with a normal lifespan distribution methodology (Babbitt et al. 2009) and lifespan assumptions were from Kozak (2003) and Oguchi et al. (2008). For *TVs* and *computer monitors*, published material flow analysis reports from the U.S. EPA (2008, 2011) were used to calculate stock. For the *blu-ray player* and *VCR*, sales data was from Roth and McKenney (2007) and Coplan (2006) and CEA (2010), respectively. Material flow analyses were calculated for the VCR and blu-ray player using a normal lifespan distribution methodology (Babbitt et al. 2009). Average VCR lifespan was assumed to be 8.9 years with a 2.1 standard deviation (Oguchi et al. (2008), and the average lifespan for a blu-ray player was assumed to be the same as a DVD player (7. 2 years with a 2.4 standard deviation) (Oguchi et al. 2008). Stock for the *DVD player*, *MP3 player*, and *gaming console* was based on published household ownership rates: Eskelsen et al. (2009) and CEA (2009, July/August 2010) for DVD players, Eskelsen et al. (2009) and CEA (July/August 2010) for MP3 players, and Arendt (2007) and Grabstat.com (2011) for gaming consoles.

Table S-4 Number of Products Owned Per Household-Year for the Hardcopy Interface, Audio Visual Recording, and Voice Communication Functional Groups

	Hardcopy Interface	**Audio Visual Recording**		**Voice Communication**	
	Printer	**Digital Camera**	**Digital Camcorder**	**Basic Mobile Phone**	**Smartphone**
1990	0.15	0	0	0.06	0
1991	0.16	0	0	0.08	0
1992	0.18	0	0	0.11	0
1993	0.21	0	0	0.17	0
1994	0.23	0	0	0.25	0
1995	0.27	0	0	0.33	0
1996	0.32	0	0.02	0.38	0
1997	0.37	0.01	0.04	0.50	0
1998	0.44	0.02	0.05	0.69	0
1999	0.53	0.07	0.08	0.90	0
2000	0.62	0.16	0.10	1.12	0
2001	0.69	0.24	0.12	1.36	0
2002	0.77	0.36	0.13	1.61	0.02
2003	0.83	0.52	0.14	1.82	0.04
2004	0.90	0.69	0.15	2.07	0.08
2005	0.96	0.85	0.15	2.34	0.16
2006	1.02	1.00	0.17	2.65	0.26
2007	1.08	1.13	0.19	2.88	0.38
2008	1.12	1.38	0.23	3.02	0.58
2009	1.13	1.71	0.27	3.24	0.79
2010	1.13	2.11	0.32	3.48	1.03

Note: The *printer* stock was based on published material flow analysis data from the U.S. EPA (2008, 2011). Material flow analysis was calculated for the *digital camera* and *digital camcorder* with sales data from Wilburn (2008) and a normal lifespan distribution methodology (Babbitt et al. 2009). The average lifespan for the camera and camcorder were assumed to be 8.5 and 7.2 years, respectively, and a standard deviation of 2.4 years for both products (Oguchi et al. 2008). Stock for the *basic mobile phone* was calculated using sales data from the U.S. EPA (2008, 2011) and Eskelsen et al. (2009). Smartphone stock sales data was from Eskelsen et al. (2009). It was assumed that common usage of smartphones began in 2002 (Reed 2010). A material flow analysis was calculated for both the basic mobile and smartphones using the constant average lifespan methodology from the U.S. EPA (2008, 2011) and average lifespan assumptions of 2 and 5 years, respectively (U.S. EPA 2008, 2011).

Table S-5 Changes in Household Units and Size of Household Per Year

	Number of Households	**Average Size of Households**	**Sources**
1990	91,947,410	2.29	a
1991	93,300,679	2.44	Estimated
1992	94,653,948	2.44	Estimated
1993	96,007,217	2.45	Estimated
1994	97,360,486	2.45	Estimated
1995	98,713,756	2.45	Estimated
1996	100,067,025	2.61	Estimated
1997	101,420,294	2.61	Estimated
1998	102,773,563	2.61	Estimated
1999	104,126,832	2.61	b
2000	105,480,101	2.59	c
2001	106,848,114	2.6	d
2002	107,740,595	2.61	e
2003	108,633,076	2.61	f
2004	109,525,557	2.6	g
2005	111,090,617	2.6	h
2006	111,617,402	2.6	i
2007	112,377,977	2.6	j
2008	113,101,329	2.6	k
2009	113,616,229	2.6	l
2010	114,567,419	2.58	m

Note: The abbreviations in Table S-5 represent data sources and are as follows: a) U.S. Bureau of the Census (1990), b) U.S. Bureau of the Census (2000), c) U.S. Bureau of the Census (2000), d) U.S. Bureau of the Census (2001), e) U.S. Bureau of the Census (2002), f) U.S. Bureau of the Census (2003), g) U.S. Bureau of the Census (2004), h) U.S. Bureau of the Census (2005), i) U.S. Bureau of the Census (2006), j) U.S. Bureau of the Census (2007), k) U.S. Bureau of the Census (2008), l) U.S. Bureau of the Census (2009), m) U.S. Census Bureau (2010).

Tables S-6 to S-9 identify the functions observed for each product and year. Table 6 summaries abbreviations used in Tables S-7 to S-9. Tables S-7 to S-9 are organized by functional group.

Table S-6: Description of Function Abbreviations

Functions	Abbreviation
Conversing	C
Copying	CO
Emailing	E
Faxing	F
GPS Navigation	G
Messaging	M
Organizing	O
Manipulating and analyzing data	MD
Playing audio	PA
Playing games	PG
Playing videos	PV
Printing	PT
Recording still image	RSI
Recording video	RV
Scanning	SC
Storage	S
Viewing videos, images, & words	V
Web Browsing & interactivity	WBI
Wi Fi connectivity	WFC

Table S-7 Functions for Products in the Data Manipulation Functional Group

	Desktop	**Laptop**	**Tablet**	**Netbook**
1990	MD, S			
1992	E, MD, S, WBI	E, MD, S, V, WBI		
1995	E, F, MD, PG, S, WBI	E, F, MD, PA, PG, PVS, V, WBI		
1997	E, F, MD, PA, PG, PV, S, WBI	E, F, MD, PA, PG, PV, S, V, WBI		
1998	E, F, MD, PA, PG PV, S, WBI	E, F, MD, PA, PG, PV, S, V, WBI		
1999	E, F, MD, PA, PG PV, S, WBI	E, F, MD, PA, PG, PV, S, V, WBI		
2000	E, F, O, MD, PA, PG PV, S, WBI	E, F, O, MD, PA, PG, PV, S, V, WBI		
2001	E, F, O, MD, PA, PG PV, S, WBI	E, F, O, MD, PA, PG, PV, S, V, WBI,		
2002	E, F, O, MD, PA, PG PV, S, WBI	E, F, O, MD, PA, PG, PV, S, V, WBI		
2003	E, F, O, MD, PA, PG PV, S, WBI	E, F, O, MD, PA, PG, PV, S, V, WBI, WFC		
2005	E, F, O, MD, PA, PG PV, S, WBI, WFC	E, F, O, MD, PA, PG, PV, S, V, WBI, WFC		
2007	E, F, O, MD, PA, PG PV, S, WBI, WFC	C, E, F, O, MD, PA, PG, PV, RSI, RV, S, V, WBI, WFC	E, O, MD, PA, PG, PV, S, V, WBI, WFC	
2010	E, F, O, MD, PA, PG PV, S, WBI, WFC	C, E, F, O, MD, PA, PG, PV, RSI, RV, S, V, WBI, WFC	E, O, MD, PA, PG, PV, S, V, WBI, WFC	C, E, O, MD, PA, PG, PV, S, V, WBI, WFC

Note: Function data was observed in the following: 1) review articles such as Heater (2011) and Stein (2010); 2) buying guides from Consumer Reports (1995, 1999, 2001, 2003, 2005) and Consumers Union of United States (2010); and 3) magazine articles from Consumers Union of the U.S. Inc. (2000) and Consumer Reports (2007).

Table S-8 Functions For Products in the Hard Copy Interface, Audio Visual Recording, and Voice Communication Functional Groups

	Hardcopy Interface	**Audio Visual Recording**		**Audio Visual Recording**	
	Printer	**Digital Camera**	**Digital Camera**	**Basic Mobile Phone**	**Smartphone**
1990	PT			C	
1992	PT			C	
1995	CO, F, PT, SC			C	
1997	CO, F, PT, SC	RSI, S	RV, S	C, M	
1998	CO, F, PT, SC	RSI, S	RSI, RV, S	C, M	
1999	CO, F, PT, SC	RSI, RV, S	RSI, RV, S	C, M	
2000	CO, F, PT, SC	RSI, RV, S	RSI, RV, S	C, E, M, O, PG, RSI, WBI	
2001	CO, F, PT, SC	RSI, RV, S	RSI, RV, S	C, E, M, O, PG, RSI, WBI	
2002	CO, F, PT, SC	RSI, RV, S	RSI, RV, S	C, E, M, O, PG, RSI, WBI	C, E, M, O, PA, PG, RSI, V, WBI
2003	CO, F, PT, SC	RSI, RV, S	RSI, RV, S	C, E, M, O, PG, RSI, WBI	C, E, M, O, PA, PG, RSI, S, V, WBI
2005	CO, F, PT, SC	RSI, RV, S	RSI, RV, S	C, E, M, O, PA, PG, RSI, RV, S, V, WBI	C, E, M, O, PA, PG, RSI, RV, S, V, WBI
2007	CO, F, PT, SC	RSI, RV, S	RSI, RV, S	C, E, G, M, O, PA, PG, RSI, RV, S, V, WBI, WFC	C, E, G, M, MD, O, PA, PG, RSI, RV, S, V, WBI, WFC
2010	CO, F, PT, SC, WFC	RSI, RV, S	RSI, RV, S	C, E, G, M, O, PA, PG, RSI, RV, S, V, WBI, WFC	C, E, G, M, MD, O, PA, PG, PV, RSI, RV, S, V, WBI, WFC

Note: MFD is an abbreviation for multi-functional device, the first of which was first produced in 1997 (Consumer Reports 1998). Function data was observed in the following: 1) review articles such as McCracken (1998), Himowitz (1998), and CNET (2003); 2) buying guides from Consumer Reports (1995, 1997, 1998, 1999, 2000, 2001, 2003, 2004, 2005), Consumers Union of United States (2009, 2009, 2010), and Consumer Reports Books (1995); 3) magazine articles from Consumers Union of the U.S. Inc. (1997) and Consumer Reports (2007); and 4) trade industry reports (CEMA 1998, 1999).

Table S-9 Functions for Products in the Audio Visual Playback Functional Group

	E-reader	LCD Monitor	CRT Monitor	CRT TV	Plasma TV	LCD TV	DVD Player	VCR	Blu-Ray Player	MP3 Player	Gaming Console
1990		V	V	PA, V				PV, RV, S			PG
1992		V	V	PA, V				PV, RV, S			PG
1995		V	V	PA, V				PV, RV, S			PG
1997		V	V	PA, V			PV	PV, RV, S			PG, S
1998		V	V	PA, V			PV	PV, RV, S		PA, S	PG, S, WBI
1999		V	V	PA, V	PA, V	PA, V	PV	PV, RV, S		PA, S	PA, PG, PV, S, V, WBI
2000		PA, V	PA, V	PA, V	PA, V	PA, V	PA, PV	PV, RV, S		PA, S	PA, PG, PV, S, V, WBI
2001		PA, V	PA, V	PA, V	PA, V	PA, V	PA, PV	PV, RV, S		PA, S	PA, PG, PV, S, V, WBI
2002		PA, V	PA, V	PA, V	PA, V	PA, V	PA, PV	PV, RV, S		PA, S	PA, PG, PV, S, V, WBI
2003		PA, V	PA, V	PA, V	PA, V	PA, V	PA, PV	PV, RV, S		PA, S, V	PA, PG, PV, S, V, WBI
2005		PA, V	PA, V	PA, V	PA, V	PA, V	PA, PV	PV, RV, S		PA, S, V	PA, PG, PV, S, V, WBI
2007	PA, V, WFC	C, PA, RSI, RV, V	PA, V	PA, V	PA, V	PA, V	PA, PV	PV, RV, S	PV	E, O, PA, PG, S, V, WBC, WFC	PA, PG, PV, S, V, WBI, WFC
2010	E, S, PA, V, WBI, WFC	C, PA, RSI, RV, V	PA, V	PA, V	PA, V, WBI	PA, V, WBI	PA, PV	PV, RV, S	PV, WBI, WFC	C, E, O, M, PA, PG, PV, RSI, RV, S, V, WBC, WFC	C, M, PA, PG, PV, S, V, WBI, WFC

Note: Function data was observed in the following: 1) review articles such as Polsson (1992), France (2008), Breen (2010), Carey (2012), and Poh (2012); 2) buying guides from Consumer Reports (1997, 1998, 1999, 2000, 2001, 2004, 2004, 2005), Consumers Union of United States (2009, 2010), and Consumer Reports Books (1992, 1995); 3) magazine articles from Consumers Union of U.S. Inc. (1990) and Consumer Reports (2007); and 4) trade industry reports (CEMA 1998, 1999) and books (Forster 2005; Wolf 2008).

Tables S-10 to S-13 identify the binary factor values (β) for each product. This factor indicates if a function is or is not available for that product and modeled year (1990, 2000, 2010). $\beta = 1$ if the function (e.g., conversion) is available or 0 if it is not available in that year. The header lists letter abbreviations, which are matched to products (see note at the bottom of each table). Table S-13 summarizes the binary factors on a community basis for the years 1990-2010.

Table S-10 Binary Factor Values (β) for Available Functions for each Product in the 1990 Community

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**T**
Conversing	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Copying	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Emailing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Faxing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GPS navigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Messaging	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Motion sensing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organizing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Manipulating and analyzing data	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Playing audio	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Playing games	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Playing videos	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Printing	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recording still images	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recording video	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Scanning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Storage	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Viewing videos, images, & words	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
Web browsing & interactivity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wi Fi connectivity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Note: Product names are indicated by the following letters: desktop (A), laptop (B), tablet (C), netbook (D), printer (E), camera (F), camcorder (G), basic mobile phone (H), smartphone (I), e-reader (J), LCD monitor (K), CRT monitor (L), CRT TV (M), plasma TV (N), LCD TV (O), DVD Player (P), VCR (Q), blu-ray player (R), MP3 player (S), gaming console (T)

Table S-11 Binary Factor Values (*β*) for Available Functions for each Product in the 2000 Community

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**T**
Conversing	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Copying	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Emailing	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Faxing	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GPS navigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Messaging	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Motion sensing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organizing	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Manipulating and analyzing data	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Playing audio	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	1	1
Playing games	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Playing videos	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1
Printing	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recording still images	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Recording video	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
Scanning	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Storage	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	1	1
Viewing videos, images, & words	0	1	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	1
Web browsing & interactivity	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
Wi Fi connectivity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Note: Product names are indicated by the following letters: desktop (A), laptop (B), tablet (C), netbook (D), printer (E), camera (F), camcorder (G), basic mobile phone (H), smartphone (I), e-reader (J), LCD monitor (K), CRT monitor (L), CRT TV (M), plasma TV (N), LCD TV (O), DVD Player (P), VCR (Q), blu-ray player (R), MP3 player (S), gaming console (T)

Table S-12 Binary Factor Values (β) for Available Functions for each Product in the 2010 Community

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**T**
Conversing	0	1	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	1
Copying	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Emailing	1	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0
Faxing	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GPS navigation	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
Messaging	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0
Motion sensing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Organizing	1	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0
Manipulating and analyzing data	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Playing audio	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	0	0	1	1
Playing games	1	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1
Playing videos	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1
Printing	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recording still images	0	1	0	0	0	1	1	1	1	0	1	0	0	0	0	0	0	0	1	0
Recording video	0	1	0	0	0	1	1	1	1	0	1	0	0	0	0	0	1	0	1	0
Scanning	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Storage	1	1	1	1	0	1	1	1	1	1	0	0	0	0	0	0	1	0	1	1
Viewing videos, images, & words	0	1	1	1	0	0	0	1	1	1	1	1	1	1	1	0	0	0	1	1
Web browsing & interactivity	1	1	1	1	0	0	0	1	1	1	0	0	0	1	1	0	0	1	1	1
Wi Fi connectivity	1	1	1	1	1	0	0	1	0	1	0	0	0	0	0	0	0	1	1	1

Note: Product names are indicated by the following letters: desktop (A), laptop (B), tablet (C), netbook (D), printer (E), camera (F), camcorder (G), basic mobile phone (H), smartphone (I), e-reader (J), LCD monitor (K), CRT monitor (L), CRT TV (M), plasma TV (N), LCD TV (O), DVD Player (P), VCR (Q), blu-ray player (R), MP3 player (S), gaming console (T)

Table S-13 Binary Factor Values (*β*) for Available Functions in the Product Community 1990-2010

	1990	**1992**	**1995**	**1997**	**1998**	**1999**	**2000**	**2002**	**2003**	**2005**	**2007**	**2010**
Conversing	1	1	1	1	1	1	1	1	1	1	1	1
Copying	0	0	1	1	1	1	1	1	1	1	1	1
Emailing	0	1	1	1	1	1	1	1	1	1	1	1
Faxing	0	0	1	1	1	1	1	1	1	1	1	1
GPS navigation	0	0	0	0	0	0	0	0	0	0	1	1
Messaging	0	0	0	1	1	1	1	1	1	1	1	1
Motion sensing	0	0	0	0	0	0	0	0	0	0	0	1
Organizing	0	0	0	0	0	0	1	1	1	1	1	1
Manipulating and analyzing data	1	1	1	1	1	1	1	1	1	1	1	1
Playing audio	1	1	1	1	1	1	1	1	1	1	1	1
Playing games	1	1	1	1	1	1	1	1	1	1	1	1
Playing videos	1	1	1	1	1	1	1	1	1	1	1	1
Printing	1	1	1	1	1	1	1	1	1	1	1	1
Recording still images	0	0	0	1	1	1	1	1	1	1	1	1
Recording video	1	1	1	1	1	1	1	1	1	1	1	1
Scanning	0	0	1	1	1	1	1	1	1	1	1	1
Storage	1	1	1	1	1	1	1	1	1	1	1	1
Viewing videos, images, & words	1	1	1	1	1	1	1	1	1	1	1	1
Web browsing & interactivity	0	1	1	1	1	1	1	1	1	1	1	1
Wi Fi connectivity	0	0	0	0	0	0	0	0	0	1	1	1

Table S-14 provides the diversity results that were used in Chapter III's analysis, as well as other diversity results computed using Microsoft Excel and ecological statistical software, Plymouth Routines in Multivariate Ecological Research (PRIMER) version 6 (Clark and Gorley 2006).

Table S-14 Primer V6 Diversity Results Used for Analysis

	Species Richness	**Total Number of Individuals**	**Pielou Evenness**	**Brillouin Diversity**	**Shannon Weiner Diversity**	**Simpson Dominance**
	S	N	J'	H	H' (loge)	Lambda
1990	8	3.5	0.68	0.37	1.42	0.34
1991	8	3.7	0.69	0.62	1.44	0.34
1992	9	4.0	0.67	0.62	1.48	0.34
1993	9	4.3	0.69	0.62	1.53	0.32
1994	9	4.8	0.72	0.82	1.58	0.31
1995	9	5.3	0.71	0.60	1.63	0.28
1996	10	5.9	0.71	0.80	1.70	0.26
1997	11	6.5	0.74	0.96	1.77	0.24
1998	13	7.4	0.73	0.96	1.86	0.21
1999	13	8.4	0.72	1.10	1.94	0.19
2000	13	9.5	0.74	1.15	2.02	0.18
2001	14	10.3	0.76	1.26	2.07	0.16
2002	15	11.4	0.77	1.30	2.13	0.15
2003	15	12.2	0.79	1.40	2.18	0.14
2004	16	13.2	0.81	1.44	2.25	0.13
2005	16	14.1	0.83	1.52	2.31	0.13
2006	16	15.1	0.84	1.53	2.37	0.12
2007	19	16.0	0.84	1.61	2.46	0.11
2008	20	17.3	0.85	1.68	2.54	0.10
2009	20	18.7	0.86	1.77	2.59	0.10
2010	20	20.1	0.87	1.83	2.62	0.09

7.2 Chapter IV’s Supplemental Tables

Tables S-15 to S-53 are associated with assumptions and analyses found in Chapter IV.

7.2.1. Summary of Literature

Table S-15 is a summary of literature used to identify energy consumption data points for this research. This summary is primarily composed of U.S.-based studies on consumer electronic products used by residents at the product, household, state, regional, or national studies. If life cycle impacts identified in the study are not based on the U.S., it is noted as a ‘global’ scale, or the country is indicated parentheses after the scale.

Table S-15 Literature Review of Energy Impact Studies

Study Source	Life Cycle Phase:			Scale	Products Included	Year	Impact Analyzed
	Manu-facturing	Use	End of life				
Deng et al. 2011	X	X		Product	Laptop (2001 Dell Inspiron 2500)	2002	Energy & GHG
Foster and Caldwell 2003		X		Product	Laptop and desktop (with CRT and LCD monitor)	NA	Energy
Hittinger 2011		X		Product	Gaming consoles	2005, 2007, 2010	Energy
King and Ponoum 2011		X		Product	LCD and Plasma TVs (active power mode use trends and power density trends (active and standby modes)	2003-2010	Energy
Koomey et al. 1995		X		Product	Office equipment (copiers, printers, fax, computer, monitor, mainframe)	1985 to 2002	Energy

Study Source	Life Cycle Phase: Manu-facturing	Use	End of life	Scale	Products Included	Year	Impact Analyzed
McWhinney et al. 2004		X		Product	Printers, fax machines, copiers, scanners, and multifunction devices for home/small business use	2002	Energy
Ostendorp et al. 2005		X		Product	TVs	2004	Energy
Roberson et al. 2002		X		Product	CRT and LCD monitors, desktop computer, laptop (office equipment)	2000-2001	Energy
Socolof et al. 2001	X	X	X	Product	CRT and LCD computer monitors	1999	Energy, materials, waste
Teehan and Kandlikar 2013	X			Product	Desktop, laptop, netbook, thin client device, LCD monitor, iPad, iPod Touch, Amazon Kindle, rack server, network switch	Depend on device (2002-2003, 2005, 2009-2010)	Mass, GHG
Williams 2004	X	X		Product	Pentium III desktop computer and 17 inch monitor	1997	Energy
Bensch et al. 2010		X		Household (Minnesota)	Computing, audio, phone, TV, HVAC, kitchen, and other plug-in devices	2009	Energy
Hertwich and Roux 2011	X	X	X	Household (Norwegian)	All products included in the European Union electric and electronic equipment category	2008	GHG

Study Source	Life Cycle Phase:			Scale	Products Included	Year	Impact Analyzed
	Manufacturing	Use	End of life				
Hendron and Eastment 2006		X		Product and Household (for 1,920 ft^2, three bedroom house in Colorado)	119 devices that supply miscellaneous electronic loads such as computing and entertainment devices, as well as kitchen, personal care, heating/cooling, and miscellaneous devices	2005	Energy
Peters et al. 2010		X		Product and Household (California)	Provided average energy consumption for 21 plug in devices but focused on 8.	2006	Energy
McAllister and Farrell 2007		X		Product and State (California)	34 miscellaneous household devices including VCR, mobile phone, laptop, MP3 player, video camera, camera	2003	Energy
Porter et al. 2006		X		Household, State (California), and National	Measured power draws for nearly 30 different consumer electronics	2005	Energy
Kawamoto et al. 2002				Product and National	Laptop, desktop computer, printers, copier, fax, monitor	1999	Energy
Meier et al. 1992		X		Product and National	35 appliances listed as miscellaneous end use	1989	Energy
Rosen et al. 2001		X		Product and National	Set top box (analog and digital), gaming consoles, and wireless receivers, answering machines, chargers, cordless phones, combined cordless phone/answering machines	1999	Energy

Study Source	Life Cycle Phase: Manu-facturing	Use	End of life	Scale	Products Included	Year	Impact Analyzed
Roth and McKenney 2007		X		Product and National	Answering machine, cable set-top box, compact audio, cordless telephone, desktop computer, DVD player, DVD recorder, home theater in a box, monitor, notebook computer, personal video recorder, satellite set-top box, television (analog & digital), video game console, and VCR	2006	Energy
Sanchez et al. 1998; Sanchez et al. 1998 (LBNL-40295)		X		Product and National	More than 90 miscellaneous residential products	1976-1995 and est. 1996-2010	Energy
Urban et al. 2011		X		Product and National	Audio visual equipment (receivers, blu-ray player, DVD devices, televisions, video game consoles), set top boxes, (cable satellite, telco, stand-alone), networking equipment (integrated access device, modem, router), desktop PC, portable PC, computer speaker, monitor, and Printer	2010	Energy
Zogg and Alberino 1998		X		Product and National	16 small residential kitchen appliances and some computing and entertainment devices: VCR, color TV, cable box, compact audio system, and computer	1997	Energy

Study Source	Life Cycle Phase: Manu-facturing			Scale	Products Included	Year	Impact Analyzed
	Manu-facturing	Use	End of life				
Huber 1997		X		National	435 audio, communication, computing, personal care, video, kitchen, and miscellaneous devices (standby power modes)	1997	Energy
Rosen et al. 1999		X		National	Home audio products clock radios, portable stereos, compact stereos, and component stereos	1998	Energy
Malmodin et al. 2010	X	X		Global	All products within information technology and communication and entertainment sectors	2007	Energy (use phase only) and GHG (manu-facturing and use phase)

Notes: Roth and McKenney (2007) list other sources of energy consumption data points for many of the devices included and limited information about other devices not included in the analysis. GHG is in CO_2-eq.

7.2.2 Community Structure

Table S-16 identifies the number and type of each product used in the analysis for each modeled year. This data is from a previous study (Ryen et al. 2014). Devices are grouped into assemblages based on timing of their first appearance in U.S. households and the closest subsequent EIO-covered year. For example, the '1992 assemblage' only consisted of devices introduced by and before 1992 (e.g., CRT TV and desktop computer), while the '1997 assemblage' is comprised of devices introduced after 1992, but through 1997 (e.g., the digital camera and camcorder).

Table S-16 Evolving Product Community Structure: Number and Type of Devices Owned in the Community

	Device	1992	1997	2002	2007	2010
1992	CRT TV	2.15	2.8	3.17	2.94	2.94
	VCR	0.57	1.0	1.79	1.81	1.77
	Desktop CPU	0.40	0.7	1.31	1.67	1.65
	CRT monitor	0.37	0.7	1.06	0.69	0.35
	Printer	0.18	0.4	0.77	1.08	1.13
	Gaming console	0.15	0.2	0.33	0.38	0.46
	Basic mobile phone	0.11	0.5	1.61	2.88	3.48
	LCD monitor	0.03	0.1	0.16	0.75	1.08
	Laptop	0.01	0.1	0.22	0.45	0.59
1997	Camcorder	0	0.04	0.13	0.19	0.32
	Camera	0	0.01	0.36	1.13	2.11
2002	DVD player	0	0	0.35	0.83	0.79
	MP3 player	0	0	0.07	0.33	0.50
	Smartphone	0	0	0.02	0.38	1.03
	LCD TV	0	0	0.01	0.30	0.98
2007	Plasma TV	0	0	0	0.11	0.25
	Blu-ray player	0	0	0	0.03	0.23
	Tablet	0	0	0	0.06	0.24
	E-reader	0	0	0	0.01	0.09

Notes: The devices are organized by year introduced into the community.
Reference: Ryen et al. 2014.

7.2.3. China-Based Manufacturing Energy

To account for the trend in overseas manufacturing of consumer electronics overseas, input values from the Chang et al. (2011) China-based IO model were used in a sensitivity analysis on manufacturing energy. Table S-17 compares IO sector information for U.S. and China, and is organized by product assemblage or year devices are introduced into the community.

Table S-17: Summary of U.S. and China IO Sector Information (Per Nominal U.S. Dollar and Yuan)

	U.S.				China		
	Products Included	**Sector Name**	**Sector Number**	**IO energy (MJ/USD)**	**Sector Name**	**Sector Number**	**IO energy (MJ/Yuan)**
1992	Desktop, laptop, gaming console	Electronic computer manufacturing	510103	6.0			
	Printer, CRT monitor, LCD monitor	Computer peripheral equipment	510104	6.8			
	Basic mobile phone	Communication equipment	560500	5.4			
	CRT TV and VCR	Household audio and video equipment	560100	10			
1997	Desktop, laptop, gaming console	Electronic Computer Manufacturing	334111	4.3			
	Printer, CRT monitor, LCD monitor, camera	Other Computer Peripheral Equipment Manufacturing	334119	4.5			
	Basic mobile phone	Broadcast and wireless communications equipment	334220	3.7			
	CRT TV, VCR, Camcorder	Audio and video equipment manufacturing	334300	7.0			
2002	Desktop, laptop, gaming console	Electronic Computer Manufacturing	334111	4.3	Electronic computer	75	3.66
	Printer, CRT monitor, LCD monitor, camera	Other Computer Peripheral Equipment Manufacturing	334119	5.4	Other computer device manufacturing	77	
	Basic mobile phone and smartphone	Broadcast and wireless communications equipment	334220	4.8	Communication equipment	74	3.51
	CRT and LCD TVs, DVD player, VCR, MP3 player, camcorder	Audio and video equipment manufacturing	334300	8.4	Household audio-visual equipment manufacturing	79	3.92

	U.S.				China		
	Products Included	**Sector Name**	**Sector Number**	**IO energy (MJ/USD)**	**Sector Name**	**Sector Number**	**IO energy (MJ/Yuan)**
2007	Desktop, laptop, e-reader, tablet, gaming console	Electronic Computer Manufacturing	334111	3.1 (est.)	Electronic computer	84	2.71
	Printer, CRT monitor, LCD monitor, camera	Other Computer Peripheral Equipment Manufacturing	334119	4.2 (est.)	Electronic computer	84	
	Basic mobile phone and smartphone	Broadcast and wireless communications equipment	334220	4.0 (est.)	Communication equipment	82	2.85
	CRT, LCD, and Plasma TVs, DVD player, VCR, blu-ray player, MP3 player, camcorders	Audio and video equipment manufacturing	334300	6.9 (est.)	Electronic appliances	86	2.75

Note:

- U.S.-manufacturing data from CMU (2008)
- IO Sector Energy (MJ per US or Yuan) is in nominal dollars.
- For the US manufacturing data: used 1992 producer price model 485 sectors, 1997 producer price model has 491 sectors, and the 2002 producer price model has 428 sectors.
- U.S. 2007 manufacturing IO energy is estimated based on data points from the 1992, 1997, and 2002 models (see Table S-?)
- China IO manufacturing energy data is from Chang et al. (2011). Chinese IO manufacturing data is based on 42 sectors for 2002 products and 2007 IO data is based on 135 sectors. Due to sector aggregation for the 2007 manufacturing data, only one sector (#84) is used for desktop, laptop, e-reader, tablet, gaming console, printer, monitors, and camera.

7.2.4 Extrapolating 2007 IO Energy (MJ) Per Dollar

Energy per IO sector data for 2007 was projected using a linear extrapolation of existing aggregated IO sector level energy per input dollar from the 1992, 1997, and 2002 IO sector data points. The estimated 2007 IO sector energy data points were used to suggest how introductions of newer products such as plasma TVs, tablets, and e-readers contributed to overall changes in net household energy demand. This approach was deemed reasonable because converting energy per constant input dollar for each IO sector indicated a relatively flat trend for the time period covered as shown in Table S-18. Further, the products added to the community in that time frame also had very low ownership rates. Using the U.S. BEA CPI calculator, the conversion of nominal to real dollar was based on the ratio of $1.00 in each year divided by the dollar value in 2007. IO energy (MJ) per nominal dollar used for each product is summarized in Table S-19.

An example of converting IO energy (MJ) per nominal dollar to IO energy (MJ) per real 2007 dollar is noted below for the electronic computer manufacturing sector in 1992:

$\text{IO energy}_{\text{electronic computer manufacturing}}$ per real dollar_{2007} = $\text{IO energy}_{\text{electronic computer manufacturing}}$ per nominal dollar_{1992} $*(\$1.00_{1992}/(\$1.48_{2007}) = 6.03 * 0.68 = 4.1$

Table S-18 Estimation of 2007 IO sector energy per real U.S. dollar

Sector	1992	1997	2002	2007
Per nominal U.S. Dollar:				
Electronic computer manufacturing	6.03	4.32	4.28	3.1
Computer peripheral equipment	6.81	4.5	5.41	4.2
Communication equipment	5.43	3.73	4.78	4.0
Household audio and video equipment	10	6.98	8.43	6.9
$1.00 worth in 2007:	$1.48	$0.77	$0.87	$1.00
Per constant U.S. Dollar (2007):				
Electronic computer manufacturing	4.1	3.3	3.7	3.0
Computer peripheral equipment	4.6	3.5	4.7	4.0
Communication equipment	3.7	2.9	4.2	3.9
Household audio and video equipment	6.8	5.4	7.3	6.6

Note: 2007 values are estimated based on a linear extrapolation of the IO sector energy/dollar from 1992, 1997, and 2002 using the CMU (2008) EIO LCA online tool.

Table S-19 Summary of IO energy (MJ/USD) per product (U.S.-based manufacturing, in nominal US dollars)

	Device	1992	1997	2002	2007
1992	CRT TV	10	7.0	8.4	6.9
	VCR	10	7.0	8.4	6.9
	Desktop CPU	6.0	4.3	4.3	3.1
	CRT monitor	6.8	4.5	5.4	4.2
	Printer	6.8	4.5	5.4	4.2
	Gaming console	6.0	4.3	4.3	3.1
	Basic mobile phone	5.4	3.7	4.8	4.0
	LCD Monitor	6.8	4.5	5.4	4.2
	Laptop	6.0	4.3	4.3	3.1
1997	Camcorder	10	7.0	8.4	6.9
	Camera	6.8	4.5	5.4	4.2
2002	DVD player	0	0	8.4	6.9
	MP3 player	0	0	8.4	6.9
	Smartphone	0	0	4.8	4.0
	LCD TV	0	0	8.4	6.9
2007	Plasma TV	0	0	0	6.9
	Blu-Ray player	0	0	0	6.9
	Tablet	0	0	0	3.1
	E-reader	0	0	0	3.1

Note: IO energy for 2007 was estimated based on IO values for 1992, 1997, and 2002 from the CMU (2008) EIO LCA online tool. Devices organized by year introduced into the community. IO energy values are in MJ per nominal USD.

7.2.5. Summary of Consumer Prices

Consumer prices were from publicly available trade publication and commercial sources such as the Consumer Electronics Manufacturing Association (1998), review articles, or *Consumer Reports* publications. A summary of consumer prices converted into producer prices for the model is shown in Table S-20.

Table S-20 Summary of average nominal consumer prices

	Device	1992	1997	2002	2007	Sources
1992	CRT TV	$663	$546	$479	$590	a
	VCR	$428	$256	$99	$97	b
	Desktop CPU	$1,364	$1,982	$810	$581	c
	CRT monitor	$1,471	$767	$284	$134	d
	Printer	$403	$390	$207	$186	e
	Gaming console	$215	$150	$152	$371	f
	Basic mobile phone	$294	$109	$117	$77	g
	LCD monitor	$2,999	$2,000	$515	$227	h
	Laptop	$2,217	$2,525	$2,212	$753	i
1997	Camcorder	na	$1,229	$1,168	$492	j
	Camera	na	$560	$499	$295	k
2002	DVD player	na	na	$271	$90	l
	MP3 player	na	na	$240	$204	m
	Smartphone	na	na	$487	$500	n
	LCD TV	na	na	$2,219	$580	o
2007	Plasma TV	na	na	na	$1,271	p
	Blu-ray player	na	na	na	$280	q
	Tablet	na	na	na	$1,962	r
	E-reader	na	na	na	$471	s

Note:

- Devices are organized by year introduced into the community and are in nominal dollars.
- Average CRT and LCD TV prices are based on 27-inch screens (except for the 2007 LCD is based on 26-inch screen size). Average prices for plasma TVs are based on 42-inch screens.
- Average prices for CRT and LCD monitors are based on 17-inch screen.
- Laptops prices are based on screen sizes of 8-10 inches for 1992, 11-12 inches for 1997, 14-15 inches for 2002, and 15-inch budget models for 2007.
- 1992 printers are a combination of inkjet and laser, 1997 are inkjet, and 2002 and 2007 are inkjet, laser, and multifunctional.
- Because desktop CPU prices in 1992, 1997, and 2002 are tied with monitors, average prices were calculated first by adjusting each individual data point exclude the price of the monitor. 1992 and 1997 data points are adjusted are based on a15-inch CRT monitor from 1997, and 2002 data points are adjusted based on the average price of a 17-inch CRT monitor from 2002. 1997 and 2002 monitors are based on typical model for that year. The 1997 desktop CPU models included a 200-MH processor and Pentium MMX or Cyrix 6x86 PR200+ and 17-inch monitor. 2002 desktop CPU models included a 2.0 GH Pent 4 processor, 60-80 GB HD, 256 RAM, and 17-inch CRT monitor.
- Average prices for e-readers are based on 6-inch screen size.
- Average prices for tablets are based on a combination of 5 to 12 inches.

Sources:

- a) Consumer Reports Books 1992, 1995; Consumer Reports 2002, 2005
- b) Consumer Reports Books 1992;Consumer Reports 2002, 1997;
- c) Ballou 1992; Lewis 1992; Hildebrand 1992; Consumer Reports 1997, 2002, 2006
- d) Consumer reports 2002, 1997; CNET 2007; Retrevo 2013; Hurricane Computer Systems 2013; Teksale.com 2013; Gruman 1992; Pepper 1992.
- e) Consumer Reports 1997, 2002; Consumer Reports Books 1992; Consumers Union of United States 2007.
- f) Consumer Reports 2003; Malik 1997; Miller 2005; Shilov 2007; CNET 2009.
- g) Consumer Reports 1997, 2003; Consumers Union of United States 2007; CEMA 1998;
- h) Consumer Reports 1997; Consumer Reports 2002; Consumer Reports 2007; Gruman 1992; Pepper 1992. English 1992; Teresko 1996
- i) Consumer Reports 1993. PC Magazine 1997; Kirchner 1998; Chen 2010.
- j) Consumer Reports 1999; 2001; Consumers Union of United States 2007.
- k) CEMA 1998; Consumer Reports 2003; Consumers Union of United States 2007
- l) Consumer Reports 2000, 2003; Consumers Union of United States 2007
- m) Consumer Reports 2001; Consumers Union of United States 2007
- n) Clark 2002; Consumer Reports 2007
- o) Consumer Reports 2003; Consumers Union of United States 2007
- p) Consumers Union of United States 2007
- q) Consumer Reports 2009.
- r) PCMag 2007; Glade 2007; Patel 2007; Thornton 2007; Boggs 2007; Cheng 2007
- s) Consumer Reports. 2009, 2010.

7.2.6 Adjusting Consumer Prices to the Appropriate Model Year

For some products, consumer prices from the modeled years were not available, and so estimates were obtained from close years and then inflated or deflated to the appropriate model year (1992, 1997, 2002, and 2007). This step was conducted using a ratio of producer price index values (PPI) from the U.S. Bureau of Labor and Statistics (BLS) (2013) (See Tables S-21 to S-23). According to the U.S. BLS, PPI measures average changes in selling prices that domestic producers received for their output of products and services (2014). PPI was used rather than the Consumer Price Index (CPI) because it provided more detailed inflation/deflation values for each IO sector. For certain products that needed to be adjusted (i.e., gaming console and printers), PPI values were not available until after 1992. Therefore, prices were converted using BLS's CPI inflation calculator (2013).

An example of changing the consumer price for a 2009 LG BD390 blu-ray player ($P_{c,2009}$) of \$330 to the 2007 consumer price ($P_{c,2007}$) is noted below:

$$P_{c,2007} = P_{c,2009} * (PPI_{2007}/PPI_{2009}) = \$330*(131.6/131.8) = \$329$$

Table S-21 PPI values: electronic computer, audio and video equipment manufacturing, 1992-1999

Product	PPI Info	1992	1993	1995	1996	1997	1999
Laptop, tablet, e-reader	PCU 33411133411172- Electronic computer manufacturing	11751.9	10088.7				
TVs, monitors	PCU 334310334310 - Audio & video equipment manufacturing			82.6	82.4	80.5	
MP3 player, Camcorder, DVD player, VCR, blu ray player	PCU 3343103343105- Other consumer audio and video equipment, incl. audio & video recorders & players (camcorders)					132.7	133.2

Note: Only the years used in the analysis are included in the table. Source: U.S. BLS 2013.

Table S-22 PPI values: electronic computer, audio and video equipment manufacturing, 2001-2010

Product	PPI Info	2001	2002	2003	2005	2006	2007	2009	2010
Laptop, tablet, & E-reader	PCU 33411133411172- Electronic computer manufacturing		396	299.8		127.8	97.1		46.5
TVs & monitors	PCU 334310334310 - Audio and video equipment manufacturing		74	72.8	69.2		65.8		
MP3 player, Cam-corder, DVD player, VCR, & blu ray player	PCU 3343103343105- Other consumer audio and video equipment, incl. audio & video recorders & players (camcorders)	135.6	134.4	134.6			131.6	131.8	

Note: Only the years used in the analysis are included in the table. Source: U.S. BLS 2013.

Table S-23 PPI Values: personal computer, computer and peripheral equipment, and broadcast and wireless communication manufacturing

Product	PPI Info	1992	1993	2002	2003
Desktop CPU Gaming console	PCU33411133411173-Personal computers and workstations (excluding portable computers)			336	268.9
Printer Digital camera	PCU 33411-33411-Computer & peripheral equipment manufacturing			139.5	123.9
Basic mobile & smart phones	PCU334220334220 -Broadcast and wireless communication equip manufacturing	101.6	102.9		

Note: Only the years used in the analysis are included in the table. Source: U.S. BLS 2013.

7.2.7 Converting Consumer to Producer Prices

Producer prices in the year corresponding to modeled years (1992, 1997, 2002, and 2007-forecast) were as used as inputs for the producer price EIO models. Because consumer, rather than producer, prices are more readily available from public sources, consumer prices were transformed into producer prices. A product's average consumer price is multiplied by the ratio (f_{io}) of the relevant IO sector producer price values to consumer (purchaser) price values from the U.S. Bureau of Economic Analysis (BEA) Bridge Tables for Personal Consumption Expenditures for 1992, 1997, 2002, and 2007. An example of converting a consumer (i.e., purchaser) price to a producer price (P_p) is noted below for the 2007 blu ray player:

$P_{p,2007} = P_{c,2007} * f_{io\ 334300,2007}) = \$280 * 0.63 = \$177$

Table S-24 summarizes conversion factors calculated from the purchaser and producer price values from the U.S. BEA.

Table S-24 Conversion factors for each IO sector

Year	IO sector	Description	Purchaser Price	Conversion Factor (f_{io})	Producer price
1992	510103	Electronic computers	$5,271	0.59	$3,104
1997	334111	Electronic computer manufacturing	$12,553	0.61	$7,647
2002	334111	Electronic computer manufacturing	$17,031	0.63	$10,700
2007	334111	Electronic computer manufacturing	$27,428	0.61	$16,732
1992	510104	Computer peripheral equipment	$3,501	0.57	$1,996
1997	334119	Other computer peripheral equipment manufacturing	$9,603	0.64	$6,132
2002	33411A	Computer terminals and other computer peripheral equipment manufacturing	$12,391	0.55	$6,828
2007	33411A	Computer terminals and other computer peripheral equipment manufacturing	$10,668	0.64	$6,790
1992	560100	Household audio and video equipment	$28,933	0.60	$17,398
1997	334300	Audio and video equipment manufacturing	$3,066	0.47	$1,452
2002	334300	Audio and video equipment manufacturing	$18,418	0.64	$11,741
2007	334300	Audio and video equipment manufacturing	$36,863	0.53	$19,536
1992	560500	Communication equipment	$1,341	0.69	$921
1997	334220	Broadcast and wireless communications equipment	$746	0.66	$495
2002	334220	Broadcast and wireless communications equipment	$1,834	0.64	$1,177
2007	334220	Broadcast and wireless communications equipment	$959	0.49	$466

Notes: Data is from U.S. BEA 1992, 1997, 2002, 2007.

7.2.8 Calculation of Use Phase Energy

The annual average unit energy consumption (UEC) amount of energy consumed per device per year. The annual average UEC is calculated as the product of each power draw (watts) per mode and usage (hours/year) per mode for each year. Tables S-25 to S-45 identify the power draws, usage assumptions, and references used to calculate average UEC for each device in a given year. Table 6 in the main document summarizes the UEC values used in the analysis. This section also describes how use phase energy was disaggregated for devices such as the TV and desktop, which are owned in quantities greater than one and how certain model year use phase energy was forecasted.

7.2.8.1 Disaggregation of Use Phase Energy for Desktop CPUs and TVs

Because desktop computers and televisions were owned in quantities greater than one, it stands to reason that household members are unlikely to use these devices equally. Instead, it is expected that, say, one TV is the primary one selected for main viewing, with additional TVs used less frequently. Therefore, estimates of use phase energy must take into account the different use patterns and power consumption in parallel primary and secondary uses. The televisions (TV) were particularly complicated because in 2007 a household owned three different types of TVS (plasma, LCD, and CRT), but only the equivalent of ‘one’ TV would be viewed as a primary device. The net energy impact for all the televisions owned by an average U.S. household in 2007 was based on summation of the use phase energy for the equivalent of one TV viewed as the primary device and use phase energy for the remaining devices viewed on a secondary basis. One primary TV was equal to all plasma and LCD TVs in addition to a number of CRT TVs to equal a balance of 1 (0.11 plasma + 0.3 LCD + 0.59 CRT = 1 primary TV). The remaining CRT TVs (2.94 - .59 = 2.35) were assumed to be viewed on a secondary usage basis. Differentiation between primary and secondary usage patterns was confirmed by sources (Rosen et al. 1999; Ostendorp et al. 2005; Roth and McKenney 2007; Urban et al. 2011) that noted varied consumer use patterns for multiple devices.

Primary TV Energy Demand$_{2007}$ (kWh):
= (.3 TV$_{lcd,2007}$)* (Primary TV$_{lcd,2007}$ Use phase energy kWh) +(.11 TV$_{plasma,2007}$)* (Primary TV$_{plasma,2007}$ use phase energy kWh) + (.59 TV$_{CRT,2007}$)* (Primary TV$_{CRT,2007}$ use phase energy kWh/year)

= (.3 * 229 kWh/year) +(.11* 568 kWh/year) + (.59 * 214 kWh/year) = 69 + 62+126 =257 kWh/year

Secondary TV energy demand$_{2007}$ (kWh):
= 2.35 TV$_{CRT,2007}$ * Secondary TV$_{CRT,2007}$ use phase energy kWh = 2.35 *147 kWh/year = 346 kWh/year

7.2.8.2. Unit Energy Consumption For Each Product

Tables S-25 to S-45 identify the existing data points (power mode, usage, and total unit energy consumption) found in the literature and used to represent or estimate use phase energy. If data is not available for the years 1992, 1997, 2002, or 2007, then UEC is either forecasted using linear regression in Excel (with the forecast function) based on existing power draws and usage information or from UEC data points (as noted by the shading). If usage is estimated, then the off mode is calculated by subtracting the estimated active and sleep/standby modes from 8760 (total hours per year). UEC values are generally estimated, where needed, based on power modes and usage data points found in the literature (note 'a). If there are *less than five* consistent power draw and usage data points, then each product's UEC is estimated based on the UECs found in the literature (note 'b'). Exceptions are noted below in each table.

Products Introduced in 1992

Table S-25 Desktop CPU - primary

	Active (w)	Sleep (w)	Off (w)	Active (h/yr)	Sleep (h/yr)	Off (h/yr)	UEC (total kwh/yr)	Source	notes
1991	75	75						Koomey et al. 1995	Power/mode for non- energy star computer, no model specification
1998	40	25						Koomey et al. 1995	Power /mode for non- energy star computer, no model specification
1999	50	25	2	717	65	7978	49	Urban et al. 2011	Power enabled 25%, residential; used reported value
2001	50	25	1.5	1495	163	7102	89	Urban et al. 2011	Power enabled 20%
2005	75	4	2	2950	350	5460	234	Urban et al. 2011	Power enabled 20%, residential; used reported value
2006	75	4	2	2954	1779	5456	235	Urban et al. 2011	Power enabled 20%, residential; used reported value
2009	69	2		4088	4672		262	Bensch et al. 2010	Used reported UEC average number of active hours/day is 11.2-no off mode/hours data; UEC is based on average of 42 devices metered onsite; no model info

	Active (w)	**Sleep (w)**	**Off (w)**	**Active (h/yr)**	**Sleep (h/yr)**	**Off (h/yr)**	**UEC (total kwh/yr)**	**Source**	**notes**
2010	60	4	2	3530	2159	3071	227	Urban et al. 2011	UEC calculated based on power mode data and primary usage data noted in report; power enabled 20%
1992	69	66	2	284	263	8214	50		a
1997	54	39	2	352	321	8086	46		a
2002	40	11	2	1771	567	6422	89		a
2007	64	4	2	3190	2174	3396	218		a

Note: Primary desktop computer usage was based on Urban et al. (2011) and total hours per year of 8760. The 1992 and 1997 sleep usage data points were estimated with line estimate function (not forecast function)-otherwise the estimated data points would be negative. The active and sleep power modes for 92, 97, and 2002 were estimated based on 1991to 2001 data points because Energy Star standard 4.0 was implemented in 2007 (US Energy Star 2014).

Table S-26 Desktop CPU- secondary

	Active (w)	**Sleep (w)**	**Off (w)**	**Active (h/yr)**	**Sleep (h/yr)**	**Off (h/yr)**	**UEC (kwh/yr)**	**Source**	**notes**
2010	60	4	2	2717	2321	3,363	179	Urban et al. 2011	UEC is calculated is based on secondary computer usage data an primary power modes in Table S-25.
2002	40	11	2	1363	609	6787	74		a
2007	64	4	2	2455	2337	3967	173		a

Note: UEC values for 2002 and 2007 were estimated based on the primary computer power modes and usage data points were based on the ratio of 2010 primary and secondary computers active and sleep usage because only 2010 data points were available. For example, the 2002 active usage data point for secondary desktops is estimated by calculating the product of 2010 secondary usage data point and a ratio of the 2002 primary usage data point and 2010 primary usage data point.

Table S-27 Laptop

Year	Active (w)	Sleep (w)	Off (w)	Active (h/yr)	Sleep (h/yr)	Off (h/yr)	UEC (kWh/ yr)	Source	Notes
1999	15	3	0	521	261	7,978	9	Kawamoto et al. 2001	Power draws for a residential laptop is from Kawamoto et al. 2001
2000	19	3	2					Roberson et al. 2002	Average power modes were based on nine computers metered (2000 and 2001 computers)
2001	15	3	0	1,007	651	7,102	17	Roth and McKenney 2007; Meier et al 2008	UEC is calculated based on values shown in Roth et al. 2007
2002	18	9	1	2628	876	5256	63	Deng et al. 2011	Used hours from U.S. EPA Energy Star data from 2009
2005	25	2	2	2,368	935	5,457	72	Roth and McKenney 2007	Assumed power management enabled 40%
2006	25	2	2	2,368	935	5,457	72	Roth and McKenney 2007	Based on TIAX 2006 study
2009	30	1						Bensch et al. 2010	Active and sleep power draw values from metering study-based on 17 laptops metered
2010	19	2	1	3,030	2,258	3,467	66	Urban et al. 2011	Base on average annual usage values for a primary computer
2007	23	2	2	2,645	1,483	4,632	73		a
2002	19	4	2	1,606	699	6,455	46		a
1997	15	5	3	566	155	8,039	29		a
1992	10	6	3	210	144	8,406	28		a

Note: 1992 active usage and 1992 and 1997 sleep usage were estimated using line estimate function.

Table S-28 CRT monitor

	Active (w)	**Sleep/ stand-by (w)**	**Off (w)**	**Active (h/yr)**	**Sleep/ off (h/yr)**	**Off (h/yr)**	**UEC (kWh/yr)**	**Source**	**Notes**
1999	112	16	7	522	793	7445	123	Socolof et al. 2001	Average usage pattern (hrs/year) based on 1999 EIA REC report; power draws average of meter reads from 30+, 17 CRT monitors; 'sleep' mode is an average of their stand by and suspend consumption
2010	61	2	1	2336	2336	2811	150	Urban et al. 2011	Power draws are weighted average for screen size of 17; hours are just for desktop for computer monitors between 2006-2010 so this became the upper range
2001	61	2	1					Roberson et al. 2002	Average power draw for 17 in crt monitor-no usage information
2006	61	2	1	1865	875	2020	118	Roth and McKenney 2007	UEC is calculated. Power draws measured from 17 inch monitors and high usage based on higher penetration of high speed Internet access
2006	67.2	13.3					82	Porter et al. 2006	Average power modes and UEC from 17 in CRT monitor. No model info available
1992							99		b
1997							106		b
2002							113		b
2007							121		b

Table S-29 LCD monitor

	Active (w)	Sleep/ standby (w)	Off (w)	Active (h/yr)	Sleep/off (h/yr)	Off (h/yr)	UEC (kwh/yr)	Source	notes
1999	40	8	5.3	522	793	7445	66	Socolof et al. 2001	Average usage pattern (hrs/year) based on 1999 EIA REC report; power draws average of meter reads from 12-15 inch LCD monitors
2005	20	1	1.0	2482	3541	2701	56	Urban et al. 2011	Reported UEC for a 15 inch monitor actively used 6.8/hr day, sleep 9.7 hr/day and off 7.4 hr/day
2006	20	1	1.0	1865	875	6020	44	Roth and McKenney 2007	Used power draws for a 15 inch monitor and usage information originally from TIAXX 2008 survey.
2008	34	6	0.9					Urban et al. 2011	Only average power draws available; no model or screen size information available
2010	31	0.8		1935	6,825		65	Bensch et al. 2010	Average power draws for LD monitor and active on average 5.3 hr/day--no model or screen size information. Sleep hrs found in Urban et al. 2011 (citing Bensch study). Calculated UEC based on this information
2010	16	0.8	0.6	2482	3541	2701	43	Urban et al. 2011	Reported UEC for a 15 inch monitor actively used 6.8/hr day, sleep 9.7 hr/day and off 7.4 hr/day
1992	43	10	8	141	356	8263	74		a
1997	37	7	6	592	395	7774	68		a
2002	32	5	3	1295	1536	5930	68		a
2007	26	3	1	1998	3510	3253	65		a

Note: Active usage for 1992 and sleep usage for 1992 and 1997 were estimated using line estimate function rather than the forecasting function because the resulting data point would be negative.

Table S-30 Printer

Year	Active (w)	Sleep (w)	Ready (w)	Off (w)	Active (h/yr)	Ready (h/yr)	Sleep (h/yr)	Off (h/yr)	UEC (kWh/yr)	Source	notes
1995	45	15			45				20	Sanchez et al. 1998	Used 45 hours/year
2005									39	Bensch et al. 2010	Inkjet printer-no usage or model information
2005	15	9	6.2	5.3	7884		613	263	55	Urban et al. 2011	Ink jet MFD, from Ecos 2006, but noted in Urban et al. 2011-used reported UEC value
2005	9	3	1.7	1.9	88		8672		15	Urban et al. 2011	Single function inkjet printer; used reported UEC
2009	12.5	4.3							40	Bensch et al. 2010	No model specified, average UEC per year; assumes active 0.9 hours per day
2010	17	6	2	1	5	35	1220	7400	10	Urban et al. 2011	Single ink jet device; usage from EPA 2010 and EUP 2007b
2010	22	7	4	0.7	7	105	1211	7437	11	Urban et al. 2011	Inkjet MFD
1992									31		b
1997									30		b
2002									28		b
2007									27		b

Table S-31 VCR

	Active (w)	Idle (w)	Off (w)	Active (hr/yr)	Idle (hr/yr)	Off (hr/yr)	UEC (kWh/yr)	Source	Notes
1990							40	Meir et al. 1992	Average energy consumption for VCR-no info on model/usage pattern
1995	15.7	10.7	5.4	262	1,256	7,242	58	Sanchez et al. 1998; Roth and McKenney 2007	Used reported UEC. Usage and power draws originally from Carrie Webber
1998	17	13.5	5.9	240	2,429	6,091	71	Roth and McKenney 2007; Rosen et al. 1999	
2001							40	U.S. EIA 2001	
2005	16	12	4.5	156	793	7,811	47	Roth and McKenney 2007	UEC was calculated by on previous power draws and usage data from surveys. Their survey data showed VCRs are used an average of 156 hours per year (approximately 3 hours per week). Survey data noted that VCR players sit in idle mode an average of 15 hours per week (10% of the time not in active mode).
2006							39.3	Porter et al. 2006	Average annual energy usage based on 11 devices but power modes not available-no model information available
2006							34.3	Porter et al. 2006	Average annual energy usage based on 16 devices. No model information available. Only kwh/mode-year
2009	6.6	1.2					34	Bensch et al. 2010	Average of 13 devices metered and assumed 4.1 active hours per day- no model information available
2010	16	12	4.5	156	793	7,811	47	Urban et al. 2011	2010 UEC based on power draws from Roth et al. 2007 and usage from Bensch et al. 2010
1992	18	13	6	291	1850	6619	69		a
1997	15.7	10.7	5.6	264	1,259	7,237	57	Zogg and Alberino 1998; Roth and McKenney 2007	Reported UEC
2002	15	10	5	207	1246	7307	53		a
2007	13	9	5	165	943	7651	46		a

Table S-32 Gaming console

	Active (w)	Video (w)	Idle (w)	Off (w)	Active (hr/y)	Video (hr/y)	Idle (hr/y)	Off (hr/y)	UEC (kWh/y)	Source	Notes
1995	20		0	2	365		0	8,395	24	Sanchez et al. 1998; Urban et al. 2011	Sanchez et al. (1998)-Power draws same as ones in Huber 1997-same UEC reported in Sanchez 1998
1999	8		0	1	175			8,585	10	Urban et al. 2011; Rosen et al. 2001	Based on sample of 12 units
2005	172			2.2					106	Hittenger 2013	For original xbox 360 but with Hittenger usage patterns (from a Nielsen 2010 usage survey)
2005									20.4	Meier et al. 1992	no models indicated
2006	36		36	0.8	405		560	7,795	41	Roth and McKenney 2007	power draws are weighted averages of different game system consoles-usage time based on survey data averages
2007	189			1.1	81		9		90	Hittenger 2013	for original PlayStation 3, but with Hittenger (2013) usage patterns (from a Nielsen 2010 usage survey)
2010	85			0.5					40	Hittenger 2013	PS3slim and usage patterns is from a Nielsen 2010 usage survey
2010									80	Hittenger 2013	Nintendo WII connect 24 enabled and usage patterns from a Nielsen 2010 usage survey
2010	88			0.7					51	Hittenger 2013	Xbox 360s and usage patterns from a Nielsen 2010 usage survey
2010	89	151		2	750	700		7,310	135	Urban et al. 2011	UEC based on usage patterns rom a CEA survey that 10% left console on all the time-based on a weighted average of other video gaming systems. Combined video and navigation modes data points.
1992									24	Sanchez et al. 1998; Urban et al. 2011	According to Urban et al. 2010, the active power draw for the Nintendo systems in the 1990-1995 didn't change so I used the 1995 value for 1992 b

	Active (w)	Video (w)	Idle (w)	Off (w)	Active (hr/y)	Video (hr/y)	Idle (hr/y)	Off (hr/y)	UEC (kWh/y)	Source	Notes
1997									22		b
2002									44		b
2007									65		b

Table S-33 CRT TV- primary

	Active (w)	Sleep/off (w)	Active (h/yr)	Sleep/off (h/yr)	UEC (kwh/yr)	Source	Notes
1990					200	Meier et al. 1992	Average unit energy consumption for color TV-no screen size or model info
1995	77	4	1498	7262	141	Sanchez et al. 1998; Roth and McKenney 2007	4 hours a day of viewing. Usage and power draws are originally from Webber (LBNL) 2/97; used reported value of 141
1997	60	4	1456	7300	87	Zogg and Alberino 1998	Report uses 4 hr/day original from Webber 1997 (LBNL study), viewing it as the most realistic for HH viewing per day. Reports uses average active power draw of 60 as mid point power draw for screens 19-32 as most common. Didn't use their reported UEC of 117 which was a weighted average of all TVs in the household
1998	90	4.9	2591.5	8755.1	233	Rosen et al. 1999	Active and stand by watts are for a 25-27 inch TV (the report also indicates 75 and 4.5 watts as weighted average for all TVs); primary TV is watched 7.1 hours per day--study is the remaining time
2001					137	U.S. EIA 2001	Based on UEC for Color TV
2004	86	3.9	1825	6935	184	Ostendorp et al. 2005	Assumes active power for a crt analog of less than 40 inch as primary TV (about 5 hours per day)-viewing time based on US Census data from 2000.
2005					215.5	Hendron and Eastment 2006	No model, power, or usage information--UEC is for the first color TV
2006	115	4	2592	6169	323	Roth and McKenney 2007	Calculated UEC value based on power modes and usage information for a 30 inch analog primary TV watched 7.1 hours/day
2006	92	1.2	1898	6862	178	59 Roth and McKenney 2007	Digital CRT TV average UEC for average 32 inch TV watched 5.2 hours/day
2006					123	Porter et al. 2006	UEC values only based on 78 metered-no model info
2009			2373	6388		Urban et al. 2011	Primary TV usage information only based on survey showing active usage of 6.5hr/day
2009	80.2	4.6	1424	7337	137.2	Bensch et al. 2010	Assumes 3.9 hours/day and average power mode and UEC for TV between 26 - 31 inches; used reported UEC
1992	70	4	1733	7027	152		a
1997	78	4	1835	6925	171		a
2002	86	4	1937	6823	192		a
2007	93	4	2038	6722	214		a

Table S-34 CRT TV- secondary

	Active (w)	Sleep/ standby (w)	Active (h/yr)	Sleep/off (h/yr)	UEC (kwh/yr)	Source	Notes
1995	77	4	1095	7665	115	Sanchez et al. 1998 as noted in Roth and McKenney 2007; Ostendorp et al. 2005	Calculated using data from Sanchez et al.(1998) as noted in Roth and Mckenney and secondary active viewing of 3 hours/day from dorf 2005
1997	60	4	1095	7665	96	Zogg and Alberino 1998; Ostendorp et al. 2005	Assumes 3 hours for active viewing for a secondary TV from Ostendorf 2005 and same power draw as primary from Zogg and Alberino 1998
1998	90	4.9	1168	7592	142	Rosen et al. 1999	Rosen et al. 1999 recommend average secondary TV active usage of 3.2 hours/day in a 2 TV household; power draws per mode are from primary TV; UEC is calculated.
2006	93	4	1533	7227	171	Roth and McKenney 2007	this is calculated based on the report's average active power draw and standby modes for 24 inch TV that is viewed as a secondary TV. The report notes secondary TV usage of 4.5 viewing hours/day-household.
2004	86	3.9	1095	7665	124	Ostendorp et al. 2005	Assumes same power draws as primary, but 3 active hours of viewing for a second TVs and power draws for screen size of less than 40 inch
2009			1132	7629		Urban et al. 2011	Secondary TV usage information (3.1h/day) only
1992	67	4	1066	7694	105		a
1997	76	4	1129	7631	118		a
2002	85	4	1252	7567	137		a
2007	93	4	1256	7504	147		a

Table S-35 Basic mobile phone

	Active/ Charg-ing (w)	Standby/ charging main-tenance (w)	No load (w)	Off (w)	Active/ charg-ing (hours/ yr)	Standby/ charging main-tenance (hr/yr)	No load (hr/yr)	Off (hr/ yr)	UEC (kWh/ yr)	Source	Notes
1999		0.6							2.3	Rosen et al. 2001	Based on sample of 7 most popular cell phones/chargers-but felt confident on data b/c chargers do not vary much. Charged 50 times/year for 2 hours.
2003	3.72	0.53	0.45						4.9	McAllister and Farrell 2007	Based on survey of 34 households in California and measurement of 9 devices
2006	3.7	0.5	0.25		265	1,050	7,445		3.5	Roth and McKenney 2007	
2006									2.9	Porter et al. 2006	No models identified. Based on 26 models metered
2009	4	0.1			109.5				1.1	Bensch et al. 2010	Based on survey in 2009 and metering of four cell phone charging devices with .3 active hours/day
2010	4	2.2		0.2	110			8650	2.2	Urban et al. 2011	
1992									9.8		b
1997									7.5		b
2002									5.1		b
2007									2.8		b

Products Introduced in 1997

Table S-36 Camera

	Charg-ing (W)	No load* (W)	Standby /charging maintenance (W)	Off (W)	Charg- ing (hr/yr)	Standby/ charging maintenance (hr/yr)	Off (hr/yr)	UEC (kWh/yr)	Source	Notes
2004	3	0.2	0.2					7.2	McAllister and Farrell 2007	Average UEC from 2 devices
2006	1.8		0.3					3.3	Porter et al. 2006	Based on two devices-model information unknown from homes from field tests in CA homes in 2006
2006								4.2	Porter et al. 2006	Based on three devices; wattage or usage not available--model information unknown from homes from field tests in CA homes in 2006
2009	2							11.4	Bensch et al. 2010	Average kwh/year based on two chargers metered
2010	4			0.3	13		8752	3	Urban et al. 2011	Calculated based on power draws and usage information noted in report. The active charging and off hours is based on Wood 2011's estimates of 2,000 images per year for a typical user and 150 images/charge, yielding about 13 hours/year charging (Wood 2011)
1992								na		na
1997								5.0		b
2002								5.4		b
2007								5.8		b

Note: No load refers to charger plugged in, but device is not in the charger. Charging maintenance (from McAlliser and Farrel 2004) is similar to standby and refers to a device in a charger, but fully charged. So a continuous charge is being drawn.

Table S-37 Camcorder

	Charg -ing (w)	**No load (w)**	**Standby/ idle/ charging maintennace (w)**	**Off (w)**	**Charg -ing (hr)**	**no load* (hr/yr)**	**Standby/ idle/ charging maintenance (hr/yr)**	**Off (hr/yr)**	**UEC (kWh/ yr)**	**Source**	**Notes**
2003	9.6	0.37	0.39						2.3	McAllister and Farrell 2007	Average UEC from two devices; this value was used in Roth et al. 2007 for the 2006 Camcorder UEC
2006	10		0.4	0.4	0.3		15.8	8	4	Groves 2009	No model information given. Assumed device is actively charged 0.3 hours per day, idle 15.8 hours/day and off 8 hours/day and is based on McAllister and Farrell 2007 data
2010	9.6		0.4	0.4					2.4	Urban et al. 2011; McAllister and Farrell 2007	
1992									na		na
1997									3.0		b
2002									2.9		b
2007									2.9		b

Products Introduced in 2002

Table S-38 MP3 player

	No load (w)	Charging (w)	Idle (w)	No load (hr/yr)	Charging (hr/yr)	Idle (hr/yr)	UEC (kWh/yr) hr/yr)	Source	Notes
2003							5.6	McAllister and Farrell 2007	Based on a measurements 3 devices
2006	0.3	3.7	0.6	4818	526	1134	4.1	Roth and McKenney 2007 and Rosen et al. 1999	Calculated based on power draws in McKenney 2007 and usage (1999 estimate) from Rosen et al. 2000
2006							5.8	Porter et al. 2006	Based on 1 device, modes unknown
1992							na		na
1997							na		na
2002							5.8		b
2007							4.7		b

Table S-39 Smartphone

	Active/ Charging (w)	Standby/ charging maintence (w)	Off (w)	Active/ Charging (hrs/year)	Standby/ charging maintence (hrs/year)	Off (hrs/yr)	UEC (kWh/yr)	Source	Notes
2007							2.2	EPRI 2013	iPhone 3 g, launched in 2007; charged every day
2010							3.3	EPRI 2013	iPhone 4; charged every day
2012	5						4.5	Fischer 2012	Based on Galaxy SIII consuming 12.3 watts to charge, taking 2 hours and 26 minutes. Maximum wattage is 6.6 watts, with an average of approximately 5.0 W.
2012	5						3.5	Fischer 2012	Based on iPhone 5: consuming 9.5 watt to charge, taking 1 hour and 50 minutes. Maximum wattage is 6.3 watts, with an average of approximately 5.0 W.
1992							na		na
1997							na		na
2002	4.7	0.4	0.4	265	1050	7445	4.6	Nokia 2002; Urban et al. 2011	UEC calculated based on the power draws of a Nokia 7650, released in 2002 and charges for 1 hour and 50 min; assume off and standby have same watts; usage from Urban et al. 2011 for 2007.
2007							3.7		b

Table S-40 LCD TV

	Active (w)	**Sleep/ off (w)**	**Active (hr/yr)**	**Sleep/off (hr/yr)**	**UEC (kWh/ yr)**	**Source**	**Notes**
2004	125				255	Ostendorp et al. 2005	32 in Sony KLV-32M1 measured by Ecos Consulting in 2004 as noted in Ostendorp et al. 2005; UEC as reported from report
2004	157				314	Ostendorp et al. 2005	32-inch screen Toshiba 32HL83P measured by Ecos Consulting in 2004 as noted in Ostendorp et al. 2005; UEC as reported from report
2004	52				122	Ostendorp et al. 2005	17-inch zenith L17W36 measured by Ecos Consulting in 2004 as noted in Ostendorp et al. 2005; UEC as reported from report
2004	49				116	Ostendorp et al. 2005	20-inch screen, Xenith L20V26c measured by Ecos Consulting in 2004 as noted in Ostendorp et al. 2005
2006	87	0.9	2409	6351	215	Roth and McKenney 2007	Reported average UEC was 166 b/c it assume 5.1 hr/day for that screen size. This UEC was calculated using primary TV viewing of 6.6 hr/day and power draws for a 26 inch screen
2006	72	0.9	2409	6351	179	Roth and McKenney 2007	This UEC was calculated using primary TV viewing of 6.6 hr/day and weighted average power draws from all TVs, but for an average size of 23 inch
2006					76.7	Porter et al. 2006	Average annual energy use for 4 LCD TVs-no screen size/model info
2009	75.7	1.9	3942	4818	329.7	Bensch et al.2010	Power draws for average household with screen size of 26-31 inches. UEC is their average reported. TV of this size found to watched 10.8 hours/day
2010			2373	6388		Urban et al. 2011	Average primary TV is watched 6.5 hours per day
2002					142		b
2007					229		b

Table S-41 DVD player

	Active (w)	Sleep/ standby (w)	Off (w)	Active (hr/yr)	Sleep/ standby (hr/yr)	Off (hr/yr)	UEC (kWh/yr)	Source	Notes
1998	17	15	4	350	2102	6307	64	Rosen et al. 1999	
2005							50	Hendron and Eastment 2006	
2005	11	5	1	964	88	7709	19	Urban et al. 2011	Based on weighted average of power draw and off; idle based on Meier et al 2008; usage from CEA survey
2006							29	Porter et al. 2006	Average annual energy usage for 2 devices
2006	15	11	3	270	900	7590	37	Roth and McKenney 2007	
2007	13	10	2	270	900	7590	30	Urban et al. 2011	Reported UEC
2008							21	Öko-Institut e.V. 2010	Average of 24 DVD players
2009							23.9	Bensch et al. 2010	DVD player only-average of 37 devices metered
2010	9	5	2	210	700	7850	18	Urban et al. 2011	reported UEC
1992							na		na
1997							na		na
2002	15	12	3	454	1322	6985	43		b
2007	12	8	2	390	722	7648	25		b

Products Introduced in 2007

Table S-42 Plasma TV

	Active (w)	Sleep/ standby (w)	Active (hr/yr)	Sleep/off (hr/yr)	UEC (kWh/yr)	Source	notes/screen
2009	387				610	Bensch et al. 2010	UEC based on power draw of 387 and 32+ inch screen
2009			2373	6388		Urban et al. 2011	Usage only information for a primary TV (6.5 h/day)
2006	256	3.7	2409	6351	640	Roth and McKenney 2007	for plasma screens less than 41 assumes watched 6.6 hours per day on average (primary TV)
2006	245.9	0.9	1767	7000	440.7	Porter et al. 2006	usage is back calculated from active and standby kwh/yr and power draw data points; data from two TVs metered, no screen size available
2004	257				496	Ostendorp et al. 2005	42 inch screen, Zenith P42W34/34H measured by Ecos Consulting in 2004 as noted in Ostendorf et al. 2005
2004	287				550	Ostendorp et al. 2005	42 inch screen, Sony KE-42x5910 measured by Ecos Consulting in 2004 as noted in Ostendorf et al. 2005
2007					568		b

Table S-43 Blu-ray player

	Active (w)	Idle (w)	Off (w)	Active (hr/y)	Idle (hr/yr)	Off (hr/y)	UEC (kWh/y)	Source	Notes
2008	26.3		0.6	730		8,030	24	Öko-Institut e.V. 2010	average of 28 devices,
2010	18.5	15.9	0.2					Sust-it 2010 as noted in Urban et al. 2011	Power draws from Sust-it 2010 average power draws are an average of 62 devices and from Sust-it 2010
2010	30	16	0.5	300	30	8430	14	Urban et al. 2011	Power draws from usage survey in 2010
2007							29		b

Table S-44 E-reader

	Active Charging (watt)	Off (w)	Active Charging (hr/yr)	Off (hr/yr)	UEC (kWh/yr)	Source	Notes
2002-2006	11	0	1092	7644	12	Kozak 2003	Assumes 3 hours/ per day of charging-otherwise assume rest of day unplugged and device is RCA REB 1100, screen size of 5.5 inches
1992					na		na
1997					na		na
2002					na		na
2007					12		UEC for 2007 is the same as the data point from Kozak 2003 due to the lack of information.

Note: Active charging means the device is plugged in while charging

Table S-45 Tablet

	UEC (kWh/yr)	Source	Notes
2012	11.9	EPRI 2013	iPad 3,assumed it is charged every other day
2011	7.2	EPRI 2013	iPad 2, assumed it is charged every other day
2010	7.1	EPRI 2013	iPad 1,assumed it is charged every other day
1992	na		na
1997	na		na
2002	na		na
2007	7.1		Assumed the same UEC for 2010 due to lack of data and forecasting creates negative values

7.2.8.2 Converting kWh to MJ

To convert kWh to MJ, the consumption-weighted unit energy consumption is multiplied by the conversion factor of 11.3 MJ/kwh (US EPA 2006), which accounts for both the unit conversion of 3.6 MJ/kWh and the cumulative energy inputs required to produce the electric energy output as noted below:

Consumption-weighted Primary TV Energy Demand$_{2007}$ (MJ):
= (Primary TV$_{lcd,2007}$ Use phase energy kWh)*(11.3 MJ/kWh) +(Primary TV$_{plasma,2007}$ use phase energy kWh)*(11.3 MJ/kWh)) + (Primary TV$_{CRT,2007}$ use phase energy kWh/year) *(11.3 MJ/kWh)

= (69 kWh/year) *(11.3 MJ/kWh) +(62 kWh/year) *(11.3 MJ/kWh)+ (126 kWh/year) *(11.3 MJ/kWh)
= 779 + 701+1424 =2,904 MJ/year

7.2.9 Results

7.2.9.1 Summary Net Annualized Energy Impact

Table S-46 notes the net annualized energy impact for each product on a ‘per product’ and ‘per community basis’. For each product, the percent contribution from manufacturing is indicated in the parentheses.

Table S-46 Net annualized energy impact, per product and per community

	Device	**Per Product MJ Per Device Per Year (% contribution from manufacturing)**				**Per Community MJ Per Device Per Year (% contribution from manufacturing)**			
		1992	**1997**	**2002**	**2007**	**1992**	**1997**	**2002**	**2007**
1992	CRT TV	2,100 (17%)	2,100 (10%)	2,400 (10%)	2,600 (7.0%)	3,900	4,800	6,300	5,900
	VCR	1,200 (33%)	770 (16%)	680 (12%)	570 (9.0%)	660	750	1,200	1,030
	Desktop	1,751 (67%)	1,800 (71%)	1,600 (35%)	2,700 (10%)	690	1,300	2,000	4,200
	CRT monitor	2,500 (55%)	1,800 (31%)	1,500 (14%)	1,500 (6%)	940	1,200	1,600	1,000
	Printer	610 (43%)	520 (36%)	420 (24%)	390 (21%)	110	190	320	420
	Gaming console	450 (40%)	340 (25%)	590 (17%)	910 (19%)	70	90	200	350
	Basic mobile phone	550 (80%)	200 (56%)	200 (71%)	90 (65%)	60	100	320	270
	LCD monitor	3,700 (77%)	2,200 (65%)	1,200 (33%)	880 (17%)	100	160	190	660
	Laptop	2,200 (86%)	2,000 (83%)	2,000 (73%)	1,200 (30%)	20	190	430	530
1997	Camcorder	0	650 (95%)	980 (97%)	300 (91%)	0	20	130	60
	Camera	0	440 (87%)	420 (85%)	250 (72%)	0	2	150	290
2002	DVD player	0	0	750 (36%)	340 (18%)	0	0	260	290
	MP3 player	0	0	430 (85%)	260 (82%)	0	0	30	90
	Smartphone	0	0	650 (92%)	430 (90%)	0	0	10	170
	LCD TV	0	0	3,500 (54%)	2,900 (11%)	0	0	20	880
2007	Plasma TV	0	0	0	7,100 (10%)	0	0	0	790
	Blu-ray player	0	0	0	510 (37%)	0	0	0	20
	Tablet	0	0	0	1,300 (94%)	0	0	0	80
	E-reader	0	0	0	440 (69%)	0	0	0	5
Total		15,020 (60%)	12,700 (51%)	17,100 (44%)	24,700 (22%)	6,500	8,800	13,100	17,020

Note:

- Devices are organized by year introduced into the community
- Each product's energy demand is rounded to ceiling to 2 significant figures except for the totals, in which some cases are rounded to three significant figures.
- The percentage contribution of manufacturing on a 'per product' and 'per community' are similar because 'per community'
- Manufacturing contribution is noted in the parentheses in the 'per product' columns

7.2.9.2 Comparing Changes in 'Per Community' Net Annualized Energy Impact to Annual Vehicle Fuel Consumption

This analysis calculates and compares how per community's net annualized energy demand to average fuel consumed passenger vehicle fuel per year. Using data from the U.S. Bureau of Transportation Services (BTS), the average fuel consumed by a passenger vehicle (gallons) is converted into fuel units (MJ). A percentage of how per community's net annualized energy demand compares to the vehicle fuel consumption was then calculated.

Table S-47 Comparison of annual vehicle fuel consumption to the "per community' net annualized energy demand

	1992	**1997**	**2002**	**2007**
Per Community Net Annualized Energy Demand (MJ)	6,500	8,800	13,100	17,020
Average fuel consumed per light duty vehicle (gallons)	517	539	555	456
Average energy consumed per light duty vehicle (MJ)	68,100	71,000	73,200	60,100
The product community as a percent of light duty vehicle fuel consumption	10%	12%	18%	28%

Note:

- 1 gallon of U.S. gas = 131.76 MJ (convertunits.com 2014).
- Average fuel consumed an annual basis per passenger car was from the U.S. BTS (2014).
- Light duty vehicle refers to passenger car and excludes motorcycles.

7.2.9.3 China-based Manufacturing Energy

Table S-48 shows the percentage contribution of manufacturing energy for each 1992 product assemblage on a ‘per product’ basis, and Table 49 shows the manufacturing energy for each device, on a ‘per product’ basis. In modeled year 2002, 37% of ‘per product’ net annualized energy impact is attributed to the 1992 product assemblage’s manufacturing energy (assuming U.S.-based manufacturing energy). However, using China-based manufacturing, 80% of net annualized ‘per product’ net energy was attributed to the 1992 product assemblage’s manufacturing energy.

Table S-48 Comparing U.S. vs. China percentage contribution of manufacturing energy of ‘per product’ net annualized energy impact, by product assemblage and total per year

	2002		**2007**	
	U.S.	**China**	**U.S.**	**China**
Percent Contribution of Manufacturing Energy, by Product Assemblage				
1992	37%	80%	15%	59%
1997	93%	98%	82%	94%
2002	58%	86%	25%	56%
2007			26%	30%
Percent Contribution of Net Manufacturing Energy Per Year				
Total	44%	81%	22%	57%

Note: Percentage contribution of energy from manufacturing is determined on a ‘per product’ basis and indicated for the group of products introduced in each modeled year.

Table 49 Annualized China-based manufacturing energy impact, ‘per product’ basis

	2002	2007
CRT TV	9,900	6,300
VCR	2,040	1,030
Desktop	15,400	7,020
CRT monitor	5,010	1,700
Printer	3,600	2,300
Gaming console	2,900	4,500
Mobile phone-basic	2,200	780
LCD monitor	9,100	2,900
Laptop	42,100	9,097
Camcorder	24,100	5,200
Camera	8,800	3,700
DVD player	5,600	960
MP3 player	5,000	2,200
Smartphone	9,100	5,100
LCD TV	45,900	6,200
Plasma TV	0	13,500
Blu-ray player	0	3,000
Tablet	0	23,700
E-reader	0	5,700
Total	191,000	105,000

Note: Data is adjusted to two significant figures except for the desktop computer in 2002 and the plasma TV and tablet in 2007.

7.2.9.4 Sensitivity and Scenario Analysis Results

The consumption weighted LCA method is used to compare the net annualized energy impact for conventional intervention strategies of energy efficiency and lifetime extension in Table S-50. Results are presented on ‘per product’ and ‘per community’ basis. Savings for the total community are noted at the bottom of the table. The methodology is also applied the converging device scenarios and the results are shown in Table S-51 to S-53. The lifespan sensitivity analysis results are shown in Table S-54.

Table S-50 Comparison of sensitivity analyses on a ‘per product’ and ‘per community’ basis

	Product	**Baseline 2007**		**Energy Efficiency**		**Lifetime Extension**	
		Net Energy (MJ) Per Product	**Net Energy (MJ) Per Community**	**Net Energy (MJ) Per Product**	**Net Energy (MJ) Per Community**	**Net Energy (MJ) Per Product**	**Net Energy (MJ) Per Community**
1992	CRT TV	2,600	5,900	2,400	5,400	2,600	5,900
	VCR	570	1,030	520	940	570	1,020
	Desktop	2,700	4,200	2,490	3,800	2,700	4,200
	CRT monitor	1,500	1,000	1,300	900	1,400	990
	Printer	390	420	360	390	380	410
	Gaming console	910	350	830	320	890	340
	Basic mobile phone	90	270	90	260	90	250
	LCD monitor	880	660	810	600	870	650
	Laptop	1,200	530	1,100	490	1,100	520
1997	Camcorder	300	60	300	60	280	50
	Camera	250	290	250	280	240	270
2002	DVD player	340	290	320	260	340	280
	MP3 player	260	90	260	80	240	80
	Smartphone	430	170	430	160	400	150
	LCD TV	2,900	880	2,700	800	2,900	870
2007	Plasma TV	7,100	790	6,500	720	7,100	780
	Blu-ray player	510	20	480	20	500	20
	Tablet	1,300	80	1,300	80	1,200	80
	E-reader	440	5	420	4	410	4
Total		24,700	17,020	22,800	15,600	24,200	16,800
% change				-7.8%	-8.5%	-2.0%	-1.4%

Note: net energy values are adjusted to two significant figures, except in the case of the totals where rounded to three significant figures.
Percentage change is calculated for the community as a whole as the difference between total baseline energy ($E_{B,pp}$) and adjusted energy from the intervention strategy ($E_{EE,pp)}$ divided by the baseline energy ($E_{B,pp}$) where percent savings = (($E_{EE,pp)\,-}$ ($E_{B,pp}$))/ $E_{B,pp}$. Negative values represent savings and positive percentage represents a percentage increase in the footprint. Note that certain products results in small reductions from the intervention strategies, such as with the camera are not seen in this table because of the significant figures. Percentage savings are shown in the dissertation (Table 9).

Table S-51 Comparison of converging device scenarios' energy and number of products on a 'per community' basis

	Product	Baseline 2007		Smart Communication & Image Capturing		Mobile Data Processing & Browsing	
		No. Products	Net Energy (MJ)	No. Products	Net Energy (MJ)	No. Products	Net Energy (MJ)
1992	CRT TV	2.9	5,900	2.9	5,900	2.9	5,900
	VCR	1.8	1,030	1.8	1,030	1.8	1,030
	Desktop	1.7	4,200	1.7	4,200	0	0
	CRT monitor	0.7	1,000	0.7	1,000	0	0
	Printer	1.1	420	1.1	420	1.1	420
	Gaming console	0.4	350	0.4	350	0.4	350
	Basic mobile phone	2.9	270	0	0	2.9	270
	LCD monitor	0.7	660	0.7	660	0	0
	Laptop	0.5	530	0.5	530	1	1,200
1997	Camcorder	0.2	60	0	0	0.2	60
	Camera	1.1	290	0	0	1.1	290
2002	DVD player	0.8	290	0.8	290	0.8	290
	MP3 player	0.3	90	0	0	0	0
	Smartphone	0.4	170	2.6	1,100	0.4	160
	LCD TV	0.3	880	0.3	880	0.3	880
2007	Plasma TV	0.1	790	0.1	790	0.1	790
	Blu-ray player	0.03	20	0.03	20	0.03	20
	Tablet	0.1	80	0.1	80	2.6	3,400
	E-reader	0.01	5	0	0	0	0
	Total		17,020		17,300		15,040

Note:

- Smart Communication & Image Capturing: replace camera, video camera, e-reader, mp3 player, and basic cell with smartphone for each household member.
- Mobile Data Processing & Browsing: replace e-reader, mp3 player, desktops computer, CRT and LCD monitors with one laptop to share and tablet for each household member.
- Net energy data is adjusted to two significant figures except for the totals, which are adjusted to three significant figures.

Table S-52 Comparison of converging device scenarios’ energy and number of products on a ‘per community’ basis

	Product	Baseline 2007		On Demand Digital Viewing		Digital Streamlined	
		No. Products	Net Energy (MJ)	No. Products	Net Energy (MJ)	No. Products	Net Energy (MJ)
1992	CRT TV	2.9	5,900	0	0	0	0
	VCR	1.8	1,030	0	0	0	0
	Desktop	1.7	4,200	0	0	0	0
	CRT monitor	0.7	1,000	0	0	0	0
	Printer	1.1	420	1.1	420	1.0	390
	Gaming console	0.4	350	0.4	350	1.0	910
	Basic mobile phone	2.9	270	2.9	160	0	0
	LCD monitor	0.7	660	0	0	0	0
	Laptop	0.5	530	1	1,200	1	1,200
1997	Camcorder	0.2	60	0.2	90	0	0
	Camera	1.1	290	1.1	60	0	0
2002	DVD player	0.8	290	0	0	0	0
	MP3 player	0.3	90	0	0	0	0
	Smartphone	0.4	170	0.4	160	2.6	1,100
	LCD TV	0.3	880	1	2,900	1	2,900
2007	Plasma TV	0.1	790	0.1	0	0	0
	Blu-ray player	0.03	20	1	500	0	0
	Tablet	0.1	80	2.6	3,400	2.6	3,400
	E-reader	0.01	5	0	0	0	0
	Total		17,020		9,300		9,900

Note:

- On Demand Digital Viewing: replace CRT TVs, CRT and LCD monitors, desktop CPU, VCR, MP3 player, DVD player, e-reader with one LCD TV, one blu-ray player, and one laptop to share and a tablet for each household member ('out with the old and in with the new').
- Digital Streamlined: smartphone and tablet for each household member, as well as one laptop, one printer, one LCD TV, and one gaming console to share for the household ("out with the old and in with the new").
- Net energy values rounded to two significant figures (except for the total baseline line, which is adjusted to three significant figures).

Table S-53 Comparison of baseline and digital streamlined plus scenarios on a 'per community' basis

	Product	Baseline 2007		Digital Streamlined + Energy Efficiency		Digital Streamlined + Lifespan Extension	
		No. Products	Net Energy (MJ)	No. Products	Net Energy (MJ)	No. Products	Net Energy (MJ)
1992	CRT TV	2.9	5,900	0	0	0	0
	VCR	1.8	1,030	0	0	0	0
	Desktop	1.7	4,200	0	0	0	0
	CRT monitor	0.7	1,000	0	0	0	0
	Printer	1.1	420	1.0	360	1.0	380
	Gaming console	0.4	350	1.0	830	1.0	890
	Basic mobile phone	2.9	270	0	0	0	0
	LCD monitor	0.7	660	0	0	0	0
	Laptop	0.5	530	1	1,100	1	1,100
1997	Camcorder	0.2	60	0	0	0	0
	Camera	1.1	290	0	0	0	0
2002	DVD player	0.8	290	0	0	0	0
	MP3 player	0.3	90	0	0	0	0
	Smartphone	0.4	170	2.6	1,100	2.6	1,020
	LCD TV	0.3	880	1	2,700	1	2,900
2007	Plasma TV	0.1	790	0	0	0	0
	Blu-ray player	0.03	20	0	0	0	0
	Tablet	0.1	80	2.6	3,400	2.6	3,100
	E-reader	0.01	5	0	0	0	0
	Total		17,020		9,400		9,500

Note: Net annualized energy values rounded to significant figure.

Table S-54 identifies the net energy on after conducting a lifespan sensitivity analysis. An example of savings is calculated on a 'per product' basis is shown below for 1992:

$= -(E_{B,pp,1992} – E_{highlife,pp1,1992})/ E_{B,pp,1992}$

= -(15,020 – 12,200)/ 15,020 = -18% or a 18 percent decrease in total 'per product' energy from the baseline value if products in the community are used longer

Table S-54 Lifespan sensitivity analysis on net annualized energy impact (MJ), 'per product' and 'per community'

Lifespan	**'Per Product' Energy (MJ)**				**'Per Community' Energy (MJ)**			
	1992	**1997**	**2002**	**2007**	**1992**	**1997**	**2002**	**2007**
Baseline	15,020	12,700	17,100	24,800	6,500	8,800	13,100	17,020
Low	17,300	15,400	20,100	26,900	6,900	9,700	14,300	18,100
High	12,200	11,200	15,500	23,500	5,800	8,300	12,500	16,500
Percent Change From Baseline								
Low	15%	21%	17%	9%	5%	10%	9%	6%
High	-18%	-12%	-10%	-5%	-11%	-6%	-4%	-3%

Note: Energy values are adjusted to three significant figures, except for the 'community' 1992 and 1997 values, which are adjusted to three significant figures. Negative percentages indicate percent decrease in net energy and positive values signify percent increase in net energy. Computations may not sum due to adjusting data to significant figures.

7.3 Supplemental Tables for Chapter V

A list of components and associated material masses for the metals is shown in Table S-55 and for all other materials (plastics, glass, and miscellaneous) in Table S-56. Tables S-55 and S-56 are the results of a disassembly conducted in the laboratory for a 2008 Elitebook 6930 notebook (RIT 2010) and a 2008 iPhone 3G (RIT 2013). Table S-57 and S-58 compare the material mass values for the smartphone and laptop that were used in this analysis to other information found in the literature. Table S-59 to S-65 provide data used to calculate the average base case parameters, as well as minimal, maximum, and average values used in the analysis. The base case and sensitivity analysis results are noted in Tables S-66 to S-68. Each table includes a description of how the base case variables have been adjusted and subsequent model decisions. Profit maximization model is in Table S-66, the e-waste foraging model results are in Table S-67, and modularity scenario analysis results (profit maximization model with distinct disassembly times) are noted in Table S-68.

Table S-55 List of components and associated metals

	Ferrous	**Li**	**Co**	**Cu**	**Al**	**Ni**	**Sn**	**Ag**	**Au**	**Pd**	**Mg**	**Hg**	**Brass**
Laptop													
LIB	30	19	55	1.6	0	0	0	0	0	0	0	0	0
Battery PCB	0.2	0	0	0.5	0.14	0.03	0.1	6.6 x10^{-3}	1.3 x10^{-3}	1.6 x10^{-4}	0	0	0
Hard drive	49	0	0	2.9	46	0	0	0	0	0	0	0	0
Hard drive PCB	0.8	0	0	1.8	0.51	0.11	0.43	0.02	4.7 x10^{-3}	5.9 x10^{-4}	0	0	0
Optical drive	108	0	0	4.4	9.3	0	0	0	0	0	0	0	1.9
Optical drive PCBs	1.2	0	0	2.9	0.83	0.18	0.69	0.04	7.7 x10^{-3}	9.6 x10^{-4}	0	0	0
Memory	0.1	0	0	0	0	0	0	0	0	0	0	0	0
Memory PCB	0.7	0	0	1.5	0.44	0.10	0.37	0.02	4.1 x10^{-3}	5.1 x10^{-4}	0	0	0
RTC Battery	0.40	0.25	0.72	0.40	0.2	0	0	0	0	0	0	0	0
Display	42	0	0	0.6	78	0	0	0	0	0	0	3.2 x10^{-3}	0.24
Display PCB	1.7	0	0	1.1	4.0	0.3	1.0	0.1	0.01	1.3 x10^{-3}	0	0	0
Audio, smart card, etc. PCB	2.9	0	0	6.9	2.0	0.4	1.7	0.1	0.02	2.3 x10^{-3}	0	0	0
Blue tooth, etc.	21	0	0	0	0	0	0	0	0	0	0	0	0.3
Fan and heat sink	21	0	0	16	19	0	0	0	0	0	0	0	0
System board PCB	13	0	0	31	9	1.9	7.5	0.40	0.1	1.0 x10^{-2}	0	0	0
System board screws	0.5	0	0	0	0	0	0	0	0	0	0	0	0
Processor PCB	0.4	0	0	0.8	0.24	0.05	0.20	0.01	2.2 x10^{-3}	2.8 x10^{-4}	0	0	0

	Ferrous	**Li**	**Co**	**Cu**	**Al**	**Ni**	**Sn**	**Ag**	**Au**	**Pd**	**Mg**	**Hg**	**Brass**
Housing	48	0	0	0.2	230	0	0	0	0	0	340	0	0
Housing PCBs	2.0	0	0	1.3	4.6	0.29	1.1	0.06	0.01	1.5 x10^{-3}	0	0	0
Wires	0	0	0	9.7	0	0	0	0	0	0	0	0	0
Smartphone													
SIM card	0.01	0	0	0.02	0.01	0	0	0	0	0	0	0	0
LCD assembly	0.00	0	0	0.10	13	0	0	0	0	0	0	0	0
System board PCB	0.9	0	0	2.2	0.62	0.14	0.52	0.03	0.01	0	0	0	0
System board assembly-other materials	0.30	0	0	0.6	6.40	0	0	0	0	0	0	0	0
LIB	2.3	1.4	4.1	2.5	1.2	0	0	0	0	0	0	0	0
LIB PCB	0.04	0	0	0.09	0.03	0.01	0.02	0	0	0	0	0	0
Back casing	0.10	0	0	1.40	18	0	0	0	0	0	0	0	0
Total	348	21	60	90	443	4	13	1	0.1	0.02	340	0.003	2

Note: Values adjusted to two significant figures.

Table S-56 List of components and associated plastics, miscellaneous, and glass materials

	PC	**PC-ABS**	**PVC**	**Plexi-glass**	**Plastics (mixed)**	**Plastics non-recover-able**	**Misc. rubber**	**Recover-able Glass**	**Non-recover-able Glass**
Laptop									
LIB	35	63	0	0	1.6	0	0	0	33
Battery PCB	0	0	0	0	0	0	0	0	2.2
Hard drive	0	0	0	0	21	0	1.9	0	5.0
Hard drive PCB	0	0	0	0	0	0	0	0	8.2
Optical drive	0	0	0	0	2.3	33	0.9	0	0
Optical drive PCBs	0	0	0	0	0	0	0	0	13
Memory	0	0	0	0	6.5	0	0	0	0
Memory PCB	0	0	0	0	0	0	0	0	7
RTC battery	0	0.83	0	0	0.14	0	0	0	0.4
Display	15	0	0	0	170	31	0.9	170	0
Display PCB	0	0	0	0	0	0	0	0	18
Audio, smart card, etc. PCBs	0	0	0	0	0	0	0	0	32
Blue Tooth, etc.	0	0	0	0	38	0	0	0	0
Fan and heat sink	0	0	0	0	15	0	0	0	0
System board PCB	0	0	0	0	0	0	0	0	142
System board screws	0	0	0	0	0	0	0	0	0
Processor PCB	0	0	0	0	0	0	0	0	3.8
Housing	0	0	0	0	82	79	3.5	0	0
Housing PCBs	0	0	0	0	0	0	0	0	21
Wires	0	0	0	0	22	0	0	0	0

	PC	**PC-ABS**	**PVC**	**Plexiglass**	**Plastics (mixed)**	**Plastics non-recoverable**	**Misc. rubber**	**Recoverable Glass**	**Non-recoverable Glass**
Smartphone									
SIM card	0	0	0.18	0	0	0	0	0	0.1
LCD assembly	0	0	0	12	2.4	0	0.70	23	0
System board PCB	0	0	0	0	0	0	0	0	10
System board assembly-other materials	0	0	0	0	0	0	0.64	0	0
LIB	0	4.8	0	0	0.83	0	0.20	0	2.5
LIB PCB	0	0	0	0	0	0	0	0	0.4
Back Casing	0	0	0	0	17	0	1.3	0	0
Total	50	69	0.2	12	380	140	10	190	300

Note: Data adjusted to two significant figures, so totals may not sum.

Table S-57 Comparison of smartphone materials and mass data points to the literature

	Foraging Data	IPhone 4S	IPhone 3G	Average 2005-2006	Mobile Phone	Average 1999-2003	Average	Max	Min
Ferrous	3.7	40	30		4%	8%	25	40	3.7
Li	1.4						1.4	1.4	1.4
Co	4.1						4.1	4.1	4.1
Cu	6.8				17%	14%	6.8	6.8	6.8
Al	39				2%	3%	39	39	39
Ni	0.14				2%	1%	0.14	0.14	0.14
Sn	0.55				1%	1%	0.55	0.55	0.55
Ag	0.03				1%	0%	0.03	0.03	0.03
Au	0.01					4%	0.01	0.01	0.01
Pd	0.001					0%	0.001	0.001	0.001
Mg	0						0	0	0
Hg	0						0	0	0
Brass	0						0	0	0
Other metals	0			6%	1%	0%	0	0	0
PC	4.8						4.8	4.8	4.8
PC-ABS	0.18						0.18	0.18	0.18
PVC	12						12	12	12
Plexiglass	21						21	21	21
Plastics (mixed)	0				28%	60%	0	0	0
Plastics - non-recoverable	2.8	3	19	48%			8.3	19	2.8
Misc. rubber	23	2	4		34%		9.6	23	2.0
Recoverable glass	13	47	26		12%	11%	29	47	13
Non-recoverable glass	2.9						2.9	2.9	2.9
Battery		25	22	na			24	25	22
System board		16	20	27%			18	20	16
Display		7	13				10	13	7

	Foraging Data	IPhone 4S	IPhone 3G	Average 2005-2006	Mobile Phone	Average 1999-2003	Average	Max	Min
Source		a	b	c	d	e			

Note: The Apple Inc. environmental reports combine all plastics into one category so it is listed as 'other plastics.' 'Other' material reported by Apple Inc. is listed as under miscellaneous and 'display' material is noted separately. Oguchi et al. (2011) provides percentage distribution based on average of six phones from 2005-2006, but does not have information on ferrous, aluminum, or copper materials, or the battery component. Huisman (2004) (found in Neira et al. (2006)) is an average composition of phones from 1999 to 2003. The only known smartphone material comparisons are from Apple sustainability reports. The abbreviations for the data sources include: a) Apple Inc. (2014), b) Apple Inc. (2009), c) Oguchi et al. (2011), d) Fredholm (2008); Dahmus (2007) for unknown mobile phone, and e) Huisman (2004), as noted in Neira et al. (2006). Data is adjusted to two significant figures.

Table S-58 Comparison of laptop materials and mass data points to the literature

	Foraging Data	**Dell Inspiro 2500**	**2005 15”**	**2008 17”**	**2008 15”**	**2008 14”**	**2008 12”**	**2001 15”**	**2001**	**2008**	**Average**	**Max**	**Min**
Ferrous	340	87	490	400	520	270	270	840	na	na	500	870	270
Li	19										19	19	19
Co	56										56	56	56
Cu	83	270	75	74	24	35	39	84	0.01	0.02	86	270	24
Al	400	510	38	580	230	430	220	450	na	na	360	580	38
Ni	3	0.99									2.2	3.4	0.99
Sn	13	9.3									11	13	9.3
Ag	0.8	1.4	NI								1.1	1.4	0.8
Au	0.14	0.36	NI								0.3	0.4	0.1
Pd	0.02	0.06									0.04	0.1	0.02
Mg	340		120	500	0	330	210	0			210	500	0
Hg	0										3.2 x10^{-3}	3.2 x10^{-3}	3.2 x10^{-3}
Brass	2.5										2.5	2.5	2.5
Other metals		6.0							0.12	0.11		6.0	6.0
PC	50	410	270								241	406	50
PC-ABS	64	370	140								190	370	64
PVC	0										0	0	0
Plexiglass	0										0	0	0
Plastics (mixed)	360										360	360	360
Plastics - non-recoverable	140	340	440	780	1,100	600	400	960	0.26	0.25	600	1,100	140
Misc. rubber	7.1			350	250	210	100	450			230	450	7
Recoverable glass	170	300	360								280	360	170
Non-recoverable glass	290												

	Foraging Data	Dell Inspiro 2500	2005 15”	2008 17”	2008 15”	2008 14”	2008 12”	2001 15”	2001	2008	Average	Max	Min
Other*		440	1,700								1,100	1,700	440
Battery				380	280	280	280	200	0.1	0.1	280	380	200
System board				410	270	270	230	410	0.11	0.15	320	410	230
Sources:		a	b	c	c	c	c	c	d	d			

Note: Other* for the EUP 2005 report and Deng et al. 2011 include all items except plastics, steel, copper, aluminum, epoxy, LCD screen, integrated circuits, and system board. Other metals for Deng et al. 2011 and the EUP report are for the PCB, which include PB, Zn, and Nd for Deng et al 2011. The abbreviations for the data sources include: a) Deng et al 2011; b) EUP 2005, also noted in Deng et al. 2011; c) Kahhat et al. 2011; and d) Oguchi et al. 2011. NI means not included. Data is adjusted to two significant figures.

Table S-59 Summary of scrap component prices ($2008 per gram) with data sources

	Average	Min	Max	Sources
Laptop				
LIB	$0.003	$0.002	$0.003	Didion Orf Recycling 2014; Boardsort.com 2014; Scrap Monster 2014
Hard drive	$0.001	$0.000	$0.002	Didion Orf Recycling 2014; Boardsort.com 2014; Scrap Monster 2014; Rockaway.com 2014; Gold Chip Buyer 2014; Recycling E-Scrap 2014;
Optical drive	$0.0002	$0.0001	$0.0004	Didion Orf Recycling 2014; Recycling E-Scrap 2014; Boardsort.com 2014;
Memory	$0.02	$0.001	$0.03	Rockaway.com 2014; Gold Chip Buyer 2014; Recycling E-Scrap 2014; Didion Orf Recycling 2014; Boardsort.com 2014; Scrap Monster 2014;
PCBs	$0.002	$0.0002	$0.01	Didion Orf Recycling 2014; Recycling E-Scrap 2014; Boardsort.com 2014;
Fan and heat sink	$0.002	$0.0001	$0.00	Didion Orf Recycling 2014; Boardsort.com 2014; Rockaway Recycling 2014
System board PCB	0.01	$0.003	$0.01	Didion Orf Recycling 2014; Boardsort.com 2014; Scrap Monster 2014; Rockaway Recycling 2014
Processor	$0.07	$0.01	$0.26	Gold Chip Buyer 2014; Boardsort.com 2014; Scrap Monster 2014; Rockaway Recycling 2014; Didion Orf Recycling 2014
Display	$0.002			Recycling E-Scrap 2014
Wire	$0.001	$0.0004	$0.002	Boardsort.com 2014; Scrap Monster 2014; Rockaway.com 2014
Smartphone				
LIB	$0.002	$0.001	$0.003	Gold Chip Buyer 2014; Boardsort.com 2014; Scrap Monster 2014; Didion Orf Recycling 2014
System board	$0.02	$0.02	$0.02	Gold Chip Buyer 2014; Boardsort.com 2014
SIM Card	$0.31	$0.04	$1.44	Gold Chip Buyer 2014

Note: Hard drives included prices for those with and without PCB. PCB prices were for low grade, medium grade, high grade, and integrated circuit scrap. Memory included mixed RAM, memory chips, gold memory scrap, silver memory scrap, Gold/Silver/Tin mixed fingered memory RAM, gold finger only memory RAM, silver/tin finger only memory RAM, and fingerless (trimmed) memory scrap. Display was for LCD screens (no broken). Fan/heat sink prices included Al/Cu, Cu, and Al heat sinks, and fan components. Wire included mixed wire, and insulated wire. System board (laptop) included clean green motherboards, Pentium 4 motherboard, PCI motherboard, large, small and mixed socket motherboards. Processor included mixed fiber, mixed ceramic, gold cap chips, double-sided gold cap chips, 386/486, AMD ceramic chip, AMD Al top K6, black fiber chip, green/brown fiber (no metal), Pentium 4 green fiber metal top, and no pin.

Table S-60 Summary of material recovery efficiency rates and data sources

	Average	Min	Max	Data Sources:
Ferrous	93%	80%	99%	Hageluken 2007; Rueter et al. 2006; Rigamonti et al. 2005; Xie et al. 2009
Li	78%	70%	95%	Xu et al. 2008; Umicore 2009
Co	86%	70%	99%	Electrometals Technologies Limited 2010; Xu et al. 2008; Umicore 2009
Cu	88%	63%	99%	Hageluken 2007; Xu et al. 2008; Neira et al. 2006; Cui and Zhang 2008; Williams 2006; Ruhrberg 2006; Xie et al. 2009
Al	87%	70%	98%	Hageluken 2007; Rueter et al. 2006; Željko et al. 2009; Yu et al. 2009; Rigamonti et al. 2005
Ni	73%	69%	80%	Reck and Gordon 2008; Hageluken 2007; Umicore 2009
Sn	51%	8%	85%	Hageluken 2007 siliconinvestor.com 2008, 2009; Scott et al. 1997
Ag	88%	80%	95%	Neira et al. 2006; Hageluken 2007; Petrie 2007; Cui and Zhang 2008
Au	94%	80%	100%	Neira et al. 2006; Hageluken 2007
Pd	91%	80%	98%	USGS 2004; Neira et al. 2006; Cui and Zhang 2008; Hageluken 2007
Mg	19%	0%	0%	Rueter et al. 2006
Hg	0%	0%	0%	Assumed not recovered
Brass	0%	0%	0%	Not available, so assumed not recovered
PC	84%	75%	92%	For all plastics: Umicore 2009; Qu et al. 2006; Rigamonti et al. 2005
PC-ABS	84%	75%	92%	
PVC	84%	75%	92%	
Plexiglass	84%	75%	92%	
Plastics (mixed)	84%	75%	92%	
Plastics - non-recoverable	0%	0%	0%	Assumed not recovered
Misc. rubber	0%	0%	0%	Assumed not recovered
Recoverable glass	98%	95%	100%	Umicore 2009; Rigamonti et al. 2005; Zheng et al. 2009

Table S-61 Summary of shredding costs and data sources

$/kg (reported value)	$/kg (2008 dollars)	$/g (2008 dollars)	Notes	Location	Source
$0.23	$0.25	$2.5 x10^{-4}	Shredding cost only in 2005 dollars, based on average mass per cell phone of 100 in 2003 ($.023 per unit)	Santa Clara, CA	Neira et al. 2006
	$3 x10^{-6}	$2.66 x10^{-9}	Calculated based on Eidal model shredder (see below)	na	
$0.26	$0.28	$3.0x10^{-3}	2006 processing costs per kg	Maine	Fredholm 2008
$0.26-$0.48	$0.40	$4.0x10^{-4}	Range of processing costs in $2006/kg; used an average	Maine	Gregory and Kirchain 2008
$0.28	$0.30	$3.0 x10^{-4}	$2006/kg in for the 'other' recycling costs only noted in the report (e.g., advertising)	California	CIWMB 2007
$0.31	$0.33	$3.3 x10^{-4}	Based on U.S. EPA report 2001-2001 (one company)	Maryland	Gregory and Kirchain 2008
$0.37	$0.37	$4.0 x10^{-4}	$/kg (assumed to be 2009 dollars) for processing computers	Not available	Brown-West 2010
$0.55	$0.61	$1.0 x10^{-3}	$2005/kg processing costs	California	Gregory and Kirchain 2008
$0.59	$0.63	$1.0 x10^{-3}	$2006/kg processing costs	Alberta Canada	Fredholm 2008
$0.001	$0.64	$1.0 x10^{-3}	$2006/kg the 'total recycling' costs, which includes labor, transportation, and 'other'	California	CIWMB 2007
$0.74	$0.74	$1.0 x10^{-3}	weighted average total recycling costs (assumed to be 2009 dollars). Includes shipping transportation, refurbishing, sorting, disposal	Not sure	Brown-West 2010
Average	$0.410	$0.0004			
Max	$0.740	$0.001			
Min		$2.66 x10^{-9}			

Note: Neira et al. (2006) data is based on an ECS Refining shredder processed 3959 cell phones or 910 pounds in 40 min with two employees in 2005. Data adjusted to two significant figures.

Calculating the shredding costs per gram for the Eidal Model 62x41-200 HP (wwrequip.com 2011):

Cost per kWh in 2008 =11.29 cents per kwh in 2008 (U.S. EIA 2013)

200HP * 1kW per HP*1 hour * $0.11 per kWh = $23

Eidal model shreds 8.5 tons per hour * 1 x 10^6 grams per ton = 8.5 x 10^6 grams

$23/8.5 x 10^6 grams = 3 x 10^{-6} = cost to shred ($ per gram)

Table S-62 Summary of Searching Costs and Data Sources

$/kg	**$ per kg (2008 dollars)**	**Notes**	**Location**	**Source**
$0.11	0.12	$0.11/kg for 2006 collection costs - system management costs	Maine	Gregory and Kirchain 2008; Fredholm 2008
$0.00	0.44	Weighted average total ‘recovery’ costs based on 18.7 cents per pound in 2006 (includes transportation, labor and ‘other’)	California	CIWMB 2007
$0.16	0.17	‘Other’ only portion of recovery costs based on 7.2 cents per pound in 2006	California	CIWMB 2007
$0.39	0.42	Based on 17.9 cents per pound, weighted average cost for a pick-up programs in 2006	California	CIWMB 2007
$0.25	0.27	Based on 11.3 cents per pound, weighted average cost for a permanent drop off program in 2006	California	CIWMB 2007
$0.13	0.16	MD based on EPA report 2001-2001 (one company) -different transport costs. Assumed it was in 2001 dollars and adjusted to 2008	Maryland	Gregory and Kirchain 2008
0.37	0.41	Weighted average collection costs in 2005	California	Gregory and Kirchain 2008
Average	$0.28			
Max	$0.44			
Min	$0.12			

While not used in this analysis, Neira et al. (2006) describes the different phone collection costs and programs as noted below:

Table S-63 Summary of different phone collection costs and programs

Process	**Stage**	**Method**	**Cost** ($/phone)
Collection and Transportation to accepting facility	Collection from end-user	Mail-in envelope (take-back) average	$1.4-1.9
		Mail-in (buy-back) average	$8 to 10
		Drop-off bins	$0.1-2.7
		One-day event	$0.16-0.20/pound
	Shipping from collection points to accepting facility	Ground	$0.22

Source: Neira et al. (2006)

Table S-64 Summary of disassembly times (in seconds) for the smartphone

					Average	**Min**	**Max**
SIM card	3	7	3	9	6.3	3	9
LCD assembly	75	50	56		60	50	75
System board	113	39	41		64	39	113
LIB	10	25	12	11	14	10	25
Back casing				169	169		
Source:	a	b	c	d			

Note: data sources are as follows: a) appleipodparts.com, 2014 b) pdasmartdot.com 2014 c) DirectFix.com 2014, and d) RIT laboratory disassembly 2013

Table S-65 Disassembly time for laptop, separate for each component:

	Disassembly Time per Component (seconds)
Laptop	
LIB	3.2
Battery PCB	0.4
Hard drive	28
Hard drive PCB	3.2
Optical drive	27
Optical drive PCBs	13
Memory - other	6.8
Memory PCB	15
RTC battery	21
Display	480
Display PCB	4.0
Audio PCBs	35.9
Blue tooth & other	320
Fan and heat sink	50
System board PCB	2.7
System board assembly - other	41
Processor PCB	4.0
Housing	240
Housing PCBs	26
Wires	300

Note: values are adjusted to two significant figures

Table S-66 Profit maximization base case and sensitivity analysis results (cumulative disassembly time)

	Scenario Description	Net profit	Laptop Profit	Smart-phone Profit	Total Handling Time	Total Mass Recovered	Notes
Base case		$6.42	$6.12	$0.30	60	1,600	Globally optimal solution, linear, hard drive selected for disassembly only.
Minimum recovery efficiency	Use minimum data point	$4.80	$4.50	$0.20	60	1,300	Same as base
Maximum recovery efficiency	Use maximum data point	$6.70	$6.40	$0.30	60	1,600	Same as base
Minimum shred cost	Use minimum data point	$7.40	$7.00	$0.40	60	1,600	Same as base
Maximum shred cost	Use maximum data point	$5.70	$5.40	$0.30	60	1,600	Same as base
High shred cost I	300% shred cost than base	$4.70	$4.52	$0.20	630	1,700	Dissemble hard drive, display, optical drive
High shred cost II	220% higher shred costs than base	$5.30	$5.00	$0.20	630	1,600	Decision switch (+display)
Minimum labor cost	Decrease base case labor costs by 10%	$6.40	$6.10	$0.30	60	1,600	Same as base
Maximum labor cost	Increase base case labor costs by 10%	$6.40	$6.10	$0.30	60	1,600	Same as base
Low labor cost I	20% less labor costs	$6.40	$6.10	$0.30	68	1,600	Decision switch (+SIM card)
Low labor cost II	50% less labor costs	$6.80	$6.50	$0.30	700	1,700	Disassemble hard drive, display, SIM card, phone system board
Minimum search cost	Use minimum data point	$6.80	$6.51	$0.30	60	1,600	Same as base

	Scenario Description	Net profit	Laptop Profit	Smart-phone Profit	Total Handling Time	Total Mass Recovered	Notes
Maximum search cost	Use maximum data point	$6.00	$5.76	$0.30	60	1,600	Same as base
Low search cost 1	50% less of base case search costs	$6.80	$6.46	$0.30	60	1,600	Same as base
Minimum scrap component value	Use minimum data point	$6.40	$6.07	$0.30	30	1,600	Shred all components
Maximum scrap component value	Use maximum data point	$6.50	$6.21	$0.30	60	1,600	Same as base
High scrap value I	24 percent higher scrap value than base	$6.50	$6.16	$0.30	140	1,600	Decision switch (+SIM card)
Low disassembly time I	Reduce disassembly time for each component by 10%	$6.60	$6.25	$0.30	60	980	Same as base
Low disassembly time II	Reduce disassembly time for each component by 20%	$6.60	$6.25	$0.30	60	980	Decision switch (+SIM card)
Low disassembly time II	Reduce disassembly time for each component by 30%	$6.60	$6.30	0.30	450	1,600	Disassemble hard drive, display, & SIM card
Low disassembly time IV	Reduce disassembly time for each component by 50%	$6.80	$6.50	0.30	370	1,700	Disassemble hard drive, display, SIM card, & phone system board
Reduction in PCB circuitry	Reduce mass of each PCB component by 10%	$6.20	$5.90	0.30	60	900	Same as base

Note: Except for base case profits, values are adjusted to two significant figures.

Table S-67 E-waste foraging model base case and sensitivity analysis results (cumulative disassembly time)

	Scenario Description	**Net Profit ($)**	**Laptop Profit ($/ product)**	**Smart-phone Profit ($ per product)**	**Total Handling Time (seconds)**	**Total Mass Recovered (grams)**	**Optimal En/T ($ per second)**	**Notes**
Base case		$6.37	$6.07	$0.30	30	1,500	0.42	Feasible solution to shred all components
Minimum recovery efficiency	Use minimum data point	$4.70	$4.46	$0.23	30	1,300	0.36	Same as base decision
Maximum recovery efficiency	Use maximum data point	$6.60	$6.30	$0.34	30	1,600	0.43	Same as base decision
Low material recovery I	Reduced base case data points by 10%	$5.60	$5.30	$0.26	30	1,400	0.39	Same as base decision
Minimum shred cost	Use minimum data point	$7.40	$7.0	$0.35	30	1,500	0.45	Same as base decision
Maximum shred cost	Use maximum data point	$5.60	$5.30	$0.26	30	1,500	0.39	Same as base decision
High shred cost II	Increase base case shredding costs by 50% higher case	$6.20	$5.90	$0.30	30	800	0.41	Same as base decision
High shred cost III	Increase base case shredding costs 10 times	-$2.70	-$2.60	-$0.19	30	1,500	0.12	Same as base decision
Minimum labor cost	Decrease base case labor costs by 10%	$6.40	$6.10	$0.30	30	1,500	0.38	Same as base decision
Maximum labor cost	Increase base case labor costs by 10%	$6.40	$6.07	$0.30	30	1,500	NA	Locally optimal solution, but same as base case decision
Low labor cost I	Reduce base case labor costs by 20%	$6.40	$6.10	$0.30	30	1,500	0.42	Locally optimal solution, but same decision as base case

	Scenario Description	**Net Profit ($)**	**Laptop Profit ($/ product)**	**Smart-phone Profit ($ per product)**	**Total Handling Time (seconds)**	**Total Mass Recovered (grams)**	**Optimal En/T ($ per second)**	**Notes**
Low labor cost II	Reduce base case labor costs by 50%	$6.40	6.10	$0.30	30	1,500	NA	Same as base case decision.
Minimum search cost	Use minimum data point	$6.80	$6.47	$0.33	30	1,400	0.44	Locally optimal solution, but same as base case decision
Maximum search cost	Use maximum data point	$6.30	$5.90	$0.31	30	850	0.40	Same as base case decision
High search costs II	Increase base case search costs by 20%	$6.20	$5.90	$0.29	30	1,500	0.41	Same as base case decision
High search costs I	Increase base case search costs by 50%	$6.00	$5.70	$0.28	30	1,500	0.39	Same as base case decision
Minimum scrap component value	Use minimum data point	$6.40	$6.07	$0.30	30	1,500	0.33	Locally optimal solution, but same as base case decision
Maximum scrap component value	Use maximum data point	$6.40	$6.10	$0.30	30	1,544	0.45	Same as base case decision
Low disassembly Time II	Reduce base case disassembly time by 20% for each component	$6.40	$6.10	$0.30	30	1,500	0.47	Same as base case decision
Low disassembly Time III	Reduce base case disassembly time by 30% for each component	$6.40	$6.10	$0.30	30	1,500	0.51	Same as base case decision

	Scenario Description	Net Profit ($)	Laptop Profit ($/ product)	Smart-phone Profit ($ per product)	Total Handling Time (seconds)	Total Mass Recovered (grams)	Optimal En/T ($ per second)	Notes
Low disassembly Time IV	Reduce base case disassembly time by 50% for each component	$6.40	$6.10	$0.30	30	1,500	NA	Same as base case decision
High disassembly Time I	Increase disassembly time by 20% for each component	$6.40	$6.10	$0.30	30	1500	0.38	Same as base decision
Reduction in PCB circuitry	Reduce mass of each PCB component by 10%	$5.90	$5.60	$0.28	30	1,500	0.41	Same as base decision
High shred time	Increase base case shredding time 10 times	$7.10	$6.70	$0.34	310	1,500	0.23	Same as base decision

Note: Values adjusted to significant figures, except the base case profit figures. In the low material recovery efficiency scenario, all rates decreased except if they were zero.

Table S-68 Modularity scenario analysis results (profit maximization model with distinct disassembly times)

	Scenario Description	**Net Profit ($)**	**Laptop Profit ($ per product)**	**Smartphone Profit ($ per product)**	**Total Handling Time (seconds)**	**Total Mass Recovered (grams)**	**Notes**
Base case		$6.84	$6.50	$0.40	80	1,500	Globally optimal, linear solution to disassemble hard drive, memory PCB, processor, and phone system board
Minimum recovery efficiency	Use minimum data point	$5.30	$4.90	$0.30	560	1,500	Decision switch (+ display)
Maximum recovery efficiency	Use maximum data point	$7.08	$6.70	$0.40	70	1,700	Decision switch (only hard drive, processor and phone system)
Minimum shred cost	Use minimum data point	$7.80	$7.40	$0.40	80	190	Same as base case decision
Maximum shred cost	Use maximum data point	$6.30	$5.90	$0.30	590	1,700	Disassemble hard drive, memory PCB, processor, phone system board, optical drive, and display
Minimum labor cost	Decrease base case labor costs by 10%	$6.90	$6.60	$0.40	560	1,700	Decision switch (+ display)
Maximum labor cost	Increase base case labor costs by 10%	$6.80	$6.50	$0.40	80	1,600	Same as base case decision
Minimum search cost	Use minimum data point	$7.20	$6.90	$0.40	80	1,600	Same as base case decision
Maximum search cost	Use maximum data point	$6.50	$6.10	$0.40	80	1,600	Same as base case decision

	Scenario Description	**Net Profit ($)**	**Laptop Profit ($ per product)**	**Smartphone Profit ($ per product)**	**Total Handling Time (seconds)**	**Total Mass Recovered (grams)**	**Notes**
Minimum scrap component value	Use minimum data point	$6.40	$6.10	$0.30	40	1,600	Only disassemble phone system board
Maximum scrap component value	Use maximum data point	$8.30	$7.90	$0.40	640	1,700	Disassemble hard drive, optical drive, memory PCB, display, fan and heat sink, processor, & phone system board
Low disassembly time I	Reduce disassembly time for each component by 10%	$6.90	$6.60	$0.40	510	1,700	Decision switch (+ display)
Low disassembly time II	Reduce disassembly time for each component by 20%	$7.00	$6.70	$0.40	460	1,700	Disassemble hard drive, memory PCB, processor, phone system board, display, & SIM card
Low disassembly time V	Reduce disassembly time for each component by 40%	$7.25	$6.90	$0.40	370	1,700	Disassemble hard drive, memory PCB, processor, phone system board, display, SIM card, & optical drive
Low disassembly time IV	Reduce disassembly time for each component by 50%	$7.37	$7.00	$0.40	310	1,700	Disassemble hard drive, memory PCB, processor, phone system board, display, SIM card, & optical drive
Reduction in PCB circuitry	Reduce mass of each PCB component by 10%	$6.20	$5.90	$0.30	60	250	Disassemble hard drive and processor

Note: Except for base case profits, values are adjusted to two significant figures.

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