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Evaluating Material Consumption at the Intersection of Technological Innovation and Shifting Consumer Demand: A Case Study of Consumer Electronics

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Evaluating Material Consumption at the Intersection of Technological Innovation and Shifting Consumer Demand: A Case Study of Consumer Electronics

By Barbara V. Kasulaitis

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

Department of Sustainability
Golisano Institute for Sustainability

Rochester Institute of Technology
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Submitted by Barbara V. Kasulaitis 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.

We, the undersigned members of the Faculty of the Rochester Institute of Technology, certify that we have advised and/or supervised the candidate on the work described in this dissertation. We further certify that we have reviewed the dissertation manuscript and approve it in partial fulfillment of the requirements of the degree of Doctor of Philosophy in Sustainability.

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ABSTRACT

Golisano Institute for Sustainability

Rochester Institute of Technology

Degree: Doctor of Philosophy

Name of Candidate: Barbara V. Kasulaitis

Title: Evaluating Material Consumption at the Intersection of Technological Innovation and Shifting Consumer Demand: A Case Study of Consumer Electronics

Increasing availability of consumer electronics offers the potential to improve quality of life, extend educational access, and improve efficiency of industrial processes, yet introduce their own set of challenges including increasingly diverse material supply chains, the fastest growing waste stream, and high life cycle resource demands. A significant body of research has been developed to understand material and energy flows across the product life cycle, but to date, that research has neglected to understand aggregate material flows across a community of interrelated products that are consumed, used, and disposed of together.

This research explores that research gap, first evaluating the possibility of natural dematerialization due to technological innovation as a means of reducing material flows across the life cycle. A case study of a laptop computer over subsequent generations reveals that innovation is being realized as improved performance, rather than reduced material consumption, and thus total product mass is relatively constant over time. Extending the boundaries of the study from a single product over time to a group of products that interact within the average U.S. household reveals that, although per product material consumption stays relatively constant over time, community consumption increases as more products are consumed. Similar research has been conducted evaluating energy consumption by a community of products, resulting in a recommendation for a more energy efficient community of products. Lack of data linking community structure and consumption choices, however, raises the question of whether consumers would willingly adopt these alternative communities.

Therefore, the final phase of the research collects data regarding consumption choices, product interactions, and changes in community structure, and models changes in community structure as the result of increasing technological awareness and improved product quality. The results from the model indicate that these types of improvements may shift the community structure, they do little to reduce community material consumption. Future research efforts should be directed at “closing the loop” and improving material recovery and recycling, in addition to educating consumers to move them toward more sustainable consumption (i.e. in general, consuming less).

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Finally, my husband, Christopher, and our daughter, Grace, who continually kept me on course. Had it not been for Chris's unrelenting optimism that I was "almost finished" and Grace's belief that I can do anything, I would have given up long ago.

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I. Introduction

1.1 Background and Rationale

Rapid technological innovation has created a consumption conundrum in the consumer electronics sector. Consumer electronics offer the potential to improve quality of life, extend educational access, and make industrial processes more efficient, thereby reducing environmental impacts, energy and material demands, and greenhouse gas emissions (Erdmann and Hilty 2010). Increased availability and affordability of electronic products have the potential to improve worldwide economic development and quality of life. Unfortunately, the associated growth of electronic product consumption introduces many environmental challenges (Arushanyan et al. 2013, Hageluken 2007), such as high global greenhouse gas emissions, global electricity usage (Malmodin et al. 2010), and increasing material demand across product life cycles.

Several strategies have been proposed to mitigate both increasing material consumption and potential material environmental or economic impacts. Technological innovation promises an enticing solution, whereby efficiency gains achieved from improved performance may enable dematerialization, or the absolute or relative reduction in the quantity of materials used and/or the quantity of waste generated in the production of a unit of economic output (van der Voet et al. 2005, von Weizsacker et al. 1997, Cleveland and Ruth 1999, Wernick et al. 1996, Mugdal et al. 2011, Binswanger 2001, Marechal et al. 2005, Robert et al. 2002). This goal of "doing more with less," by reducing the amount of material inputs required to provide a consistent level of functionality, may indeed be a step toward reducing the environmental impact of consumer electronic products. However, both rigorous environmental analysis and a thorough understanding of user-demanded functionality must be obtained to make such a determination.

Unfortunately, the rapidly evolving nature of electronics introduces several new challenges. First, while many static life cycle assessments (LCAs) of single or multiple products have been conducted to analyze environmental impacts of consumer electronics (Eugster et al., 2007; Gurauskiene and Varzinskas, 2006; Kozak and Keolelan, 2003; Oguchi et al., 2011; Teehan and Kandlikar, 2013; Williams, 2004; Yung et al., 2009), fewer studies have used dynamic LCA or material flow analysis (MFA) to capture the potential change in impact due to technological evolution of these products (Boyd et al., 2010, 2009; Deng and Williams, 2011; Kahhat et al., 2011; Lam et al., 2013). Product attributes and materials are usually selected based on representative or available case study products (Deng et al. 2011), and the extent to which these attributes vary over time is unknown. This is especially problematic for complex products, such as computers, because attribute data is difficult to obtain (Baumann et al. 2012, Olivetti and Kirchain 2011, Weber et al. 2010, Olivetti et al. 2012), and researchers must rely on a combined approach of disassembly and literature values (Oguchi et al. 2011). As a result, accurate evaluations of the environmental impacts of complex and rapidly evolving products are often not available until the products form factor is well established.

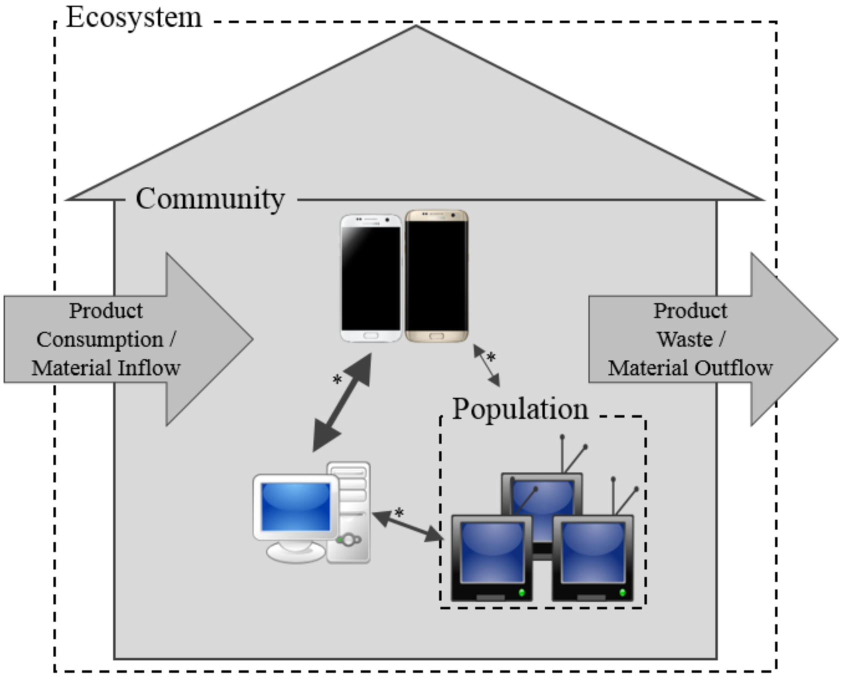
Additionally, the success of strategies to achieve dematerialization is often limited by behavioral response. For example, efficiency gains resulting from technological innovation reduce marginal costs, lowering prices and increasing demand (Allwood et al. 2011, Berkhout and Hertin 2004), a phenomenon known as the rebound effect. In the case of consumer electronics, this rebound effect (or Jevons paradox) has been observed in an increased product ownership leading to greater cumulative impact (Ryen et al. 2014, 2015). At the same time, material composition of electronic products is becoming increasingly diverse (Sthiannopkao and Wong 2013, McKinsey 2012, Wäger et al. 2011, Friege 2012), including the use of critical and rare earth metals (Dahmus and Gutowski 2007, Friege 2012; Li et al. 2009; Schluep 2009). Critical metals, whose potential economic impacts due to supply shortage are higher than most other raw materials (European Commission 2014), and rare earth metals, which are a subset of critical metals comprised of the 15 lanthanide metals plus scandium and yttrium, are especially important because of their vital role in new technologies (Binnemans et al. 2013).

While dematerialization aims to reduce material consumption, a closed-loop or circular economy aims for recovery and restorative use of materials (Frosch and Gallopoulos 1989, Ellen MacArthur Foundation 2015, Yuan et al. 2006, Andersen 2007, Haas et al. 2015). The global economy has traditionally been based upon a linear model of production and consumption. However, recent research focusing on the growing challenges of resource use and waste assimilation (Geng and Doberstein 2008) has identified the need for successful development of a circular economy (Yuan et al. 2006). Such strategies include urban mining of post-consumer end of life products (Binnemans et al. 2013, Friege 2012, Li et al. 2009, Gotze and Rotter 2012) and improving recycling and reuse of metals (Massari and Ruberti 2013), thereby closing the loop and reducing demand for new metals. Application of this type of ‘circular economy’ seems valuable, especially in the consumer electronics industry, where increasing consumption and rapidly evolving technology hinder dematerialization and material efficiency as a sustainability strategy. The circular economy may be a promising sister strategy for dematerialization, as implementation of a closed-loop system offers the opportunity to reclaim value from end of life products (Allwood et al. 2011). However, dematerialization may actually be detrimental to the success of a circular economy, by effectively reducing the material throughput of the system, thereby reducing the secondary value associated with material recycling.

These challenges increasingly underscore the need for innovative and adaptive methods for developing and evaluating strategies to quantify and reduce a variety of environmental impacts associated with groups of rapidly evolving and complex products, such as consumer electronics. Recent research demonstrates the utility of adapting ecological concepts to model groups of products or systems as interrelated and interacting products (Levine 1999, 2003, Field et al. 2000, Gutowski et al. 2010, Ryen et al. 2014). This systemic approach to modeling product communities or portfolios also lends new insights into eco-design of electronics (Komeijani et al. 2016); eco-efficient product procurement strategies (Pelton et al. 2016); and energy saving consumer behavior interventions (Raihanian Mashhadi and Behdad 2017), yet also raises the question of whether consumers can be influenced to adopt proposed solutions.

Building on this growing body of ecologically-inspired research, this dissertation aims to understand the relationship between an evolving community of consumer electronic products, its attendant material impacts, and the factors that drive consumption decisions. Meeting this objective requires expanding the community ecology perspective (Ryen et al. 2014) to include “ecosystem”-level material flows and developing a related body of data to evaluate the attendant consumption decisions. A biological ecosystem comprehends both the biotic community (living organisms) and abiotic or physical systems acting on and flowing through this community (e.g., nutrient and energy flows) (Smith and Smith 2009). These biotic and abiotic components shape each other through attendant energy exchanges and material flows (Loreau 2001, Zavaleta and Heller 2009).

Translating this concept to the industrial ecology space, the product community approach may be expanded to include external factors (regulations, consumption trends, product design, and consumer education) and abiotic flows (material consumption, waste) to consider the broader framework of a product ecosystem. To this end, this dissertation connects traditional MFA methodology with the community structure developed by Ryen et al. (2014) to evaluate the material flows through a dynamic consumer electronic product ecosystem, and to identify and evaluate the effects of biotic and abiotic forces on the ecosystem. Here, there is a compelling opportunity to advance industrial ecology methods and at the same time provide a more complete picture of the temporal trends in systems-level material usage (Hirato et al. 2009) and efficacy of promising dematerialization and circular economy strategies in the face of consumption decisions.



Population: Group of individuals of the same species in a defined habitat (Smith and Smith 2009), e.g. televisions in an average U.S. household.

Community: Collections of populations that interact within a habitat (Zavaleta and Heller 2009, Smith and Smith 2009, Holt 2009), e.g. interrelated ownership of products in an average U.S. household (Ryen et al. 2014).

Ecosystem: The entire system of organisms and external forces that interact in an area, shaping each other through energy exchange and material flows (Loreau 2009, Smith and Smith 2009), e.g. evolving community of electronic products in an average U.S. household and the attendant material flows through the household.

**The double headed arrows indicate possible pairwise interactions that impact the community structure and product ecosystem. Heavier weight lines indicate stronger interactions.*

Figure 1: Adaptation of biological ecology terminology for use with anthropogenic systems, specifically the consumer electronics ecosystem in the average U.S. household.

Ecosystem ecology seeks to understand the processes by which the community of diverse organisms shapes and is shaped by its physical environment, specifically through energy exchange and material flows (Smith and Smith 2009, Loreau 2001, Zavaleta and Heller 2009). Applied to industrial cycles, this field offers a promising approach to interpreting the relationships and resultant material flows associated with consumer electronics. Figure 1 shows biological ecology terminology adapted for use with anthropogenic systems, specifically consumer electronics. Ecosystems are characterized by the biological, chemical, and physical processes that connect organisms and their environment (Loreau 2001). Their investigation focuses on understanding the recycling of limiting nutrients to ensure the renewal of necessary elements and the factors and processes that control material and energy flows (Smith and Smith 2009, Loreau 2001).

This research aims to investigate the ecosystem of consumer electronics, including both the community structure described by Ryen et al. (2014), and the extent to which environmental forces (such as consumer preference or available income) impact the attendant ecosystem-level material flows. The benefits of the household ecosystem approach are threefold. First, an ecosystem approach enables a holistic understanding of the related impacts of individual product species and environmental forces, to evaluate the effects of technological innovations as they relate to biotic and abiotic interactions. Second, the dynamic study incorporates temporal trends of consumption, through evolving community structure, and changes in technology, enabling the assessment of material reduction by natural dematerialization and the potential of circular economy approaches for closing the loop on material supply chains. Finally, focusing on the household unit provides a platform for future research to identify the factors and processes that drive consumption, and therefore community structure, in an effort to identify effective leverage points with which to reduce the material impact of the ecosystem.

1.2 Research Goals and Objectives

The overall goal of this research is to adapt existing ecological and industrial ecological methodologies to better characterize a group of rapidly evolving products to help decision makers more sustainably manage the consumption and production trends. Using consumer electronics, a complex, but well-researched system, as a case study, findings from this research may be applied to other complex, emerging fields such as nanotechnology and renewable energy infrastructure.

The novel contributions of found in this dissertation are as follows:

- Chapter II establishes a framework to model and measure temporal trends in product species size and composition. The novelty of this work lies in the characterization of trends and relationships between product attributes. Additionally, this work highlights the necessity for additional work to understand the effects of variability and uncertainty in bill of attributes data, which can significantly affect the reliability of life cycle assessment and material flow analysis.

- Chapter III extends existing material flow analysis methodologies to evaluate the temporal effects of technological innovation as well as the effects of changes in consumption behaviors. The novelty of this work lies in linking the electronic product community's structural changes with ecosystem level material flows, using a bottom-up approach, eliminating the need for product life span data and the accompanying uncertainty due to inconsistencies in definitions.
- Chapter IV models the effects of consumption decisions and product interactions on community structure. The novelty of this work lies in linking consumption choices and product interactions, and in modeling the effects of changes in consumption choices to develop processes for managing rapidly evolving communities of complex products.

II. Evolving materials, attributes, and functionality

2.1 Introduction

The environmental impact of a product depends on attributes of the product itself as well as material, energy, and emissions associated with manufacturing, operation and end-of-life processes. The product attributes, including performance related metrics such as power consumption, material content, and components, are captured in the bill of materials (BOM), a list of masses of constituent materials in a product, and the bill of attributes (BOA), a generalization of BOM that includes the contribution of relevant component systems. Figure 2 demonstrates how methods like LCA and MFA use BOA and process data to estimate material consumption and emissions associated with individual products or groups of products.

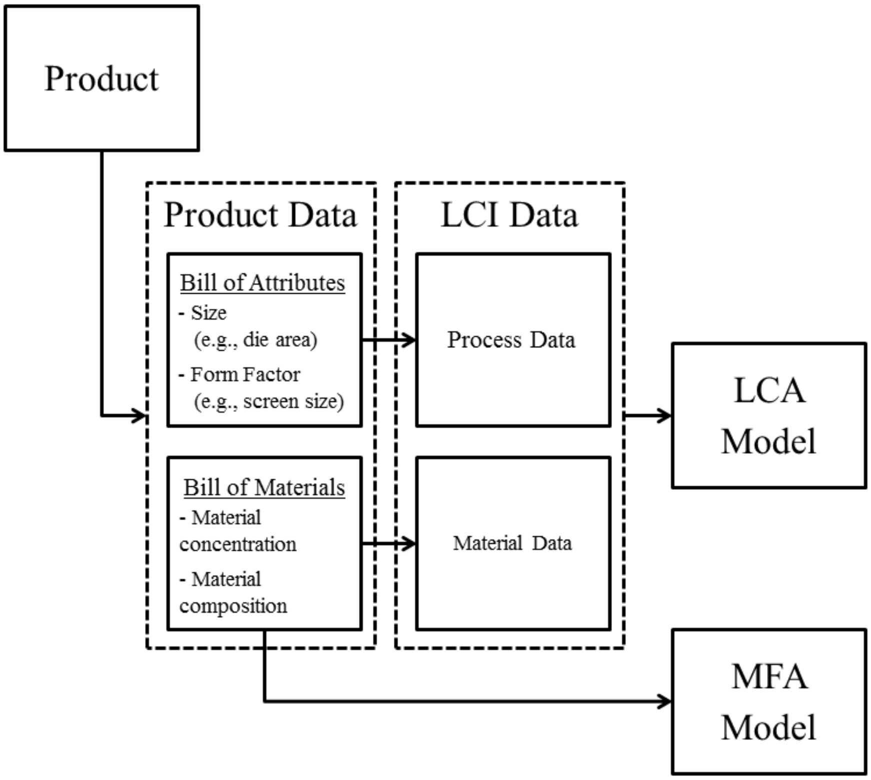


Figure 2: Relationship of bill of attributes (BOA), bill of materials (BOM), life cycle inventory (LCI), and material data, for use in LCA and MFA methods.

Research communities have made significant advances in developing comprehensive databases describing environmental parameters of processes (e.g., ecoinvent, GaBi, and NREL U.S. LCI databases). These databases, and published process-specific analyses (e.g. Boyd et al., 2010; Williams et al., 2012), also address temporal and geographic variability of process LCI data. Additionally, existing research has attempted to streamline LCA of consumer electronics by creating heuristics that link these products' attributes with potential LCI inputs (Baumann et al., 2012; Betz et al., 1998; Laurin et al., 2006; Moberg et al., 2014; Olivetti et al., 2012; Olivetti and Kirchain, 2011; Sousa et al., 2001; Teehan and Kandlikar, 2012). However, significantly less attention has been placed on developing, validating, and analyzing variability in products' attributes and materials themselves. These inputs are usually selected based on a representative or available case study product (Deng et al., 2011), and the extent to which these attributes vary over time or between products is unknown.

While reliable BOA data is as important as process data in LCA and MFA, characterizing product attributes and materials has been neglected as an object of formal analysis. This omission is particularly problematic for complex products, like personal computers, because obtaining BOA data via disassembly is labor intensive, and reverse engineering internal components can require sophisticated equipment for materials identification (Olivetti et al., 2012). Building BOA by collecting information throughout the supply chain is possible, but faces many of the same challenges associated with gathering process data, including availability, representativeness, and proprietary limitations (Baumann et al., 2012; Olivetti and Kirchain, 2011; Weber et al., 2010), and researchers must rely on a combined approach of disassembly and literature values (Oguchi et al., 2011).

The study conducted here contributes to these challenges in two novel and interconnected ways. First, the material intensity of a "typical" consumer electronic, the laptop computer, is comprehensively investigated for eight subsequent model years and for multiple models within a single year to understand the extent of material variability and dematerialization actually occurring adjacent to improvements to product performance and functionality. Second, this longitudinal study is used to determine the potential utility of LCI approximation heuristics for consumer electronics and the sensitivity of these attributes to evolving product functionality. Ultimately, this knowledge can inform the further development of product attribute-to-impact assessment estimation techniques (Olivetti and Kirchain, 2011) and provide input to future electronic product design to achieve sustainability goals.

2.2 Methodology

2.2.1 Case study products

The laptop computer was selected as a case study product, and two distinct groups of laptops were disassembled and analyzed on the basis of material composition. The first group of eight laptops consisted of successive model years (1999–2007) of a Dell Latitude business class laptop with constant screen size (14.1”), with processor speed, hard disk drive capacity and battery capacity representative of a typical product in that model year. The Dell Latitude product series was selected based on availability of products to study and representativeness of this product as a “typical” business class laptop. In the late 1990s and early 2000s, Dell, at over 30%, held the largest segment of the personal computer market in the United States, followed by Hewlett Packard at just over 20% (Kanellos 2005). Model year 2004 does not appear because the Latitude D600 was released in March of 2003 and its successor, the Latitude D610, was not released until February of 2005. The second group of three laptops consists of a specific product line and year (2008 Hewlett Packard Elitebook) with progressively larger screen sizes (12.1”, 14.1”, and 17”). The data set was selected to observe the trends in material composition over time (Dell products) as well as across varying screen sizes (HP products). Detailed specifications of each model are shown in Table 1.

3.2.2 Product disassembly methods

The disassembly process began with measuring the initial weight of the full laptop assembly, not including the power adaptor, prior to disassembly to major component assemblies including the battery assembly (full assembly including cells, wiring, printed wiring board (PWB) and enclosure), chassis bottom (bottom cover and associated connectors), chassis top (top cover and associated connectors), display assembly (LCD module, plastic display bezel, hinges and associated connectors), optical drive, fan, hard disk drive, heat sink, keyboard (including frame beneath keyboard and associated connectors), motherboard (including microprocessor, graphics and sound cards, support frame and associated connectors), speakers, and other components (DRAM, modem, palm rest, etc.).

Table 1: Characteristics of the laptop computers included in study.

Year	Model	Release Date	Screen Size	Processor Speed	Installed DRAM*	Hard Drive Capacity	Battery Capacity	Chassis Material
1999	Dell Latitude Cpi R-Series PPX	4/99	14.1”	266 MHz	(1) 64 MB	750 MB	50 Wh	Plastic
2000	Dell CPX H5005T PPX	2/00	14.1”	500 MHz	(1) 256 MB (2) 128 MB⁺	6 GB	53 Wh	Plastic
2001	Dell Latitude C600	8/01	14.1”	850 MHz	(1) 256 MB (2) 256 MB⁺	10 GB	59 Wh	Plastic
2002	Dell Latitude C610	2/02	14.1”	1.2 GHz	(1) 512 MB (2) 256 MB	30 GB	66 Wh	Plastic
2003	Dell Latitude D600	3/03	14.1”	1.6 GHz	(1) 512 MB	30 GB	53 Wh	Aluminum and Plastic
2005	Dell Latitude D610	2/05	14.1”	2.0 GHz	(1) 512 MB (2) 512 MB	40 GB	53 Wh	Plastic
2006	Dell Latitude D620	3/06	14.1”	2.33 GHz	(1) 2 GB⁺ (2) 2 GB⁺	100 GB	85 Wh	Magnesium
2007	Dell Latitude D630	5/07	14.1”	2.4 GHz	(1) 2 GB (2) 1 GB	120 GB	85 Wh	Magnesium
2008	HP Elite Book 2530P	8/08	12.1”	1.86 GHz	(1) 4 GB (2) 4 GB	120 GB	55 Wh	Magnesium
2008	HP Elite Book 6930P	9/08	14.1”	2.53 GHz	(1) 4 GB (2) 4 GB	160 GB	55 Wh	Magnesium
2008	HP Elite Book 8730P	8/08	17”	2.53 GHz	Not Available	250 GB	73 Wh	Magnesium

Note: Eight successive model years were selected for constant screen size. Three models were selected for constant product and model year, but variable screen size. *Number in parentheses indicates the first or second DRAM card. ⁺DRAM card in the disassembled product was determined to have been an aftermarket upgrades based on DRAM manufacture date as compared to laptop manufacture date.

Once the major component assemblies were removed and assigned a unique assembly number, each was weighed before further separation into individual subassemblies. Each subassembly was completely disassembled to a level where, when possible each piece was comprised of a single material identified by visual inspection and grouped into general categories of plastics, metals, or other. When complete separation of materials was not possible, the proportions of materials were estimated. Within each category, materials were more specifically differentiated using basic physical properties, labels, recycling codes, product heuristics, or, for metals, where no other identification was possible, by analysis using a Delta Handheld XRF Analyzer. Plastics were further separated into PC + ABS, as indicated by a recycling symbol provided by the manufacturer, and "other" plastics. When unmarked plastic pieces exhibited similar characteristics to the marked PC + ABS within the same laptop, PC + ABS was assumed based on the industry approach to minimize plastic types in a single product (IEEE, 2009). Metals were separated into ferrous and non-ferrous components using a magnet and then validated by XRF analysis. Items classified as magnesium were labeled by the manufacturer as Mg. Other non-ferrous materials were identified based on feedback from electronics recyclers and knowledge of common material composition (e.g., copper wiring). Other major material groups included LCD materials (the LCD module only), battery cell (main battery cells only) and printed wiring board (PWB). The material group "other" included all materials not included above, such as rubber, (non LCD) glass, and adhesive tape.

Large pieces were assigned a descriptive name and unique sub-assembly number associated with their respective component assembly for ease of tracking. Small parts, such as screws, were grouped by material and numbered together with other small parts from the same component. All pieces were weighed individually on a scale with 1200 g capacity and 0.1 g resolution. Weights were compiled into a BOM for each laptop and also summed by component assembly (Appendix A Tables A1 and A2).

2.2.3 Quantification of semiconductor area

Semiconductor manufacturing is known to be a major contributor to electronic products' environmental impact (O'Connell et al., 2010; Krishnan et al., 2008; Williams et al., 2002), and the majority of the silicon semiconductors are contained in the motherboard and dynamic random access memory (DRAM) of the laptop, which were therefore analyzed further. The area of semiconductors on the central processing unit (CPU), DRAM and all other integrated circuits (ICs) on the motherboard were measured two ways. First, the outer dimensions of the IC, which includes the IC packaging and the contained silicon die, were measured to calculate the area of each IC. None of the CPUs had outer packaging, so in these cases, outer and die areas were the same. ICs with outer packaging measuring 1 mm by 1 mm or smaller were excluded. The total outer area of the motherboard was also directly measured.

Next, the actual silicon die areas were measured one of two ways: grinding the outer packaging off of the IC using a Dremel tool or X-ray inspection using a Glenbrook JewelBox 70T X-ray Inspection System and associated GTI-5000 software. This X-ray inspection technology is typically used to view solder joints and other features of PWBs and packaged semiconductors for quality control purposes. However, Figure 3 demonstrates that the image provided by the X-ray clearly shows the outline of the silicon die inside the packaging, which makes this method ideal for quick, accurate, non-destructive determination of silicon area.

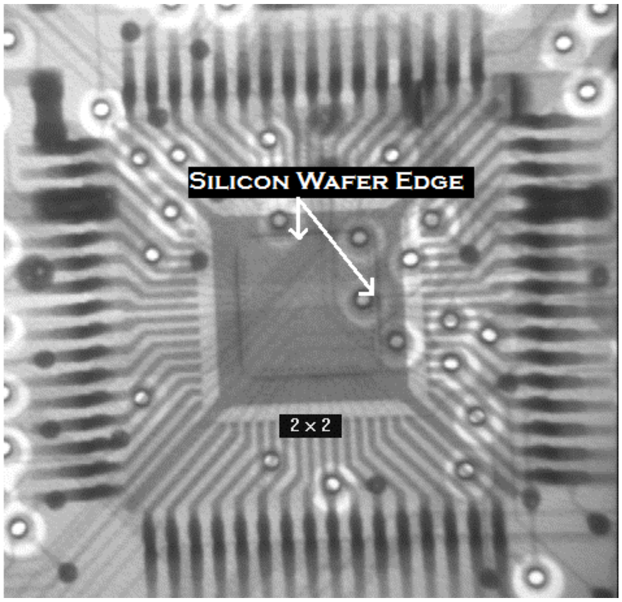


Figure 3: X-ray image of a surface mounted integrated circuit.
Image taken by a Glenbrook Jewelbox 70T X-ray Inspection System with GTI-500 software. The image clearly shows the outline of the silicon die within the outer packaging. Using a reference measurement, the software can be calibrated to enable direct measurements of the die in the image.

Measurements made with the X-ray inspection system were calibrated to a pre-measured feature on the circuit board that could be seen visibly on both sides of the board and under X-ray. After measuring the reference feature, the PWB was positioned in the X-ray system using the manipulator arm, and the GTI-5000 software was calibrated for the height of the manipulator arm using the reference measurement. The silicon dies on each side on the board were measured independently, re-calibrating to the reference feature after turning the board. In cases where two components were adjacent on opposite sides of the board, photographs of the PWB were used to clarify the identity of the components. Larger dies required changing the height of the manipulator arm and recalibration of the software.

In cases where the die was too large to measure using the X-ray inspection system, the IC outer packaging was physically removed using a Dremel tool to grind off the top layer of plastic covering until the silicon was exposed, enabling direct measurement of the die dimensions. This method of physical removal of the outer packaging was also used to verify the accuracy of the results obtained through the use of the X-ray inspection system. Measurements of one entire PWB were taken using both the X-ray and physical removal methods, to verify consistency between results of each measurement method.

Because of the large contribution of semiconductors to the environmental impact of the laptop (Deng et al., 2011), as well as the difficulty associated with measuring the die area, several methods of estimation were developed based on the measured area and characteristics of the die, the outer packaging, and the total die area on the motherboard. The methods used were based on (1) average die area per chip, (2) ratio of die area to the motherboard area, (3) ratio of die area to outer packaging area, and (4) combination of measuring and estimating using these methods. Each of these approaches had additional variants where the respective ratios or relationships were disaggregated further, for example, specific ratios for ICs with the most commonly observed outer packaging area (4-mm 5-mm) or for the largest (>100 mm2) outer area (which represented the greatest contribution to total die area). Additional details on each of these methods are provided in the Supporting Information (Table SI-19). In all cases, only the motherboard chips and die area were used to develop the method and compare the results. The CPU and DRAM ICs were excluded from the estimation. In instances where the IC had no outer packaging, the measured area was used, assuming that future researchers would be able to easily measure ICs without packaging. The estimation approaches proposed in Methods 1–4 were tested against actual observed die area for all motherboards in the 14.1” computers, and their relative predictive capacity was determined by root-mean-square (RMS) error.

During the study, it was observed that the manufacture date of the laptop preceded the printed production date on four of the installed DRAM cards, indicating that these cards had been replaced as aftermarket upgrades. As DRAM is the most easily and frequently upgraded component in a laptop computer, the DRAM study data set was expanded to ensure that sufficient data were available, for which memory amounts and total die areas could be exactly cross-referenced with production dates. Many additional DRAM cards from the study time period were made available by IT professionals at RIT. Of this set, any card for which a known production date could be determined was included for further study. Production date was determined by comparing the product numbers printed on the card’s label with the coding information provided on the manufacturer’s website. The expanded DRAM data set included a total of 30 DRAM cards from three manufacturers, representing the period 1999–2011. All DRAM die sizes were measured using the grinding method as they were too large to measure with X-ray inspection.

2.3 Results and discussion

2.3.1 Product level dematerialization

The laptops analyzed in this study represent a product with a medium to high level of product maturity. Despite technological improvement occurring over the period analyzed, no significant change in material intensity per product was observed. Some reduction in weight was accomplished in large part due to a shift from plastics to light metals for chassis construction, as well as minimal component level dematerialization (Figure 4), however, the overall decrease in product weight is less than 2% per year across the longitudinal study. On the other hand, within the HP 2008 model year computers, product level dematerialization of almost 30% was observed between the largest (17”) and smallest (12.1”) form factors.

The limited product level dematerialization observed from 1998 through 2007 results were benchmarked against more recent trends toward product “lightweighting,” which suggests the possibility of further dematerialization. Manufacturer specifications for more recent Dell Latitude laptops (2008–2014) show that newer products with similar BOA to those analyzed here consistently had approximately 2% mass reduction per year. However, a weight reduction of about 20% was observed between 2010 and 2011, due to the removal of the standard optical drive and a fundamental change in functionality (see Appendix A Figure A1).

Benchmarking our empirical data to manufacturer specifications and product reviews of Apple iPhones (2007–2014) and Apple iPad tablets (2010–2014) showed more significant weight reductions were achieved by making a technological leap to a smaller product: dematerialization of more than 90% and 70% over the laptop computer of the same model year, respectively. However, dematerialization within each of these additional products generally mirrors the rates in the laptop computer product series. The key exception was the introduction of a new, larger iPhone 6 in model year 2014 (see Appendix A Figure A1). These results suggest that once a product matures to a set form factor, minimal product-level dematerialization will occur without shifting to a smaller form (e.g., from a 14.1” to a 12.1” screen), removing previously standard functions no longer required by consumers (e.g., eliminating the optical drive) or a significant technological leap to a different product entirely (from a laptop to a netbook, tablet, or smart phone).

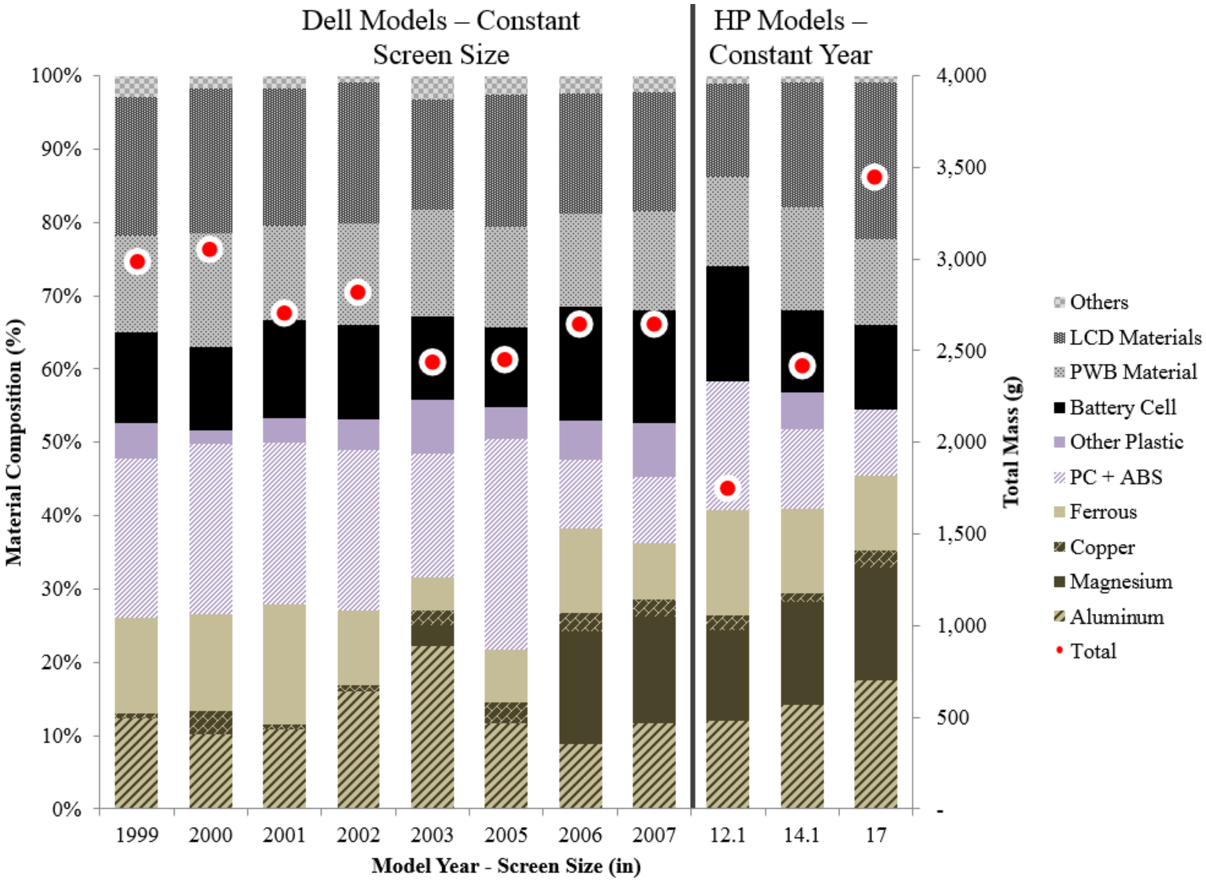


Figure 4: Laptop material composition as a percentage of total weight.
Laptop material composition (left axis) as a percentage of the total weight (shown as a circular marker, right axis). These results show that the relative contribution of each material is roughly constant over time, with the largest changes in material composition occurring as the result of a shift from a plastic to a magnesium chassis. LCD: liquid crystal display; PWB: printed wiring board; PC + ABS: polycarbonate and acrylonitrile butadiene styrene.

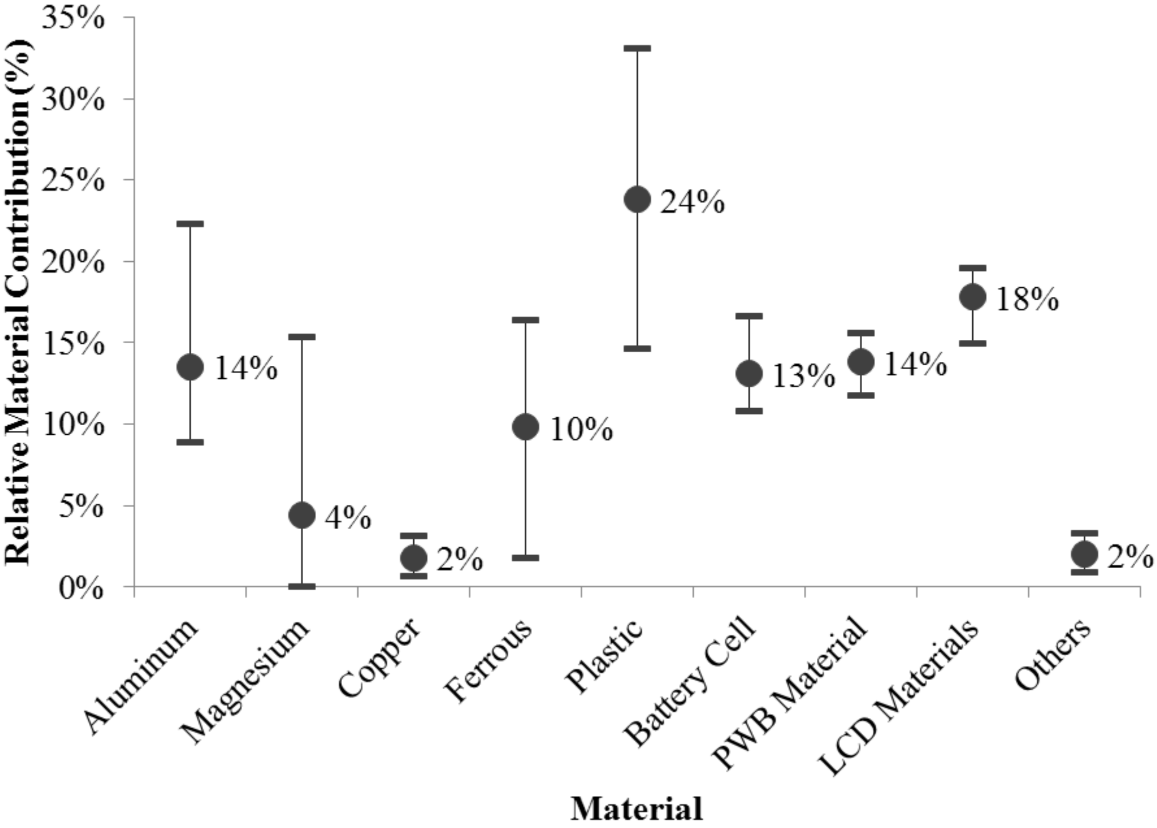


Figure 5: Representative BOM for a laptop computer.
Representative BOM based on the average material composition for the 14.1″ laptops included in the study. Error bars correspond to the range (maximum–minimum) of observed values of each material. LCD: liquid crystal display; PWB: printed wiring board.

Additionally, the relative contribution of each constituent material remains approximately constant in laptops over time and among various sizes (Figure 4). This result suggests the possibility that a representative BOM could be developed and applied to other products of the same form factor to estimate material composition based on total product mass alone. To evaluate the viability of this approach, the average material composition for all 14.1" laptops from this study was calculated and presented in Figure 5, with error bars that coincide with the widest range of compositions (maximum and minimum) among all laptops (additional data in Appendix A Tables A1 and A2). Although the majority of products included in this study are from a single manufacturer, many original equipment manufacturers share common suppliers and components (Rice and Hoppe 2001), suggesting that similar composition would be seen across manufacturers. The actual material composition for the HP Elitebook 12.1" and 17" laptops fell within the range of estimates of the representative BOM (Table 2), supporting the idea that, with additional analysis, characteristic BOMs could be generated for product categories and used in subsequent LCA and MFA studies.

The representative BOM was then compared to the actual material contributions of other form factors, including a smart phone, a tablet, netbooks and various sized laptop computers (see additional data and sources in Appendix A Tables A3 through A6). The representative BOM is less accurate for netbooks, tablet, and smart phone (Table 2), in part due to the greater variety of chassis materials used in these devices and in part due to the technological innovations that make the smaller form factors possible. While there is some utility in the use of a representative BOM for estimation of material composition, further research is necessary to develop product specific representative BOMs, as well as to account for the error introduced through product variability.

Table 2: Relative material contributions of products with different form factors.

	2007	2009	1998	2008	2008	12.1	17
Material	iPhone	iPad	Sony Vaio	Acer One	Asus EEE PC	HP 12 inch	HP 17 inch
Aluminum	21%	18%	6%	11%	14%	12%	16%
Magnesium	0%	0%	**16% (↑)**	0%	0%	12%	14%
Copper	2%	**5% (↑)**	1%	1%	0%	2%	2%
Ferrous	10%	2%	9%	4%	2%	14%	9%
Plastic	12%	**9% (↓)**	**9% (↓)**	34%	31%	18%	15%
Battery Cell	**18% (↑)**	17%	17%	12%	**24% (↑)**	16%	11%
PWB Material	**10% (↓)**	**4% (↓)**	14%	**17% (↑)**	**18% (↑)**	12%	11%
LCD Materials	**24% (↑)**	20%	**26% (↑)**	20%	11%	13%	20%
Others	**4% (↑)**	**26% (↑)**	3%	1%	1%	1%	1%

Note: When compared with the representative BOM (Figure 5), these results show that other products have similar material compositions. The percentages highlighted in bold and red indicate percent compositions that fall outside of the high / low range of the representative BOM, either higher (up arrow) or lower (down arrow). The representative BOM is closest to similar products (other laptops), but diverges for small form factors, such as netbooks, tablets and smart phones. See Appendix A, Tables A3 through A4 for additional data sources.

2.3.2 Functional dematerialization

While minimal product level dematerialization was observed in the longitudinal study without a major technological or functional shift, concepts like Moore's Law imply that, over time, more function becomes possible with less material. This suggests that some amount of functional dematerialization is occurring at the component level, yet manufacturers capitalize on technological improvements to increase functionality within the established form factor. To this end, several of the individual components from the BOA were evaluated to determine the evolving material intensity of key laptop functions.

The battery and hard disk drive (HDD) assemblies are two examples in which functional dematerialization is observed to occur over time. As shown in Figure 6, which focuses on all 14.1" laptops from this study, mass per battery cell is relatively constant over time, with slight fluctuations. At the same time, the mass required per Wh decreased by almost 50%. Similarly, the total assembly of the HDD is relatively constant, while the capacity increases by over 300 times and the mass per gigabyte shows a corresponding decrease. These results suggest that technological improvements are being traded for increased functionality, in response to consumer demand for improved performance in the form of extended battery life or hard disk drive capacity. Detailed analysis of all components is included in Appendix A (Figures A3 through A7 and Tables A9 through A18).

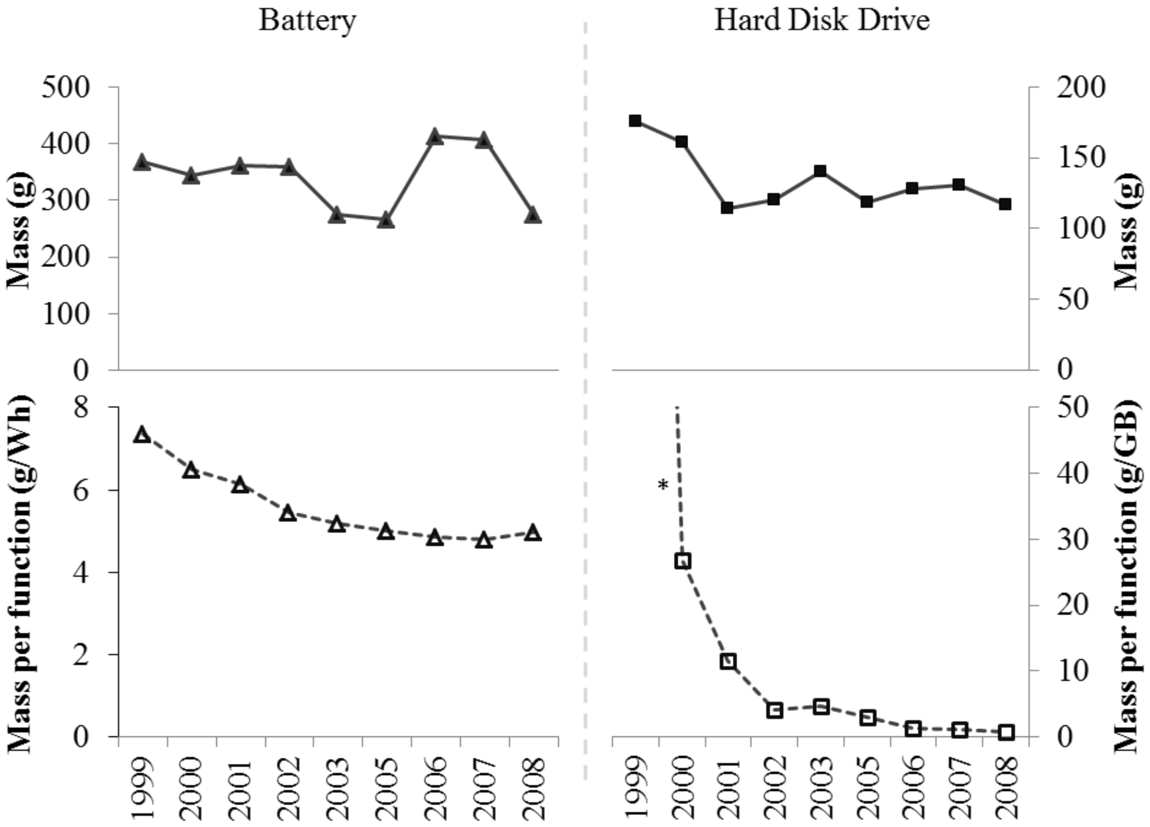


Figure 6: Battery and hard disk drive mass and mass per function as a function of time.
Analysis of battery and hard disk drive (HDD) mass (top) and mass per function (bottom) shows that the battery and HDD assembly realize minimal component level dematerialization in the longitudinal study. At the same time, the material required to provide the typical product function decreases, supporting the idea that manufacturers capitalize on technological improvements to achieve increased performance within an established form factor. *The axis for HDD mass per function was truncated for visibility – the 1999 value is 234 g/GB. These data are for all 14.1″ laptops included in the study.

Similar analysis of die area was conducted for DRAM cards, along with an assessment of their functionality (memory capacity). The final data shown in Figure 7 consisted of 30 DRAM cards from three manufacturers spanning 12 years (1999–2011), a broader data set than the initial 11 laptops, due to observed DRAM upgrades in case study products. Despite significant technological improvement demonstrated by the rapidly decreasing size per function, consistent with Moore's Law, the trend in total die area per DRAM card is roughly constant over time. This result suggests a rebound effect by which dematerialization enabled by technological progress is being leveraged for increased functionality, not for a net reduction of material inputs, consistent with previous observations on microprocessors (Deng and Williams, 2011). In addition, with each addition to functionality (e.g., from 512 MB to 1 GB per card), the amount of die required is initially similar to that of the previously available function, with a slight dematerialization over time, where the die area to memory ratio slowly declines. Note that dematerialization here only refers to the direct material content (DRAM die area) in the device. "Net" dematerialization would account for changes in upstream materials and energy use in production processes. While there is preliminary evidence of increasing materials intensity associated with newer generations of semiconductors (Williams et al., 2011), the degree of net dematerialization in semiconductors remains an open question.

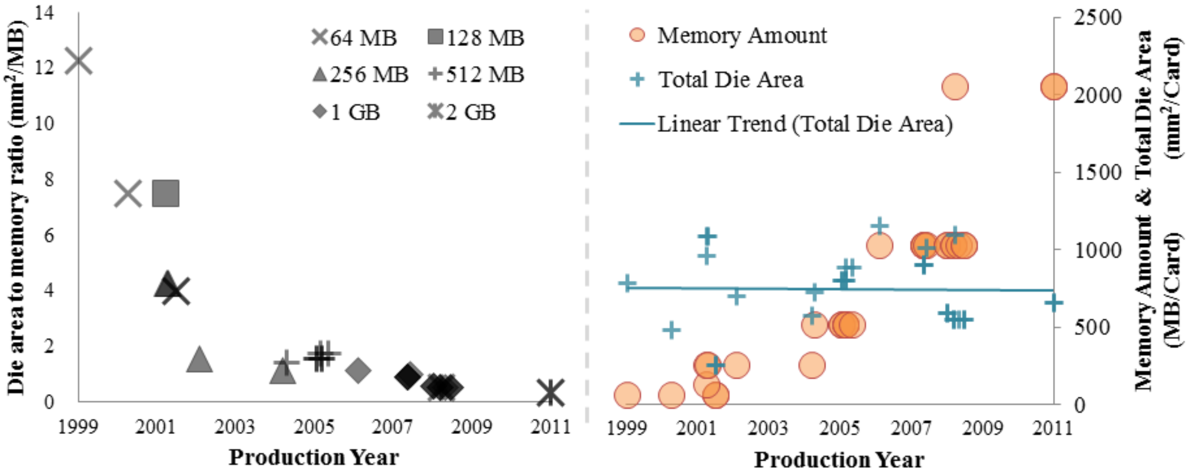


Figure 7: Temporal changes in die area per function, memory amount, and total DRAM per card. Decreases in die area per function (left axis) occur at a rate consistent with Moore's Law. However, these gains in functional capacity are counteracted by increasing memory amount contained in each DRAM card (right axis). As a result, total DRAM die area per card (also shown on the right axis) is relatively constant. These results suggest that manufacturers capitalize on technological improvements to achieve improved performance rather than component dematerialization. Darker colored markers in each figure indicate multiple occurrences of the same combination.

Finally, results indicate that total die area on the board roughly follows motherboard area over time and for increasing laptop size, with a correlation coefficient of 0.65 for all 14.1” laptops motherboards. Appendix A Figure A6 and Tables A15 and A16 show trends in total motherboard area and the silicon die present on each laptop’s motherboard, not including the CPU or DRAM. A step increase was observed between model year 2000 and 2001 as the main board became larger and a separate sound and graphics card was added. This increase correlates with a shift from CD-ROM to DVDROM modules, and suggests that the increase of board area was required to support the new functionality. Additionally, in some cases of year-to-year comparisons (1999 and 2000, 2001 and 2002, 2006 and 2007) the board shape stayed the same from one year to the next, but the amount of silicon die per board stepped down over the same period. While the motherboard area and the die area-to-motherboard area ratio are roughly constant for a typical product over time, averaging 35,000 mm2 and 0.015, respectively, the results show significant variability around these averages. Most notably, as the laptop size increases to 17”, the additional size enabled use of a much larger motherboard, with significantly higher die area, presumably to provide functional improvement or because the larger product footprint reduced space constraints on components.

2.3.3 Motherboard analysis

Semiconductor manufacturing is known to be an energy intensive process, and the motherboard contains a significant portion of the semiconductor material present in the laptop. Although accurate quantification is critical to performing LCA of consumer electronics, die area is difficult to access and measure. To this end, various heuristics (Kirchain, 2010; Zgola, 2011) have been proposed to estimate the amount of silicon present in a PWB, such as estimation based on motherboard area or established ratios between an IC’s easily measured outer packaging area and more difficult to measure inner die area. However, applying such ratios is not a straightforward task. Figure 8 shows the wide variety of die and outer packaging area combinations observed in the 625 packaged chips contained in the eleven motherboards included in the study. More than 80% of the dies measured have outer packaging areas of 50 mm2 or less, with 40% of the dies measured having outer packaging areas equal to 20 mm2. Further, the silicon die area of the more than 250 chips with an outer area of 20 mm2 show no clear trends and are fairly evenly distributed from 1 to 8 mm2.

Whereas Figure 8 shows that the most frequently found IC size on a motherboard was 20 mm2, these components only contribute a small fraction toward the total die area measured. On the other hand, between 30 and 70% of the total semiconductor area per board was concentrated in as few as five ICs per board, depending on the year. Figure 9 shows the relative contribution of the five largest ICs on each motherboard toward the total area (excluding the CPU and DRAM). Given the uneven distribution of semiconductor area among ICs, as well as the wide variety of die/packaging ratios, it is clear that attempts to estimate semiconductor area for a laptop or other electronic product must be undertaken with care and that further analysis is necessary to evaluate such estimation techniques.

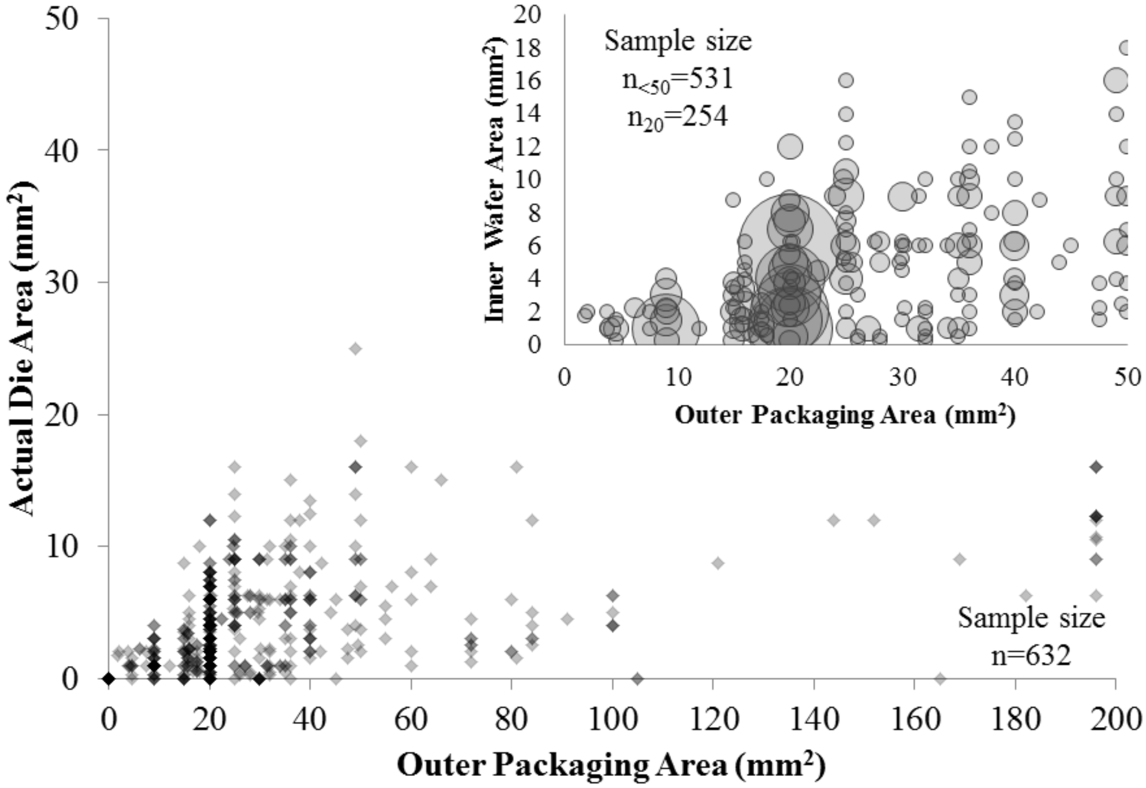


Figure 8: Silicon die area as a function of outer packaging area for integrated circuits.
Main figure: distribution of silicon die area against packaging area for all integrated circuits (ICs) found on the 14.1″ laptop motherboards (darker marker indicates multiple occurrences). There is a wide distribution of inner to outer area combinations, although there is a concentration of silicon dies with an outer packaging area of 20 mm2. Inset figure: closer analysis of the ICs with outer packaging area 50 mm2 or less. Of 632 total chips represented in the main figure, 531 (84%) have packaging smaller than 50 mm2, and 40% have packaging areas equal to 20 mm2.

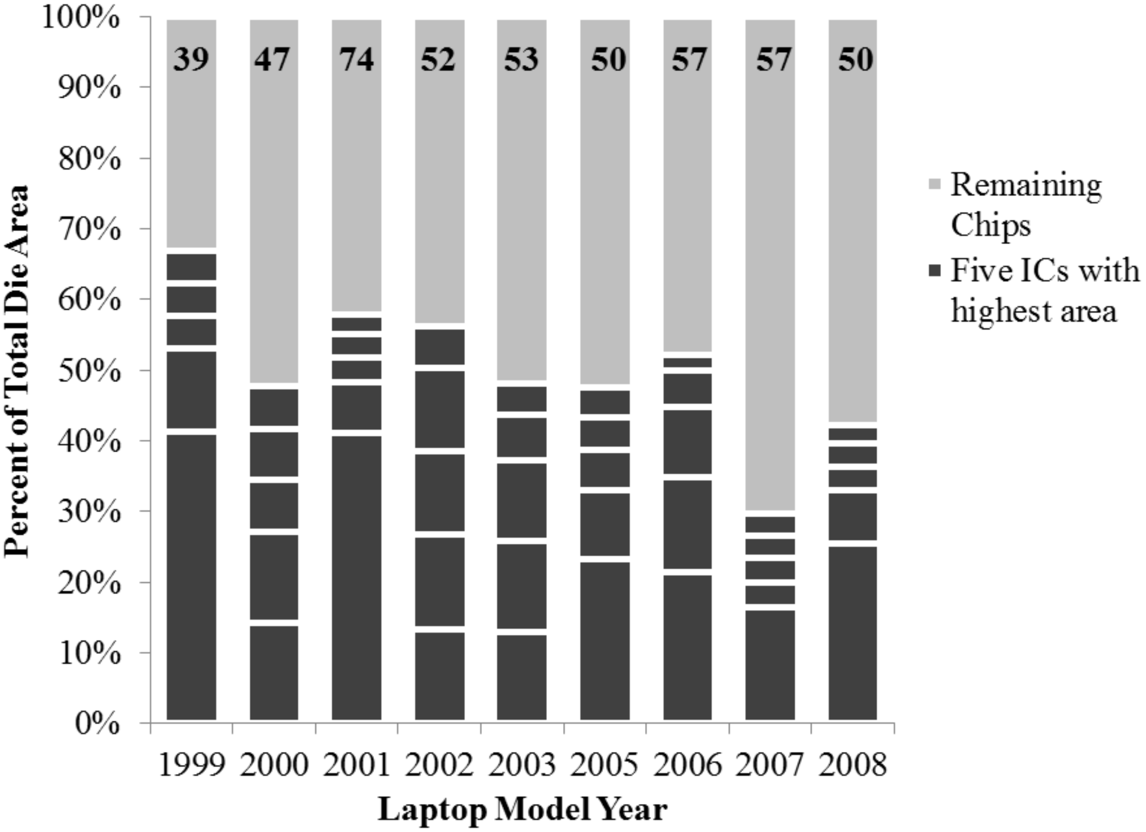
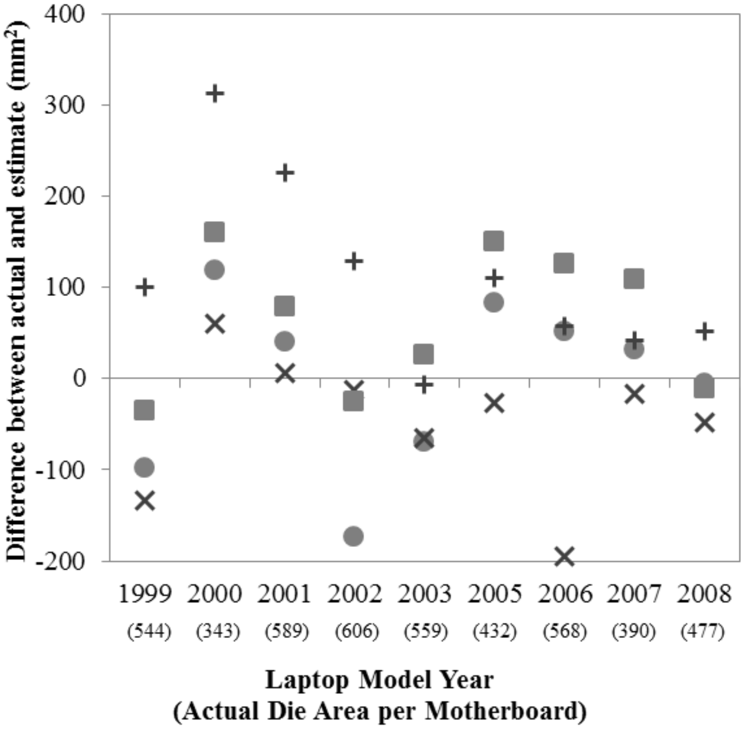


Figure 9: Temporal shifts in relative contribution of integrated circuits to semiconductor area.
Percent of semiconductor area distributed across all ICs. The dark gray sections show the relative contribution of the five ICs contributing the greatest die area; the lighter gray section shows the total contribution of all the remaining ICs. The number of ICs represented in the light gray section is included at the top of each column.

To this end, several methods of estimation were evaluated to determine their accuracy in determining silicon die area. To summarize (additional detail in Appendix A Table A19), these methods included approaches that used an average die area per IC (Method 1), an average die area per motherboard area (Method 2), the average ratio of die area to IC packaging area (Method 3), and a combination of direct measurements, estimation of the largest IC contributions, and approximation of remaining ICs (Method 4). The accuracy of each of these approaches was analyzed retrospectively on each of the motherboards from the case study, and the deviation between predicted and actual areas was determined by calculating the root-mean-square (RMS) error. Each of the above methods involved some degree of disaggregation of the averages and ratios used, based on the frequently observed packaging sizes or concentration of die area in a few large ICs. For example, Method 1 applied one value for area per IC to all components with 20 mm2 packaging (the most common size) and one value for area per IC to the remaining components. In all cases where multiple variants of the methods were compared, the four reported in the main text had the lowest RMS error for their method category (see Appendix A Tables A20 through A23 for all RMS results) (Figure 10).



Method	Description	RMS Error
1 ●	Average die area per chip	78
2 X	Ratio of die area to motherboard area	130
3 +	Ratio of die area to packaging area	154
4 ■	Combination of measuring and estimating	73

Figure 10: Graphical representation of actual versus estimated die area for various estimation approaches. Graphical representation of the difference between the actual and estimated die area per motherboard for the best results of each estimation approach. The actual die area per motherboard is shown in parentheses under the x-axis labels, and the graphed results report the difference between this actual (corresponds to zero on the y-axis) and the value estimated by the four methods. RMS error evaluation shows that Method 4, combining measuring and estimating, is the most accurate, and Method 3, using a ratio of silicon area to IC packaging area is the least accurate. These methods should be used with caution, however, because, as shown in the figure, even the most accurate methods show a wide range of accuracy when compared with the actual semiconductor area.

While results of Figure 10 indicate that some approaches based on physical measurements and approximations may perform better than others, significant uncertainty exists for all methods tested here (16 in total, including all variants). The methods with the least overall error are based primarily on the simple approach of multiplying the total number of ICs counted per motherboard by an average area per IC factor (Method 1), or by combining this estimation with a few additional measurements, including measuring the area of any unpackaged dies and including an additional factor of area per IC specific to components with packaging greater than 100 mm2 (Method 4). On one hand, this outcome offers some promise that simple, heuristic-based estimation approaches may help streamline the labor-intense task of constructing full BOA data on semiconductor area.

On the other hand, the uncertainty observed here, which ranges from about 2 to 45% deviation off the actual die area, depending on the year, could introduce significant error into LCA calculations using the estimated BOA. Given the importance of semiconductor production in the net energy impact of a laptop computer (Deng et al., 2011), a small difference in estimated die area would make a much larger impact on final results than a similar deviation between actual and estimated bulk materials (i.e., Figure 5). Widespread use of any of these or similar heuristics should be informed by further analysis and compilation of additional data sets specific to the form factor being analyzed.

2.4 Implications

2.4.1 LCA – Temporal and product type variability

LCA studies typically rely on picking a particular product to analyze, following the assumption, usually implicit, that the resulting BOA is representative of a larger group of products. Results reported here inform the true degree of representativeness. For the laptop cohort in this work, there is surprisingly little variation in BOA over time for the same product type (14.1”). A driving product attribute (i.e., screen size) affects BOA much more than change over time. This hints, but does not prove, that prior laptop studies such as Deng et al. (2011) may reasonably represent environmental impacts for laptops beyond the study year as long as form factor is the same, but results would vary more for different size computers. Proving this assertion would require future work on a large scale LCA of a cohort of laptops. Nonetheless, results here point future LCA studies toward characterizing BOA for different products within a class and for different years.

2.4.2 LCA – Parameterizing BOA

Collecting BOA data is labor intensive. Modeling has the potential to extrapolate BOA from an “easier” dataset. For example, it would be convenient if silicon die area, which requires grinding or X-ray analysis to measure, would closely correlate with the external IC package size, which can be visually measured. However, the ratio of packaging size and die area varies widely. Other parametric relationships that were tested using the large case study data set, such as die area per motherboard or average die area per integrated circuit, showed the most promising degree of accuracy. Given the high proportion of die area contained in just five or fewer ICs per motherboard, all estimation techniques can be improved by focusing more labor intensive measurements on the largest components and estimating the remaining die area using heuristics-based approaches. However, relying on such estimation techniques will certainly introduce a greater deal of uncertainty to the resulting LCA and more study of the physical relationships between BOA and silicon area is needed.

2.4.3 Dematerialization and electronics design

This work also illustrates the challenge of relying on product level dematerialization as a means of reducing the increasing environmental impact caused by the easy availability and affordability of consumer electronic products. While “doing more with less” may be a step toward reducing environmental impact of the electronics industry, the realization of this goal, at least for a mature product like the laptop computer, may be limited by lock-in to a ‘typical product’ form factor. Subsequent evolution of this form factor then is less directed toward dematerialization, but rather to meet consumer demand for increasing or evolving functionality, which may result in either increased (larger smart phones) or decreased (removal of laptop optical drive) material intensity. Thus, efforts to reduce product-level environmental impacts must instead focus on translating enhanced functionality into extended product life, reduced power consumption, features that enable product recovery and recycling at end-of-life, and user-interfaces that lead the product-user to more sustainable behavior.

III. Dematerialization and the circular economy as material consumption reduction strategies

3.1 Introduction

As discussed in Chapter II, dematerialization has been proposed to mitigate both increasing material consumption and potential material impacts. Unfortunately, the efficacy of dematerialization as a strategy to achieve net material reduction is often limited by behavioral response. For example, in the case of consumer electronics, efficiency gains resulting from technological innovation observed to achieve increased product performance, resulting in no net material reduction, as shown in Chapter II, or an increased product ownership leading to greater cumulative impact (Ryen et al. 2014, 2015).

The circular economy may be a promising sister strategy for dematerialization, as implementation of a closed-loop system offers the opportunity to reclaim value from end of life products (Allwood et al. 2011). The concept of circular material flows is a clear tenet of industrial ecology (Graedel and Allenby 2010), having evolved from the observations of nutrient cycling in biological ecosystems. Traditional industrial ecology methods, such as material flow analysis (MFA), take inspiration from these biological cycles to study anthropogenic material use cycles, in an effort to understand the supply, use, and loss of materials as they pass through technological organisms (Graedel and Allenby 2010, Brunner and Rechberger 2004). While MFA is based upon the principles of biological nutrient cycling, this method traditionally focuses on the environmental effects of a single product or material at a point in time (Socolof et al. 2001, Oguchi et al. 2011, Buchert et al. 2012, Huisman 2003, Hageluken and Buchert 2008, Gotze and Rotter 2012, Bull and Kozak 2014).

Recent research highlights the importance of considering the effects of interrelated and interacting products and also demonstrates the utility of adapting ecological concepts to model groups of products or systems (Levine 1999, 2003, Field et al. 2000, Gutowski et al. 2010). Ryen et al. (2014) drew an analogy between a biological community, or group of organisms living and interacting within a defined habitat, and a consumer electronic product community as "an assemblage of products that exist and interact directly or indirectly in a shared spatial or temporal setting." When applied to electronic products in U.S. households between 1990 and 2010, this community ecology framework captured the changing life cycle energy impact associated with dynamic trends in product consumption and use, which could not be detected when analyzing a single product at a time (Ryen et al. 2015).

To date, research has neglected the connections between the structure of the electronic product community and the ecosystem level material flows. Building on the growing body of ecologically-inspired research, this chapter aims to understand this relationship between an evolving community of consumer electronic products and its attendant material impacts, for which dematerialization or circular economy strategies may be applied. Meeting this objective requires expanding the community ecology perspective to include "ecosystem"-level material flows. A biological ecosystem comprehends both the biotic community (living organisms) and abiotic or physical systems acting on and flowing through this community (e.g., nutrient and energy flows) (Smith and Smith 2009). These biotic and abiotic components shape each other through attendant energy exchanges and material flows (Loreau 2001, Zavaleta and Heller 2009). Translating this concept to the industrial ecology space, we can expand the product community approach to include external factors (regulations, consumption trends) and abiotic flows (material consumption, waste) to consider the broader framework of a product ecosystem. To this end, this chapter connects traditional MFA methodology with the community structure developed by Ryen et al. (2014) to evaluate the material flows through a dynamic consumer electronic product ecosystem. Here, we have a compelling opportunity to advance industrial ecology methods and at the same time provide a more complete picture of the temporal trends in systems-level material usage (Hirato et al. 2009) and efficacy of promising dematerialization and circular economy strategies.

3.2 Methodology

3.2.1 Product Ecosystem MFA

This MFA evaluates material flows in terms of changes in the ecosystem by building upon the community approach taken by Ryen et al. (2014). By taking a systematic "bottom-up" or "time-step" approach that begins with the product community structure (how many of each product 'species' are contained in the system boundaries over time), this method avoids reliance on product lifespans, input-output tables (Di Donato et al. 2015, Hirhato et al. 2009), and annual time series data (Hirhato et al. 2009). MFA is based on the concept of mass conservation, and flows can be determined using a combination of the change in product stock over a given time period, an estimate of the sources, or inflows, and sinks, or outflows of each product (Graedel and Allenby 2010, Brunner and Rechberger 2004). Products are purchased, or consumed, and reside in stock for a latency period before flowing out of the household as waste:

$$\Delta P_{stk} = P_{in,t} - P_{out,t} \qquad \text{(Equation 3.1)}$$

where $P_{in,t}$ is the product inflow in a given time period and $P_{out,t}$ is the product outflow in a given time period (Graedel and Allenby 2010, Brunner and Rechberger 2004).

3.2.2 Product Ecosystem Characterization

The product ecosystem was considered to be the entire group of consumer electronic products owned by the average U.S. household between 1990 and 2010, a system boundary that allowed the use of previously-determined product population data compiled in Ryen et al. (2014). Considering each household electronic product as the equivalent of an individual species, over 30 interrelated products were identified as providing information, communication and entertainment services. Following the convention previously established (Ryen et al. 2014), automobile and most analog (non-digital) products were excluded, as were products with insufficient publicly available sales or household adoption data. Some analog products were included because of high adoption rates (VCR) or because of combined analog/digital data (CRT televisions). Printers, fax machines and scanners were combined into a single category (hard-copy devices) based on availability of sales data (US EPA 2011). The change in product stock is largely based on data published in Ryen et al. (2014), which for the most part directly obtained product ownership data from consumer trade organizations and market surveys, and to a lesser degree on past MFAs, such as the e-waste analyses performed by the US EPA (2011). To test the sensitivity of the results to the inherent assumptions and uncertainty of the initial data, product ownership was compared with other sources, including the 2001, 2005, and 2009 EIA Residential Energy Consumption Survey (EIA 2001, 2005, 2009).

3.2.3 Product Stocks and Flows

As shown by Figure 11, the household product ecosystem was the basis for the MFA, where (Pstk,i,t) is the installed stock, or population, of each electronic products included in the study (i) in each year (t). Household consumption, (Pin,i,t in sales units per year), defined as the annual product inflow per average U.S. household, was calculated by dividing current year sales (Usales,i,t in units of products) by the number of U.S. households in that year (xt), as shown in Equation 3.2. Change in household stock (ΔPstk,i,t in units of products per year) was calculated for all products for the current and previous years, as shown in Equation 3.3. Household consumption minus the change in household stock provides the household waste (Pout,i,t in units of products per year), or the annual product outflows from the household (Equation 3.4).

$$P_{in,i,t} = \frac{U_{sales,i,t}}{x_t} \quad \text{(Equation 3.2)}$$

$$\Delta P_{stk,i,t} = P_{stk,i,t} - P_{stk,i,t-1} \quad \text{(Equation 3.3)}$$

$$P_{out,i,t} = P_{in,i,t} - \Delta P_{stk,i,t} \quad \text{(Equation 3.4)}$$

Total household stocks and flows were calculated by summing the individual material stocks and flows for each product, accounting for their consumption over time.

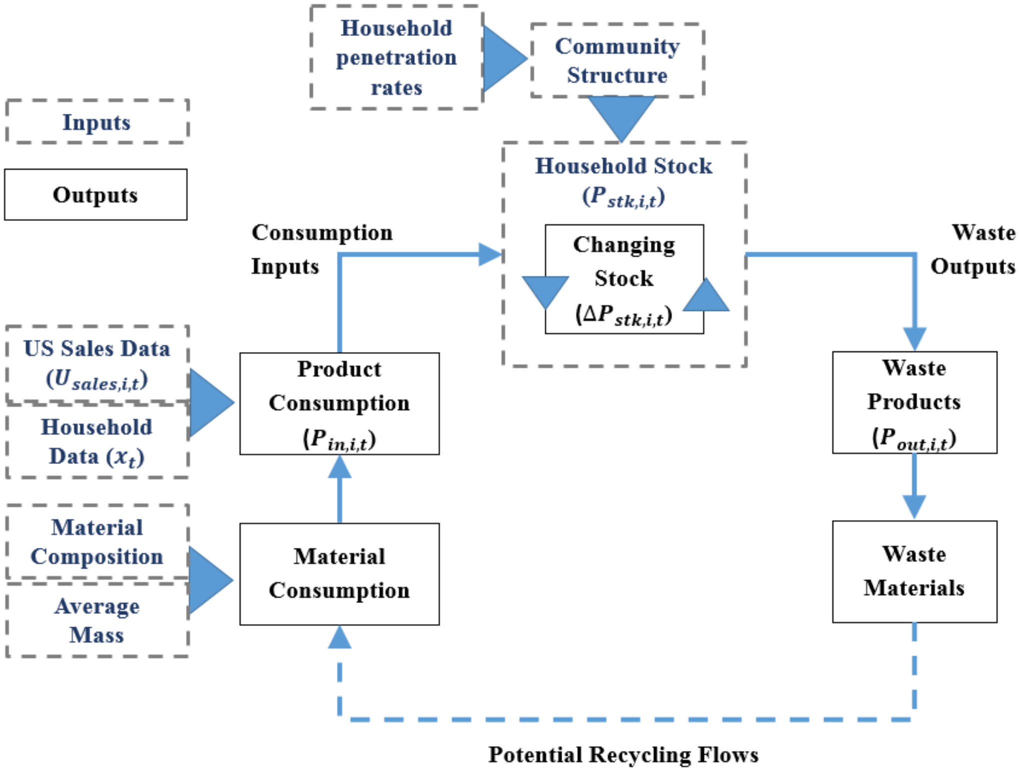


Figure 11: A household community material flow analysis.
Model inputs include product material composition and mass, US sales data, number of households, and installed household stock. Stock and inflow are used to calculate outflow. Waste materials, especially of critical metals and rare earth elements, offer a potential source for material inputs through the creation of a circular economy.

3.2.4 Material Composition

Determining the attendant material flows associated with the evolving product ecosystem was based on first calculating material composition per product, which was then combined with product flows through the household (calculated as described above). Material composition data included characterization of bulk materials (e.g., copper, plastics, steel) and composite components (e.g., battery cell, printed circuit board, liquid crystal display (LCD) module), all of which was primarily collected through product disassembly by the authors. Each product, not including power adaptors, was weighed and then disassembled to a level where each piece was comprised of a single material (if feasible). Materials were first identified by visual inspection and grouped into general categories of metals, plastics, composite materials and other. When complete separation of materials was not possible, the proportions of materials were estimated. Within each category, materials were further classified using basic physical properties, labels, recycling codes and product heuristics. Metals were separated into ferrous and non-ferrous components using a magnet and verified by handheld X-ray fluorescence (XRF). Non-ferrous metals were identified based on visual inspection and common knowledge of material composition (e.g. copper wiring). Composite material groups included LCD materials (the LCD module only), battery cell, and printed wiring board (PWB). The material group “other” included all materials not included above, such as rubber, (non LCD) glass, and adhesive tape. All pieces were weighed individually on a scale with 1200 gram capacity and 0.1 g resolution. Material composition percentages were compiled into a bill of materials for each product, as presented in Tables B6 through B28 of Appendix B.

Where primary disassembly was not possible, either due to lack of product availability or safety concerns (e.g., exposure to lead during CRT disassembly), published product data (e.g., Oguchi et al. 2011, Teehan and Kandlikar 2013) was used to establish a representative suite of material compositions for the remaining products (Appendix B, Tables B1 through B16). Published data was provided in a variety of formats and selected based on the following order of preference: 1) disaggregated data (including disaggregated metal content) accounting for 100% of the product mass, 2) partially disaggregated data (including aggregated metal content) accounting for 100% of the product mass and 3) partially or wholly disaggregated data accounting for less than 100% of the product mass.

Using published data for composite components (Oguchi et al. 2011, Wang and Gaustad

2012, Buchert et al. 2012), the composition of PWB, LCD modules and battery cells was further disaggregated to estimate the contribution of precious metals (gold, silver, platinum and palladium), rare earth metals (e.g. neodymium and praseodymium), critical metals (e.g. indium) and other metals of interest (e.g. cobalt). As these data were presented in a variety of formats, all values were normalized to a percent contribution by weight of PWB for each product. Kasulaitis et al. (2015) demonstrated that the material composition of a laptop computer as a percentage of weight remained relatively constant over the period 1999 – 2008. Primary disassembly revealed a similar trend for smartphones and digital cameras, therefore, material composition for each product was assumed to be constant over time. Available data were averaged to determine a single value for percent contribution by weight of PWB for all products, which was multiplied by the weight of the PWB in each product. While a similar trend was observed in published material composition data, this assumption introduces error in the calculations of material flows, particularly in materials that occur in small quantities, such as precious and critical metals, or where there is limited available data.

3.2.5 Material Stocks and Flows

Product weight was also assumed to be constant over time, based on empirical observations on laptop computers showing no net mass change (Kasulaitis et al. 2015). For other products, this assumption was verified with additional data gathered during primary disassembly of a smartphone and digital camera in addition to a survey of popular products. However, some products, such as the DVD player, achieved dematerialization through technological innovation, while others, like the LCD television, were subject to the competing effects of an increase in mass as the form factor becomes larger and dematerialization due to technological innovation. Additionally, published product masses vary widely between sources. While the results reported herein are primarily based upon the average of available masses, flows were also evaluated for high and low masses to determine model sensitivity (Table B29 in Appendix B).

Average material composition and average weight for each product (i) in each year (t) was combined with household stock, change of stock, inflow and outflow to calculate the specific material. Product and material flows were calculated using Wolfram Mathematica 11 (Wolfram 2016).

3.3 Results

3.3.1 Increasing Consumption Offsets Dematerialization

Over the period 1990 – 2010, the number of products in stock in the average U.S. household increased from just over three to more than sixteen. In 1990, the average household was consuming approximately 0.5 new products per year (Figure 12). By 2010, consumption had increased by more than 700% to over 3.5 new products per year. At the same time, the weighted average product mass steadily decreased from approximately 16 kilograms per product in 1990 to less than 4 kilograms per product in 2010. As a result, the total amount of material consumed almost doubles between 1990 and 2000, and then decreases by almost half from 2000 through 2010, driven by the rapid retirement of CRT televisions. Emergent functional phases described by Ryen et al. (2014) suggests that this decrease may be the combined result of a product level dematerialization and a shift in focus of ecosystem functions. The total population of televisions (CRT, LCD, and Plasma) remains roughly constant at three televisions per household from 2000 through 2010, suggesting that television population has reached saturation (See Table B1 in Appendix B). Using the methods published by Ryen et al. (2014), forecasted future stocks of LCD televisions suggest that dematerialization achieved by the shift from CRT to flat screen televisions will be short-lived as consumption of LCD televisions increases past 2010. On the other hand, the increased focus on mobile computing may allow for the adoption of lighter, more portable products. In both cases, product level dematerialization may occur, either through an incremental material reduction as technology progresses, such as larger LCD television with no net mass increase, or through the provision of the same service with a smaller product, due here to the shift from CRT to LCD television. However, additional research is necessary to determine whether net dematerialization due to shifting ecosystem functions may be sustained at the product ecosystem level despite increased product consumption.

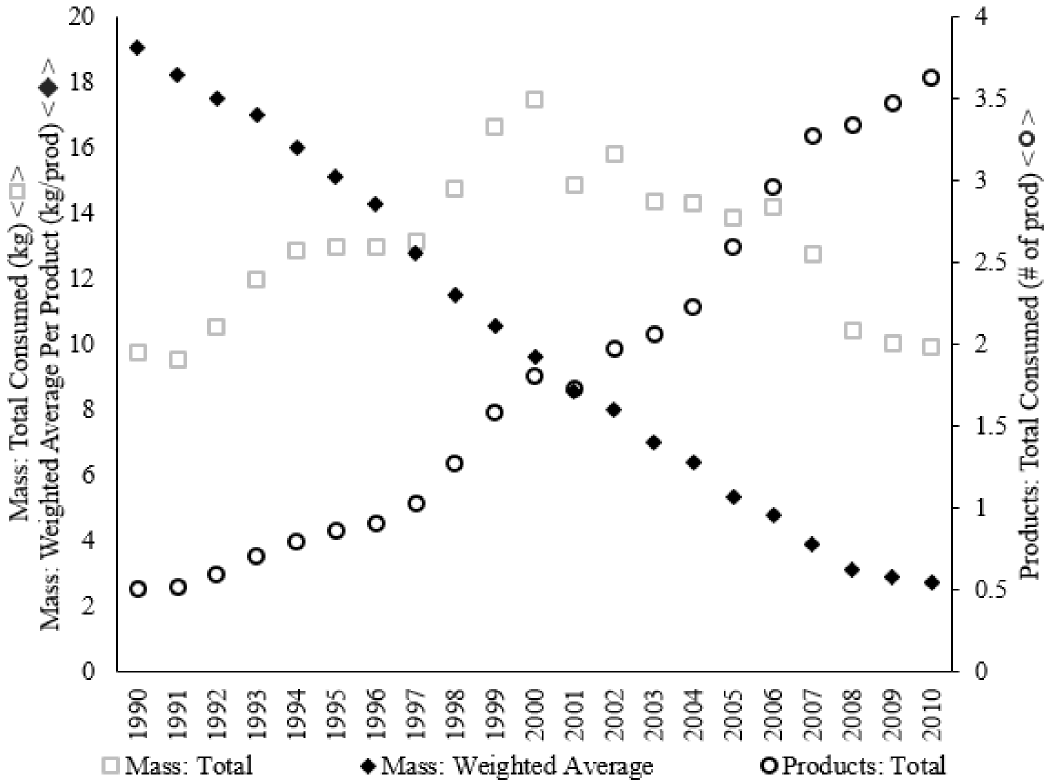


Figure 12: Household product and material consumption.
Despite decreasing weighted average product mass (shown as a solid diamond marker plotted on the left axis), the total material consumption (shown as an open square marker plotted on the left axis) of the community achieved no net material reduction due to the more than 700% increase in the total number of products consumed (shown as an open circle marker plotted on the right axis).

In addition to a net increase in consumption between 1990 and 2010, the community of products within the ecosystem became more diverse (Figure 13). In 1990, product consumption consisted of seven product species, dominated by the CRT television, which made up almost 80% of the consumption by mass. By 2000, household material consumption had approximately doubled, yet the mass contribution by CRT televisions stayed approximately constant. By 2010, the average household consumption consisted of 20 unique product species, and the dominant product by mass had shifted from the CRT to the LCD television. The technological leap from the CRT to LCD television, highlights the necessity of the ecosystem approach to MFA: Per product evaluations of the CRT television highlight high energy use and toxicity due to large amounts of lead and per product comparisons of CRT and LCD televisions suggest energy (Socolof et al. 2005) and material savings. However, an ecosystem based approach to evaluating material flows of traditional television products indicates 1) a relatively constant material consumption by televisions (Figure 13), 2) a shift in environmental burdens as new materials are introduced (Lim and Schoenung 2010, Socolof et al. 2005) to improve user experience and achieve product light weighting, and 3) net increasing material consumption as the use of auxiliary devices typically associated with television consumption (game consoles, Blu-Ray players, etc.) (Figure 13).

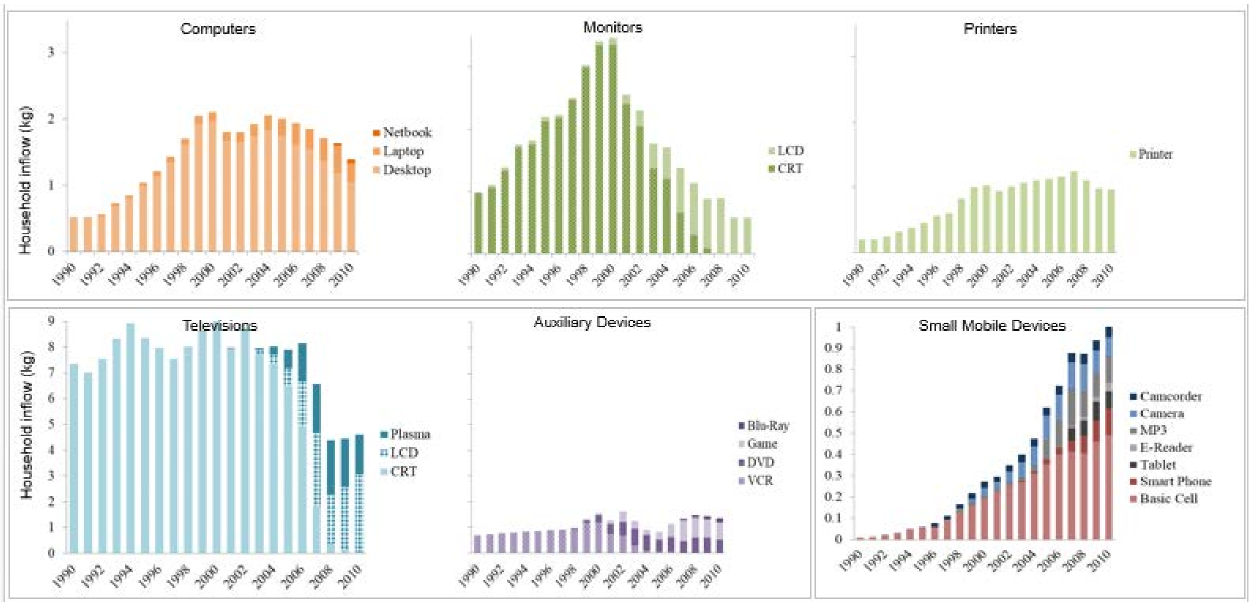


Figure 13: Household material consumption, represented as the mass inflow by product (kg).
Observation of the community of products reveals effects that cannot be seen at the individual product level, such as the net increase in material consumption by computers, despite a shift from desktops to laptops. These results highlight the necessity of a community approach to material flow analysis.

Additional detail showing the breakdown of material flows is provided in Appendix B, Figures B1 through B12.

While increasing consumption offset per-product dematerialization, negating the potential environmental benefits of decreased material use per product, the increased material flows may be beneficial for developing a circular economy. Recycling, one of the most widely pursued strategy for achieving a circular economy (Haas et al. 2015), is actively used to manage e-waste. While the United States lacks a federal regulation, several states have adopted plans individually (Kahhat et al. 2008). Current e-waste recycling policies are optimized for weight (Oguchi et al. 2011), for example the regulation in New York state requires manufacturers to provide e-waste recycling services based on their market share of products sold, by weight (NY DEC 2016). Technology, on the other hand, is optimized for recovery of precious and other metals that occur in large enough quantities to be valuable, such as copper and aluminum (Cui and Forssberg 2003, Cui and Zhang 2008).

As shown by Figure 14, total amounts of both precious metals and bulk materials, such as copper, aluminum and ferrous metals, increase proportionally with the total material usage. Although household stock increases steadily from 1990 – 2004, over the period 2005 – 2010, household material stock was roughly constant, decreasing slightly near the end of the study, This suggests that if consumption patterns continue as observed (for example installed stock of televisions remains saturated at about 3 per household, as they are between 2003 and 2010), or begin to decline, then material outflows of precious and bulk metals will also level off and decrease. Thus, based on the principles of material stocks and flows, household wastes will follow the same path, therefore, a comparable trend in growth potential is expected for electronics waste recyclers under current business models. However, as functional capacity increases across the community (Ryen et al. 2014), there is a corresponding introduction and increase in specialty metals, such as cobalt and indium, indicating a potential new revenue stream.

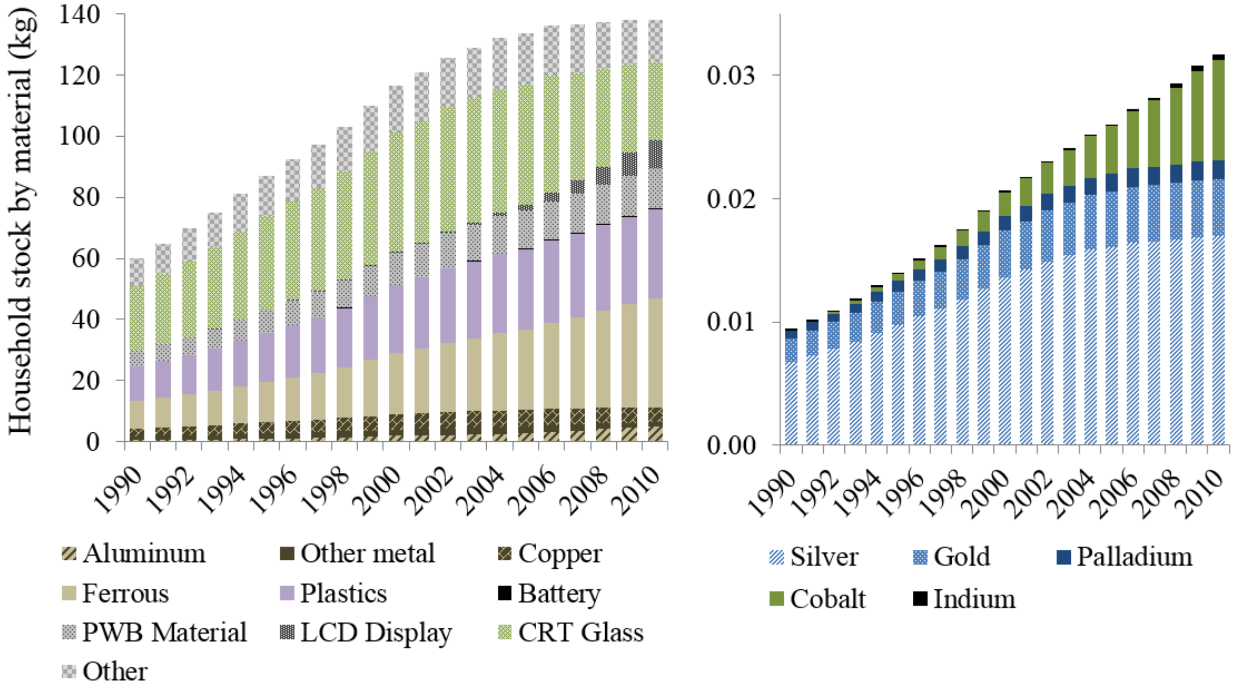


Figure 14: Household stock disaggregated by material.
Results show that total materials in stock increases over the period 1990 – 2005, and levels off through 2010. This trend is mirrored by precious metals, for which recycling is optimized. However, indium and cobalt continue to increase, suggesting that recyclers must expand their material recovery efforts enable both future growth for e-waste recyclers and the expansion of a circular economy for electronics.

Although the “bottom-up” approach developed here attempts to eliminate errors due to potentially problematic data, estimations are influenced by the definition of the inputs. For example, some stock estimations in Ryen et al. (2014) were calculated using life span data from US EPA (2011), which includes all products owned, including those in storage, versus the EIA Residential Energy Consumption Survey(RECS) (EIA 2001, 2005, 2009), which limits stock to those products in use. Comparing the two studies shows that stock values presented by Ryen et al. (2014) range from 26 – 38% higher for television stock up to approximately double the printer stock. The effects of differences are most significant in the television community, which comprises more than 60% of the household stock. Given the differences in stock estimates for televisions, computers, and printers, the total stock estimate is reduced by 37% in 2001 and 29% in 2009 when using the EIA RECS data. Although the stock estimates made by Ryen et al. (2014), and subsequently this text, are higher than the estimates presented in the RECS (EIA 2001, 2005, 2009), the resulting trends of increasing consumption are the same.

3.3.2 Dilution and dispersion of value hinders circular economy

Ecologists seek understanding of the processes which govern the flow of nutrients through the ecosystem (Smith and Smith 2009). Similarly, industrial ecologists must comprehend the processes and factors governing the flow of materials through the product ecosystem to effectively recommend sustainability strategies, such as establishing a circular economy. In the case of the consumer electronics ecosystem, dilution and dispersion of materials govern the fiscal success of e-waste recyclers. As dilution of high value materials in products occurs, higher product collection and material recovery rates will be necessary to compensate for the loss of easily accessible materials. In general, the shift from material consumption dominated by the heavy CRT television to material consumption that is more evenly distributed among 20 smaller products in 2010 has resulted in dilution of materials in the secondary waste stream. This directly affects the value of the secondary material stream, which is driven by the mass of both bulk metals, like copper and aluminum, and precious metals (Hageluken and Corti 2010). The total amount of gold in the waste stream increases as a function of rising material consumption. At the same time, the weighted average amount of gold per product, defined as the total mass of gold in the waste stream divided by the number of products in the waste stream, is decreasing (Figure 15). This dilution occurs because small, mobile products with less gold content are increasing while larger products with higher gold content are leveling off or declining.

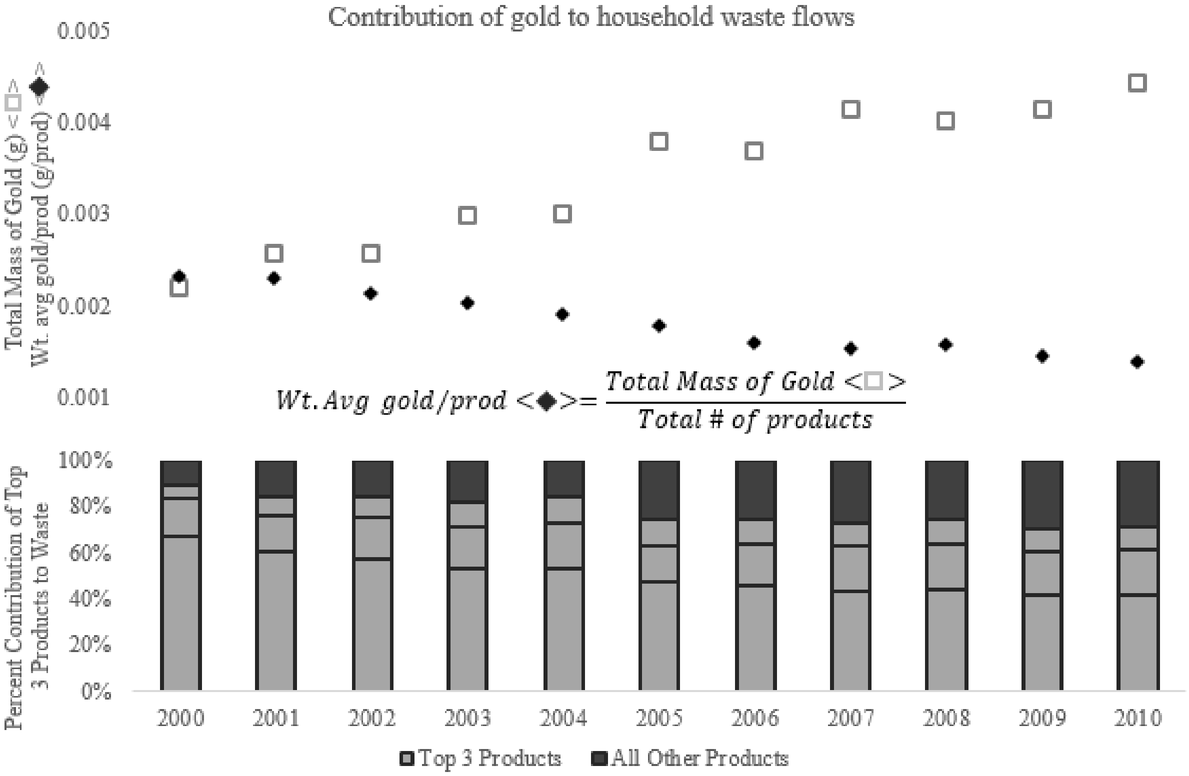


Figure 15: Dilution and dispersion of gold in the electronics waste stream.
The top graph demonstrates Dilution: While total mass of gold in the household waste stream is increasing, the weighted average gold per product is decreasing as many small products are consumed. The bottom graph conveys Dispersion: Although a large portion of gold in the waste stream still comes from few products, the contribution by the top three product types has decreased by almost 20% (between 2000 and 2010.

By the same process, materials of value are also divided among a larger number of products, rather than being found concentrated in a few places. In ecology, dispersion occurs as individuals move over a spatial range, influencing population density (Smith and Smith 2009). Figure 15 shows the shift away from few large products dominating the household waste stream, as many smaller products enter the waste stream. While ecosystem waste flows remain dominated by larger products, the contribution to total mass by the three largest products in the waste stream decreased from almost 90% in 2000 to just over 70% in 2010. These trends have serious implications to the e-waste recycling industry which has been optimized to collect and process large products that can be disassembled in order to extract high value materials and components. The increased prevalence of small products creates challenges associated with product collection and material recovery. Fewer than 10% of small products, such as smartphones, are collected for recycling, as compared to 30% or higher for larger products, like televisions (US EPA 2011). Additionally, as a greater number of small, complex products, for which disassembly is infeasible, enter the waste stream, recyclers may have to shift toward a greater use of automated handling techniques, such as shredding, crushing, or magnetic sorting (Haas et al. 2015). The resultant secondary materials often do not meet the purity necessary to fulfill the material needs of the original application (Reck and Graedel 2012). This lack of purity is a challenge for creating a true closed loop system, wherein “material from a product system is recycled in the same product system” (ISO 14044). However, recent research has shown that there is no intrinsic benefit to closed loop over open loop recycling, instead the formation of loops should be evaluated based on their environmental benefits (Geyer et al. 2016).

3.3.3 Opportunities for closing the loop on consumer electronics

While measures of dilution, and the resultant dispersion, are effective metrics for evaluating product ecosystem material flows for circular economy potential, demand matching may be used to identify material flows with the highest potential for displacing primary material consumption. As shown by Figure 16, comparing total consumption and waste flows for the same year shows that secondary supply, from household waste, and primary demand, via household consumption, of many metals are increasing proportionally. While metals can be recycled infinitely (Haas et al. 2015, Reck and Graedel 2012), given recycling inefficiencies, contamination, and material quality requirements of the electronics industry, these supply and demand “matches” represent a theoretical maximum. The high end of life recycling rates of ferrous, aluminum and copper metals (Graedel et al. 2011) suggest that, if all products were recovered for recycling, materials contained in waste streams could meet approximately half of the demand. Additionally, because these materials occur in relatively large quantities as simple components (such as steel frames), there is a greater opportunity for recovery of purer material streams, recycling of materials into new electronics components, and a truly closed loop. Additionally, supply of PWB material in waste streams is approaching demand. Given the high embodied energy of PWB manufacture (Williams 2002), reusing, remanufacturing, and then recycling PWB material can reduce life cycle impacts of electronics. However, recycling will still omit a large fraction of this material, as PWBs are diverse and complex, and current recovery methods are primarily focused on high value, low concentration materials, such as gold and silver. In reality, many electronic components are constructed of highly comingled materials, making recovery and recycling technologically and economically challenging (Reck and Graedel 2012, Haas et al. 2015)).

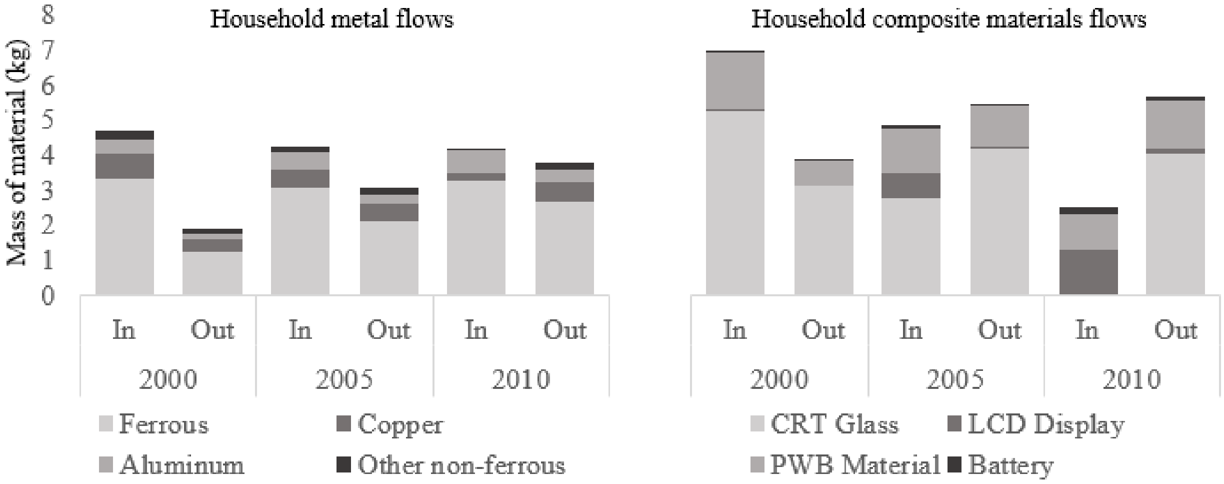


Figure 16: Comparison of household ecosystem consumption and waste demonstrates demand mismatch.
On the left, supply and demand grow proportionally, and supply, in household waste, approaches demand, in household consumption. On the right, composite materials show the demand mismatch which occurs as a result of a major technological shift (i.e. LCD replaces CRT televisions).

Although recovery of precious metals, such as gold and silver, is one of the main revenue streams in current e-waste recycling business models, precious metal content in stock has actually leveled off and decreased slightly, following total material in stock (Figure 14). As product stock flows out of the household, waste streams will exhibit similar trends, perhaps as households reach saturation levels specific to each electronic product, analogous to a natural ecosystem carrying capacity. As precious metal supply and demand dynamics change, e-waste recyclers must also examine alternative strategies, including recovery of emerging materials of interest, such as cobalt and indium (Figure 14), found in battery-powered mobile devices and flat screen modules, respectively. This increase suggests that these materials will also be proportionally released in the waste stream, offering opportunities for e-waste recyclers to both expand the circular economy and garner more value from e-waste. The ecosystem-level MFA approach highlights opportunities for future growth through recycling technologies able to recover more diverse materials. While this approach focused on mass flows of materials of interest, there is also a clear opportunity to expand this analysis to include environmental metrics associated with these waste flows, such as embodied energy or secondary value of materials recovered through recycling.

Even with improved recycling technologies, the shift in functional groups from large, stationary devices to multifunctional, hyper mobile devices make material separation and recovery difficult (Li et al. 2009, Chanceral et al. 2013, Reck and Graedel 2012, Haas et al. 2015). For example, indium is applied in the form of indium tin oxide as a coating within LCD screens, and recovery requires complete disassembly of the LCD panel, followed by gentle mechanical processing to minimize losses and contamination (Gotze and Rotter 2012). Additionally, indium is only about 0.02% total mass of the panel (Gotze and Rotter 2012) making the recovery of indium both challenging and low yield. However, the potential for recycling is important for manufacturers due to the vulnerable supply of indium, which is produced as a by-product of zinc, and does not respond to the demand for indium (Gotze and Rotter 2012). As a result, there is a need for developing local, reliable sources for indium supply. The increasing availability of indium in the e-waste stream suggests that e-waste could fill a portion of this demand.

Scaling up to national material flows to evaluate the loop closing potential as a function of technology change, Figure 17 shows the net system demand versus secondary material supply, in terms of material present in the waste stream, for indium, lead, and cobalt.. The comparison of demand for materials and the theoretical fraction that might be met (or exceeded) by secondary material supplies demonstrates hypothetically what portion of the demand could only be met by primary material supplies. Indium in the waste stream is dominated by the contribution of LCD televisions and monitors. The rapid adoption of these new products has driven consumption demand up quickly, while their relatively long life span has prevented many from entering the waste stream during the time period analyzed. As a result, consumption far outpaces secondary material supply by 2010. If these trends hold, then the supply-demand gap may be closed as the household ecosystem becomes saturated by flat panel televisions (shown in Figure 8 based on projections for stock through 2020).

Lead, on the other hand, enters the waste stream via CRT televisions and monitors. The recent retirement and removal of these products from the market has resulted in an abrupt decrease in demand. However, previously high adoption of these products, combined with long life span, means that supply of lead in the form of CRT funnel and panel glass far outpaces demand. This is especially problematic for e-waste recyclers due to the high cost of recycling these materials and lack of a secondary market. Cobalt enters the material flows in the community through the consumption of mobile devices with lithium ion batteries. If the adoption of these products continues to increase, we may expect to see both increasing cobalt demand for product manufacture and increasing supply in the e-waste stream. Unlike indium, the end of life recycling rate for cobalt in batteries is estimated to be as high as 50% (Graedel et al. 2011), suggesting that the potential for cobalt in the circular economy is quite high.

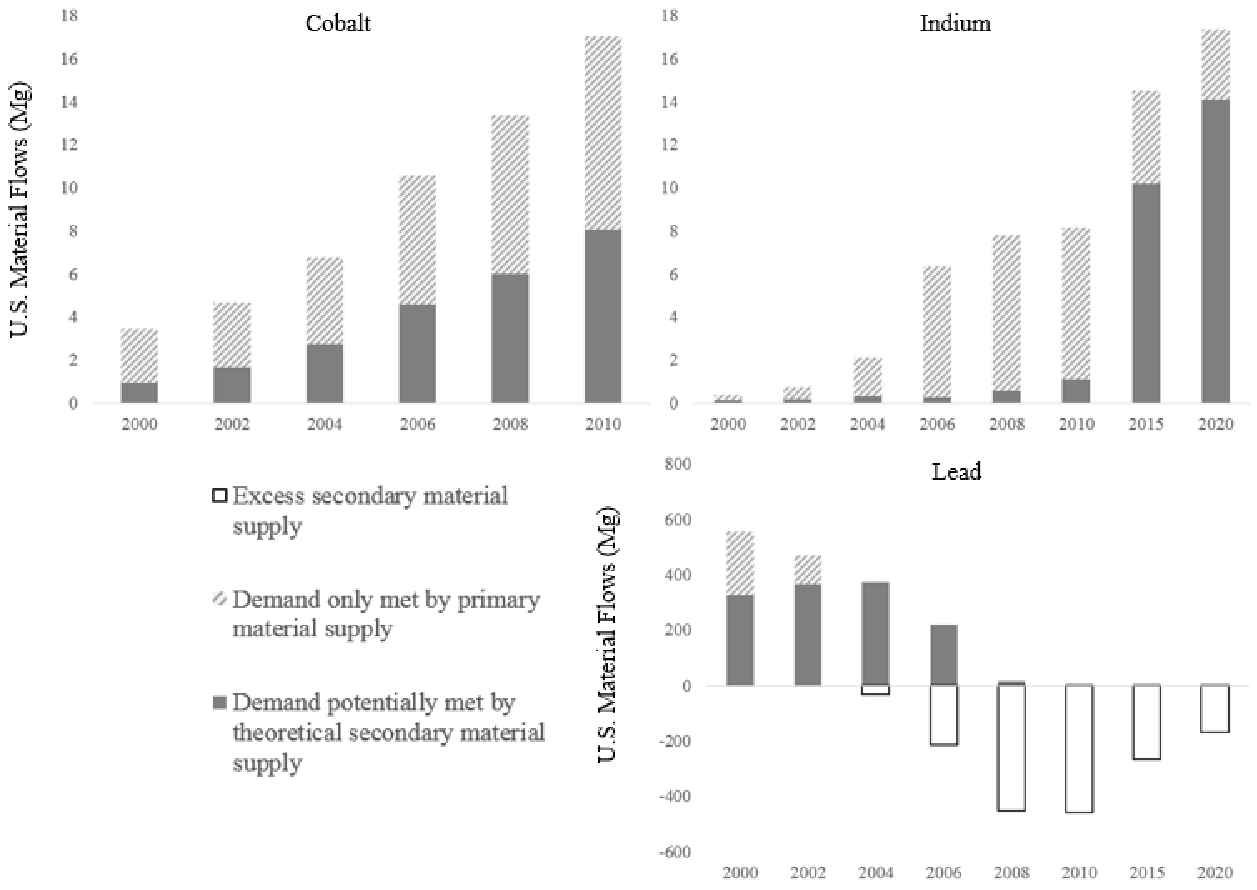


Figure 17: Comparison of national demand (material consumption) and supply (secondary material outflows). (Assumes that 100% of material can be recovered and recycled.) The supply for indium, driven primarily by LCD televisions, lags rapidly increasing demand due to relatively long life span. Conversely, due to high adoption and long life spans, lead supply is forecasted to continue through 2020. Finally, cobalt, found in lithium ion batteries of mobile devices, demonstrates proportional increases in supply and demand, likely due to the rapid evolution, turnover, and new introduction of these types of products.

3.4 Implications

Utilizing an ecosystem approach to evaluate material flows at the intersection of technological innovation and evolving consumption, reveals that in the best case, dematerialization by technological innovation is slowing the rate of material consumption by the consumer electronic product ecosystem. While efficiency gains made through technological innovations might achieve modest reductions in material intensity of specific products, those per-product reductions are offset by increasing consumption in some cases. Therefore, dematerialization, defined previously as the absolute or relative reduction in the quantity of materials or waste per unit output, is not a complete strategy for reducing net material consumption of the product ecosystem.

Although the effectiveness of dematerialization may be limited by the growth of the consumer electronics ecosystem, increased consumption may, on the other hand, actually be beneficial for circular economy strategies, as they may enable a more robust recycling system. The major limitation is that the introduction and rapid adoption of smaller products is causing dilution of materials within products and dispersion of valuable secondary materials in the waste stream, as smaller products are less likely to be collected for recycling, more likely to undergo automated material recovery resulting in less pure material streams, necessitating material downcycling. Both of these effects put the onus on recycling firms and technologies to collect and process a wider array of products and materials.

As product consumption continues to shift from larger products that provide value streams of both bulk materials and precious metals to smaller products with more diverse materials, e-waste recycling infrastructures will need to adapt to be profitable and also provide sources of materials with problematic supply chains. Unfortunately, adapting recycling infrastructure to recover new materials is challenged by complex product design and incorporation of critical metals. Currently, recycling efficiency and the associated electronics recycling regulations are focused on weight (Oguchi et al. 2011), with the goal of optimizing recovery of base metals, such as copper and ferrous metal, and precious metals, such as gold and silver (Wäger et al. 2011, Cui and Forssberg 2003, Cui and Zhang 2008). This optimization is because the greatest economic value in electronics recycling is in the recovery of precious metals with high value and recovery of base metals which occur in relatively large quantities (Kang and Schoenung 2005). Due to the lack of infrastructure, social behavior, product design, and thermodynamic limits of separation, the recovery of critical metals, such as indium, and rare earth metals, is less than 1% (Graedel et al. 2011, Chancerel et al. 2013, Reck and Graedel 2012). Significant progress in recovery of rare earth and critical metals is necessary to develop a successful closed loop system in electronics. In parallel, e-waste recycling policies and incentives must similarly evolve with the changing product landscape, with additional research needed to evaluate the feasibility or benefit of adding targets for number of products recycled or critical material recovery rates to current mass-based approaches.

The increasing quantity and diversity of material usage combined with the difficulty of product and material recovery highlights a critical need for a three pronged approach to encourage the development of a circular economy. First, evolving product and material flows provide new opportunities for manufacturers and e-waste recyclers alike. While current business models are predicated on continued growth and growing sales volumes (Allwood et al. 2011), this type of model neglects the end of life consequences associated with the product. Therefore, e-waste regulations must be formulated to both encourage adaptation of product design to favor recycling while also making recovery of additional materials economically appealing. Second, collection of products must be increased. Recently, retailers and new businesses have begun offering trade-in credits or cash in return for smartphones, tablets, netbooks and other small devices (e.g. Verizonwireless 2016 Gazelle 2016). The devices are then refurbished and reused or, in cases where renewal is not possible, are recycled. Such an expansion of the business model is beneficial both due to the extension of the service life of the device to the secondhand market and the availability of materials for recovery and recycling.

Finally, increasing consumption and the accumulation of in-use stocks is a barrier to circularity that cannot be overcome by recycling alone (Haas et al. 2015). Sustainable consumption must be incorporated in evaluations of circular economy potential. In the case study shown here, supply of a material in the waste stream only met or exceeded demand by new products when consumption of the new product, in this case the CRT television, had ceased. This result supports the idea that there is the potential to close material loops, provided that net additions to stock are also reduced (Haas et al. 2015). Therefore, there is a critical need for future research to understand the processes that govern and the environmental factors that shape product community structure.

IV. Measuring and Modeling Consumption Decisions

4.1 Introduction

The evolution of the consumer electronics industry has created a dichotomy. The development and application of new technologies have the potential for improved quality of life as well as increasing industrial process efficiency, making both their own and other industries more sustainable. At the same time, however, the rapid development of the consumer electronics industry is accompanied by an increasing environmental burden across all stages of the product manufacturing, use, and disposal life cycle.

A growing body of research has been developed to quantify the environmental, material, and energy impact of consumer electronics and, as electronics and information communication technologies have become an integral part of everyday life, an equally significant body of research has emerged, dedicated to improving the sustainability of products across every life cycle stage. Papers evaluating the lifecycle energy and material consumption of components, products, and communities of products show that manufacture, use, and disposal of electronics are environmentally significant (e.g. Roth et al. 2014, McAllister and Farrell 2007, Chancerel and Rotter 2009) and conducting the evaluations can be problematic (Teehan and Kandilkar 2012, Baumann et al. 2012, Olivetti and Kirchain 2011, Weber et al. 2010, Olivetti et al. 2012, Oguchi et al. 2011). Recognizing these concerns, Menad (1999), Li et al. (2009), Frontino Paulino et al. (2008), among others, investigate the recovery of materials from various types of electronic products.

Many strategies have been proposed to mitigate the impacts of electronics. Some strategies, including dematerialization, or “doing more with less” (van der Voet et al. 2005, von Weizsacker et al. 1997, Cleveland and Ruth 1999, Wernick et al. 1996, Mugdal et al. 2011, Binswanger 2001, Marechal et al. 2005, Robert et al. 2002) and eco-design of electronics (Komeijani et al. 2016), rely on technological innovation to improve the product itself. Others aim to change the business model, through development of a closed loop “circular economy” (Frosch and Gallopoulos 1989, Ellen MacArthur Foundation 2015, Yuan et al. 2006, Andersen 2007, Haas et al. 2015), eco-efficient product procurement strategies (Pelton et al. 2016), or an intentional overhaul of the industry (Hankammer and Steiner 2015). Still others identify the need for intentional shifts in consumer behaviors, whether as shifts in consumption and ownership (Ryen et al. 2015) or as energy saving behavior interventions (Raihanian Mashhadi and Behdad 2017).

As shown in Chapters II and III, many of these solutions are often inhibited by behavioral response, even when not intended as behavioral interventions. Although dematerialization occurs in the consumer electronics industry, and smaller quantities of material are being used to deliver the same performance (Chapter II), this dematerialization is being translated into increased performance within the same form factor, as opposed to product level dematerialization. Although smaller, less materially intensive products are being introduced as technology advances, these products are often consumed in tandem with legacy products, leading to increased overall consumption (Chapter III, Ryen et al. 2014). The task-technology fit model (Goodhue and Thompson 1995) suggests that the compatibility of the technology to the task to be done is the most critical factor, and adoption intention increases with the effectiveness of the technology (Kuo-Lun 2017). Expanding upon the task-technology fit model, Venkatesh et al. (2003) developed the unified theory of acceptance and use of technology (UTAUT) to model influences upon behavioral intentions to adopt and use a technology. Further research suggests that experience and habit are also strong predictors of adoption decisions (Venkatesh et al. 2012), and targeted educational or informational campaigns may be used to influence decisions (Sekar et al. 2016). Ultimately, the consumer's product community is driven by their needs and expectations, and the question remains whether proposed communities or substitute products would meet those needs. These results call into question the viability of solutions that rely on shifts in consumer behavior.

A growing body of research is emerging that demonstrates the utility of adapting ecological concepts to evaluate the environmental impacts of groups of products or systems, modeling these groups as interrelated and interacting, much the same way biological organisms and species live and interact within a natural habitat, community, or ecosystem (Levine 1999, 2003, Field et al. 2000, Gutowski et al. 2010, Ryen et al. 2014). This type of approach evaluates the responses of communities of products as a whole, with the aim of making informed recommendations to improve community sustainability, and offer the added benefit of incorporating external effects, such as consumer behavioral trends and changes in technology.

Ecological concepts provide a lens through which to interpret and understand results. For example, in biological ecology, species often exist in niches that are smaller than those that they are capable of existing in. Similarly, functions offered by consumer electronic products may not be fully utilized. In biological ecology, these realized niches may develop as the result of one species out competing the other for resources. Using this knowledge of ecological concepts helps us to understand that similar niches might develop in product systems if one product delivers the function with a higher degree of success, thus outcompeting the other product. Abiotic forces, such as the physical factors acting upon a species, and biotic forces, such as competition for resources, both impact the distribution of species in a habitat (Connell 1961). Drawing parallels between ecological and anthropogenic systems affords greater opportunity to understand drivers behind system behaviors that have been historically neglected.

Currently, little information is available about links between consumption and product interactions which influence product adoption, and acceptance of products to fill specific functional “niches”. These phenomena are individually well studied, and a variety of models have been developed to understand the rates at which products are adopted and the decisions to use particular devices for particular functions. In the broadest sense, product interactions have been studied to the extent that some products are designed to be adopted and used together. However, overlaying knowledge of product adoption, use, and interactions on an existing and well-studied community of products offers a holistic approach to evaluate the effectiveness of proposed sustainability strategies.

To date, there has been little effort devoted to identifying and linking consumption drivers, such as consumer characteristics, product interactions, perceptions of products, and acceptable functional performance, to consumption potential. Further, there is limited knowledge of the extent to which products aren’t fully utilized, thereby creating functional redundancy in product communities. Therefore, this research was conducted to answer the question of how interactions between consumer behavior and product functionality influence product adoption and the potential for interventions to reduce material impacts of product adoption, while also considering inherent heterogeneity, both among consumers and in the product landscape. The novelty of this research lies both in the collection and analysis of data linking consumption drivers to consumption choices, as well as the evaluation of reductions in material usage as the result of manipulating consumption choices.

4.2 Methodology

To answer the questions posed above, a product adoption-interaction framework was developed to hypothesize interactions among products and consumers in the consumer electronics ecosystem. Based on the framework, a survey was implemented to collect data on consumers and the results analyzed to understand product interactions and consumption choices. Finally, various scenarios were analytically modeled to understand the ability to leverage information collected about product interactions and suggest avenues that might reduce consumption and thereby reduce material demand. Together, these methodologies provide a more complete picture of consumption choices and the impacts of external forces.

4.2.1 Product Adoption-Interaction Framework

Figure 18 outlines the product adoption-interaction framework used to evaluate the factors influencing consumer decisions about product consumption and use for specific activities. This approach seeks to understand whether a product will be selected to be used for an activity, and thus included in the consumer's community of products. Each consumer selects a product to perform each task, based on a variety of factors. First, the relationship between the consumer's perception of how well suited a product is to each task to their willingness to accept that perceived level of quality for a particular task. Next, the consumer's interest in and knowledge of technology, as compared to the interest in and knowledge of technology demonstrated by the average consumer of each product. Finally, the framework incorporates a basic level of interaction between products, as only the product offering the highest quality is selected.

By simulating a variety of model parameters, such as changes in the consumer's perception of quality as the result of a design or product improvement, the framework allows for the evaluation of system interventions at various leverage points. Comparison of the average composition of simulated communities to actual ownership, use, and preference data measured in the associated survey demonstrates the viability of interventions as a material reduction strategy. This approach not only enables quantifiable material reduction estimates, by overlaying product mass data (available in Appendix B), but also provides insight into the question of whether consumers might adopt alternative communities.

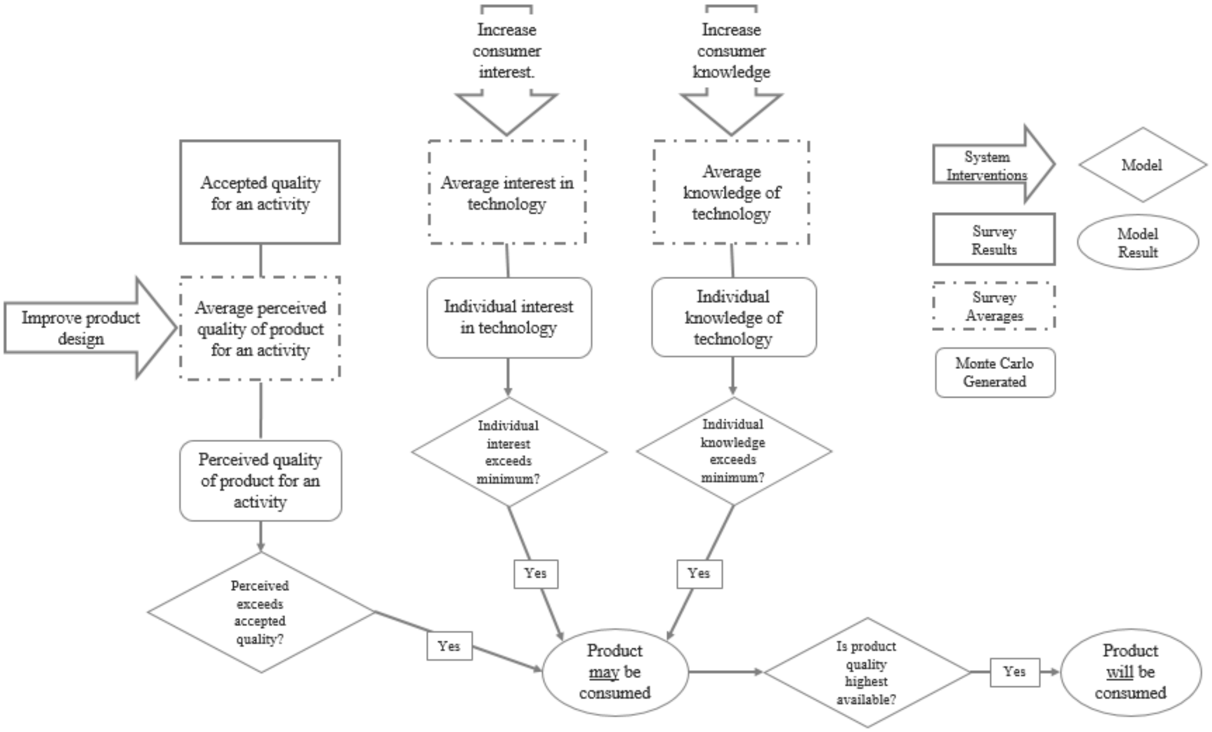


Figure 18: Conceptual model framework used to evaluate the effects of interventions such as improved product design or increased consumer interest in or knowledge of technology on community structure and total consumption.

4.2.2 Survey

After developing the framework, a survey was created to both analyze consumption choices and product interactions, and to provide the necessary data inputs for modeling consumption choices. The Internet-based survey, developed by the researchers with the support of Melioria Research, LLC, and administered in February 2015, consisted of 40 questions designed to gain insight into the consumption and use of, attitudes towards, and relationships between personally owned electronic products, plus 10 demographic and screening questions. The survey and informed consent process was reviewed by the Rochester Institute of Technology Institutional Review Board and determined to be exempt.

The survey was administered to a panel of United States adults that is recruited and maintained by Lightspeed GMI, using a proprietary sampling and panel management platform. The respondents’ identities remained confidential and the researchers had no contact with the respondents involved in the study. The panel is designed to be nationally representative population and the survey results are comprised of responses from 1,011 US adults, aged 18 years and older. Demographic characteristics of panel members were collected at the time of sampling. Statistical weights are provided by Melioria Research LLC, a market research and survey design firm, to correct distribution of respondents to align with the US Census' Population 2014 March Supplement. In determining necessary weighting factors, sociodemographic characteristics, including education, age, gender, race/ethnicity, household income, and geographic region were evaluated.

The survey questions were grouped into multiple sections, each with a particular theme. Table 3 summarizes the sections and associated themes, and includes example questions that were included in each section along with the associated research goals of that type of question. The survey (full text and responses available in Appendix C) included a variety of question types, including multiple choice, yes/no, and rating scale based questions. In the case where respondents were offered "Other" as an answer choice, they were also provided an opportunity to input a response that was not listed by the researchers.

Following the convention established in Chapter III, a similar suite of products were included in the survey questions. In the interest of creating a manageable survey, six products were eliminated from consideration: computer monitors based on the assumption that in most cases, availability or consumption of a desktop computer would necessitate availability or consumption of a monitor; VCRs because they were being phased out at the time of the survey; netbooks and plasma televisions because of their low adoption rates; and e-readers because of their similarity to tablets. 14 product species were included in Section 100 to gain insight into the full community of products. This community was narrowed in Section 200 to represent specific products that appear to be part of a naturally developing product ecosystem (like the smartphone, tablet, and laptop) and products that appear to be occupying a smaller, more specialized niche (for example, the digital camera). The hypothetical purchasing scenario provided in Section 300 focused on 12 of the original 14 products (the CRT was eliminated as it was no longer available for purchase in 2015, and the printer was eliminated because its functional use required the availability of a computer).

Table 3: Summary of themes, questions, and research goals used to develop the survey.

Section Theme	Example questions	Goal
Section 100 Ownership and frequency of product use.	Indicate whether [the electronic product listed below] is available for your use.	Gain insight into varying degrees of species presence / absence in the community.
	How often ffo you use your most recently acquired version of each of the following products?	
	How has use changed?	Understand species migration patterns and causes.
	Why is product used less frequently?	
Section 200 Species role in product ecosystem	Which tasks are performed on each product?	Understand the differences between realized and functional niches.
	Which product is used most frequently for each task?	
	What is your general impression of the quality of experience provided by a product for an activity?	Gain insight into the underlying causes of realized niche development.
Section 300 Product interactions	Hypothetical purchasing scenario: Circumstances require you to purchase all new electronic products up to [$1,500/$2,500]. Which products would you buy? Prices for each product stated. Digital camera varied [$100/$600]. Laptop varied [$250/$650]	Identify key product species, stated consumer preferences, and the impact of budget and price on consumption.
	If a product was broken, would you replace it, and if so, with the same or a different product?	Quantify competition between product species (i.e. would the consumer prefer a different product with similar functionality over the product he/she has now?).
	If replacing a product with a different product, what type?	
	If two products broke and couldn't be repaired, would you replace one, both, neither, or purchase an entirely different product? Pairwise comparisons between tablet, laptop, and smartphone.	Gain insight into interspecific interactions for key products that are specifically marketed as a "product ecosystem."
Section 400 Purchasing preferences	What reasons would prevent you from owning a tablet or smartphone for free?	Gain insight into why multifunctional generalists (smartphone and tablet) might not be adopted.
Section 500 Attitudes toward technology	How likely are you to adopt new technology?	Understand effects of self-stated attitudes on consumption behaviors.
	How interested / knowledgeable are you about technology?	
Section 600 Demographics	Standard demographic questions including age, gender, education, household income.	Understand effects of demographics on consumption behaviors.

4.2.3 Data Analysis

In the context of consumer electronics, age, education, income (Morrell et al. 2000, Im et al. 2003, Leung and Wei 1999), and technology (Goodhue and Thompson 1995) are strong predictors of technology consumption and use, therefore, the more detailed analysis was conducted in light of these potential predictor variables. Following the definitions put forth by Sanburn (2015) and the Harvard Joint Center for Housing Studies (Masnick 2012), four generational groups were identified based on their age at the time of the survey; millennials (18 - 30), generation X (31 - 50), baby boomers (51 - 70), and the silent generation (71 - 90).

The impact of demographic factors on number of products owned and separately, on number of products selected for purchase, was analyzed for each factor individually using one-way analysis of variance. When significant effects were found ($p<0.05$), a Tukey's HSD post hoc analysis was performed. Following the guidance set forth by Solon et al. 2013, the analysis incorporated weights when calculating descriptive statistics of the target population and unweighted results were used when estimating causal effects. Where appropriate, both the weighted and unweighted results are reported. A complete set of the results by question is included in Appendix C.

4.2.4 Analytical model of product adoption-interaction framework

Based upon the product adoption-interaction framework described in section 4.2.1, the model simulates interest in technology, knowledge of technology, perceived quality of products for activities, and consumption choices for 723 consumers. These consumers represent those survey respondents with an accepted quality for all activities (those consumers who didn't perform one or more of the activities were removed from the model). Four products are included within the framework; the smartphone, the tablet, the laptop computer, and the flat screen television. These products were originally chosen because they are being increasingly developed and marketed for their improved usage as a group of products, even at times being referred to by marketers as a "product ecosystem" (Markman 2017, Haselton 2017). Four representative activities were chosen based on the expectation that the average consumer would perform these activities on a regular basis, but each activity could be performed using a variety of products. The representative activities include watching movies or television, surfing or browsing the internet, send email, and writing or editing a document.

The model is based upon two major assumptions. The first is that consumers will select only a single product to perform each activity, thus creating a minimally redundant community. The second is that consumer preferences for quality are constant. Thus each consumer's response for accepted quality for an activity (measured as the perceived quality, indicated in survey questions 240 – 246, of the product they've chosen to use most frequently to perform an activity, indicated in survey questions 230 – 236) as stated in the survey is an input to the model. Perceived quality, interest in, and knowledge of technology are model generated, based on the assumption that these characteristics might be improved via an educational campaign to improve a consumer's interest in or knowledge of technology products or design changes, for example an improved keyboard for a tablet, which might improve a consumer's perceived quality for an activity.

The model was built using YASAI Version 2.7, a Microsoft Excel add-in for basic Monte Carlo simulations developed by the MSIS Department of Rutgers Business School, and standard Excel functions. The dependent variable is the binary decision about whether a product will be selected to be used for a particular activity, and thus included in the consumer's community of products. The independent variables include each how well suited for a task the consumer believes the product is (perceived quality) and the level of quality they are willing to accept for a task (accepted product quality for each activity), and his or her interest in and knowledge of technology.

Based on the survey generated mean perceived quality (survey questions 230 – 236), interest in (survey question 502), and knowledge of (survey question 504), and associated standard deviation, Excel's random number generator was used to generate the associated scores for each consumer using the equation shown below.

$$genNormal(mean, standard\ deviation) \qquad \text{(Equation 4.1)}$$

Excel's "IF" function was used to compare individual scores to average scores of those who consume the product, in the case of interest in and knowledge of technology, and to compare perceived quality to accepted quality, as shown in the equations below.

$$IF\ individual\ interest \geq average\ interest, THEN\ may\ consume = 1 \qquad \text{(Equation 4.2)}$$

$$IF\ individual\ knowledge \geq average\ knowledge, THEN\ may\ consume = 1 \qquad \text{(Equation 4.3)}$$

$$IF\ perceived\ quality \geq accepted\ quality, THEN\ may\ consume = 1 \qquad \text{(Equation 4.4)}$$

The model was built in two stages. The first generation incorporates only the comparison of perceived to accepted quality for an activity, based on the assumptions of the task-technology fit model (Goodhue and Thompson 1995). If the consumer's perceived quality meets or exceeds his or her accepted quality for an activity, the product may be consumed for that activity. In cases where multiple products offer perceived qualities that meet or exceed the accepted quality, the product offering the highest perceived quality for the activity is selected. If multiple products offer the highest perceived quality for an activity, for example the consumer perceives the laptop computer, the smartphone, and the tablet each as being satisfactory for surfing or browsing the internet, the model randomly selects from those products. The selection is made randomly to discern whether additional factors, outside of perceived quality, may influence the decision making process. Each product selected for an activity is represented once in the consumer's final community of products (i.e. if the laptop computer is selected for three activities and the smartphone for one, the final community consists of two products – one laptop computer and one smartphone). Table 4 summarizes the relationship between each variable, the calculation method, and the resultant input to the model.

The second and third generations of the model incorporated consumer interest in and knowledge of technology, in addition to perceived versus accepted quality. Although higher interest is often associated with additional purchasing (Day et al. 1991), there is value in knowing whether increasing interest will strictly increase consumption, or whether it may shift consumption to other products that may be more material efficient (i.e., if increased interest led a consumer to select a tablet over a laptop). In this generation of the model, each consumer has an interest score and a knowledge score that is randomly generated based on the average interest and knowledge scores of the survey respondents. The randomly generated interest in (knowledge of) technology scores must meet or exceed the average interest (knowledge) of those survey respondents who select the product in a hypothetical product replacement scenario as shown in Equation 4.2 (Equation 4.3). Of the products which may be consumed based on interest or knowledge, the product offering the highest quality is selected as described above. These later generations of the model evaluate the effects of interest and knowledge individually.

Table 4: Model variable definition, calculation method, and resultant input.

Variable	Definition	Calculation Method	Model Input
Interest in technology	The degree to which a consumer assesses themselves to be interested in technology (5 point scale - not at all (5) to extremely (1) interested)	Global average of self assessment of interest in technology (Q502) *Scores were inverted before average was calculated.	Mean and standard deviation used to generate random numbers for individual respondent scores.
Interest of those who consume the product	The degree to which consumers **who would select the product for consumption** assesses themselves to be interested in technology (5 point scale - not at all (5) to extremely (1) interested)	Average of self assessment of interest in technology (Q502) for only those respondents **who select the product for consumption** (Q300) *Scores were inverted before average was calculated.	Mean and standard deviation used to generate random numbers for individual respondent scores.
Knowledge of technology	The degree to which a consumer assesses themselves to be knowledgable about technology (5 point scale - not at all (5) to extremely (1) interested)	Global average of self assessment of knowledge of technology (Q502) *Scores were inverted before average was calculated.	Mean and standard deviation used to generate random numbers for individual respondent scores.
Knowledge of those who consume the product	The degree to which consumers **who would select the product for consumption** assesses themselves to be knowledgable about technology (5 point scale - not at all (5) to extremely (1) interested)	Average of self assessment of knowledge of technology (Q502) for only those respondents **who select the product for consumption** (Q300) *Scores were inverted before average was calculated.	Mean and standard deviation used to generate random numbers for individual respondent scores.
Accepted quality for an activity	The degree to which a consumer can use a product for a given task and achieve the minimum level of quality they require. Quality is subjective, so this variable depends upon what attributes a consumer feels are important to them (for example, quality in watching television or movies might be picture clarity, sound, etc.)	Each respondent's stated quality score (Q24x series) of the product selected in associated activity question (Q23x series).	Direct input to model.
Perceived quality of a product for an activity	The degree to which a consumer feels that a product can be used for a given task. Quality is subjective, so this cariable depends upon what attributes a consumer feels are important to them.	Global average of each respondent's stated quality score (Q24x series) for each product.	Mean and standard deviation used to generate random numbers for individual respondent scores.

To evaluate the model's sensitivity to system interventions, the model inputs of perceived quality for each activity, and average interest / knowledge of those consuming the product were manipulated. These metrics were selected because consumption intention will increase if a product is more effective (Goodhue and Thompson 1995) and decrease if the technology and its features are new and unfamiliar (Oliveira et al. 2014). The following system interventions were evaluated:

1) Product improvements (performance, design, etc.)
    a. General improvements to all products as demonstrated by 10% increase in perceived quality of all products for all activities;
    b. General improvements to the tablet as demonstrated by 20% increase in perceived quality of the tablet for all activities; and
    c. Targeted improvements to the tablet simulate improvements that might make the tablet to align with the laptop computer as demonstrated by setting tablet perceived quality equal to laptop perceived quality for all activities.
2) Consumer interventions (i.e. educational campaigns or targeted information)
    a. General improvements in consumer awareness of and interest in technology as demonstrated by increasing average consumer interest to 4 and 4.5;
    b. General improvements in consumer knowledge about product features and use; and
    c. Targeted campaigns to improve knowledge of and interest in particular products, in an effort to increase adoption intention for products with the potential to replace multiple other products, as indicated by lowering the interest threshold for tablet consumption to 3.5.

These improvements were simulated by modifying the averages described above before using those modified averages as inputs to the random number generation formulas.

4.3 Results

4.3.1 Survey Population Summary

Among the 1,011 respondents, 189 (19%) were millennials, 372 (37%) were generation X, 366 (36%) were baby boomers, and 84 (8%) were from the silent generation. Respondents represented all regions of the United States, including Midwest, Northeast, South, and West. Average household income was just over $65,000 and 434 (43%) of respondents completed a four year degree or higher.

Over 60% of all respondents self-identified as being very interested or extremely interested in technology products for home use, while only about one-third indicated that they were very or extremely likely to be the first to adopt new products. Approximately one-half indicated that their belief that they were very or extremely knowledgeable about technology products for home use. The global average number of products available in the existing community was 8.5 of 14 possible products for a community mass of 47 kg, or 7.4 of 12 possible products for a community mass of 34 kg, if the printer and CRT television were excluded for consistency with other questions. Of the products offered, only 5.7 of the 12 products were selected for purchase in a hypothetical scenario in which all products were destroyed, and a set budget was available to purchase all new products. This average group of selected products represents a community mass of 27 kg. While these numbers suggest a downward shift in product ownership, further analysis is necessary to determine whether decreasing ownership is occurring, or whether the decrease is a byproduct of a scenario driven budget limitation or lack of inclusion of new to market products.

Among all respondents, the flat screen television and printer were most commonly available product, with an availability rate of 86% for each product. When presented with a scenario in which the respondent has no electronics and can buy any products they wish, the flat screen is the most frequently selected (77%), followed by the smartphone (71%). Conversely, the digital camcorder (32%) and CRT television (21%) were the products with the lowest availability rates among all respondents. Additionally, the digital camcorder was one of the least frequently selected in the hypothetical purchasing scenario (30%), with the basic cell phone (20%). The CRT television was not among the products that could be selected in the hypothetical purchasing scenario, because it was no longer being manufactured and sold at the time of survey administration.

4.3.2 Demographics impacts on product consumption

Impacts of demographic characteristics on total consumption and type of consumption

As products mature, market penetration becomes more homogeneous, and consumer's stated preferences for products are consistent across demographic groups. Each respondent was first asked to select from a list of products available to them, and later to select products that they would purchase given a scenario where all electronics had been lost or destroyed and they must rebuild their community of products. Although there was variation in the number and type of products currently available to each respondent (p<0.0001 for all factors; Figure 19), there was very little variability in the number and type of products selected for purchase in the hypothetical purchasing scenario. Of 12 products offered, respondents across all generations, household incomes, and varying degrees of education selected just over 5.5 products for purchase on average (p=0.29, p=0.82, p=0.96, respectively). Level of interest in technology has some impact on the number of products selected, as those who self-identified as being either not at all interested or extremely interested in technology selecting significantly fewer or more products for purchase in the hypothetical purchasing scenario (Figure 19; p=0.002). Main ANOVA effects for each demographic group are shown in Table 5.

Table 5: Main one-way ANOVA effects

Total number of products available	df	F	p
Generation	3	23.042	<.0001
Years of Education	4	5.942	<.0001
Level of Interest	4	27.610	<.0001
Household Income	7	17.415	<.0001
Total number of products selected	df	F	Sig.
Generation	3	1.242	0.293
Years of Education	4	0.149	0.963
Level of Interest	4	4.436	0.002
Household Income	7	0.517	0.822

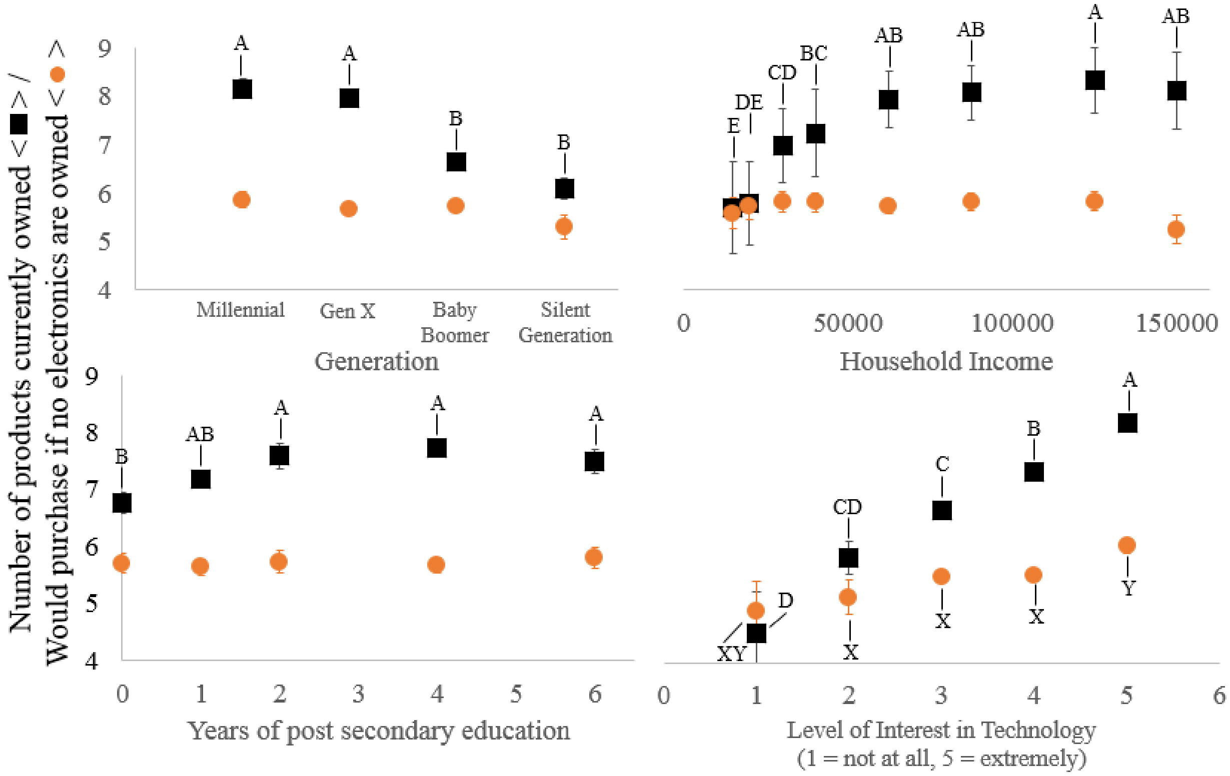


Figure 19: Total number of products available and selected by explanatory variable.
Values are mean +/- standard error. *Unique letters over product availability (solid black square) and under selected products (solid orange circle) markers indicate a significant difference among demographic groups based on Tukey's Post-Hoc HSD.

Although research has revealed differences both between Americans ages 65 or older and the rest of the population, and within the senior population (Pew 2014), survey results show that, not only would older Americans purchase the same number of products (under the prescribed set of circumstances in the hypothetical purchasing scenario), they would purchase the same type of products (Figure 20). With the exception of the game console, which was selected by almost 60% of millennials versus only about 20% of the silent generation, trends in all other products were similar across generation and income classifications. The difference in selection rate of the game console may be due to marketing, as game consoles tend to be marketed more heavily toward younger generations, while other electronics are marketed towards all ages. Additionally, older generations may tend to play different types of games that might be available on another platform, such as puzzle games on a smartphone (Brown 2017).

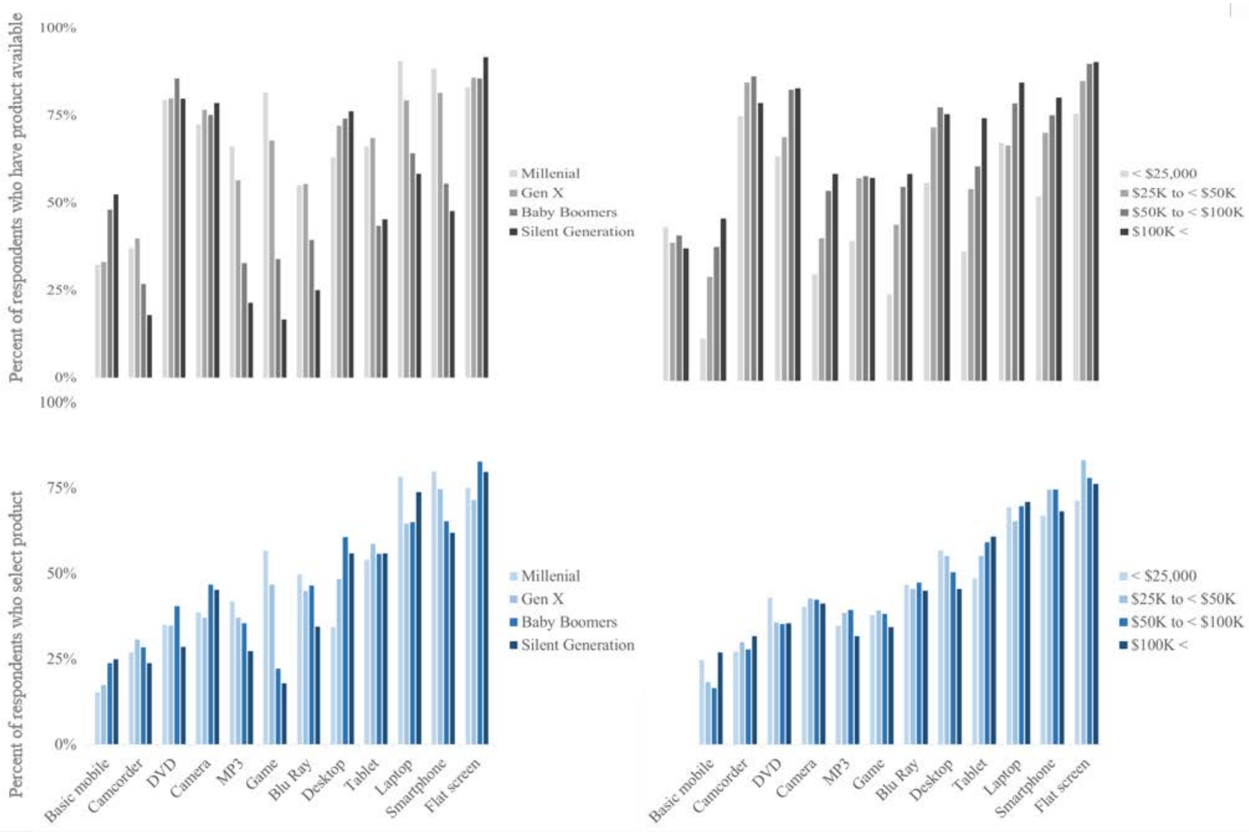


Figure 20: Comparison of types of products available to and selected by generation and income groups. Although existing product availability varies across age and income demographics, product consumption is generally homogeneous in the hypothetical buying game.

Despite limited differences across demographic groups for total numbers and types of products available, when analyzing particular groups of products, grouped heuristically as legacy technologies (evaluated by considering consumption of first the basic mobile phone and not the smartphone and then as a larger group including the CRT but not flat screen, basic mobile phone but not smartphone, and the digital camera) or newer technologies (flat screen but not CRT, smartphone but not basic mobile, and the tablet), slight differences in consumption rates of these products emerged. As shown in Table 6, older generations and groups with lower interest in technology demonstrated higher availability, use, and selection rates of legacy technologies, specifically, these groups had, used, or selected a basic mobile phone and did not have, use, or select a smartphone. On the other hand, availability, use, and selection of only newer technologies was relatively constant across generations, while results suggested that interest, income, and years of education impacted availability, use, and selection of newer technologies. Across all demographic groups, complete adoption of the legacy technologies product group was at most 5%, due to the high penetration rate of the flat screen television (at the time of the survey, the CRT television had been off the market for almost three years (Breeden 2012)).

Table 6: Percentage adoption rates by demographic classification.

		Has available		Has in active use		Selects for purchase	
		Basic mobile phone, but not smartphone	Only newer technologies (flat screen, smartphone, tablet)	Basic mobile phone, but not smartphone	Only newer technologies (flat screen, smartphone, tablet)	Basic mobile phone, but not smartphone	Only newer technologies (flat screen, smartphone, tablet)
Global		22%	26%	21%	29%	9%	30%
Generation	Millenial	7%	33%	7%	37%	5%	30%
	Generation X	12%	32%	11%	37%	7%	30%
	Baby Boomers	35%	19%	33%	20%	13%	30%
	Silent Generation	43%	15%	40%	13%	15%	27%
Years of Education	0 years	27%	20%	24%	21%	6%	26%
	1 year	21%	22%	19%	27%	7%	26%
	2 years	21%	30%	20%	32%	15%	30%
	4 years	21%	29%	20%	34%	9%	33%
	6 years	21%	31%	20%	30%	13%	33%
Interest in Technology	Not at all	37%	5%	42%	0%	37%	11%
	Not very	52%	21%	48%	19%	19%	21%
	Somewhat	32%	22%	30%	26%	13%	28%
	Very	15%	28%	14%	31%	6%	34%
	Extremely	13%	31%	12%	34%	6%	29%
Household Income	$15,000	23%	19%	23%	22%	10%	18%
	$20,000	39%	11%	33%	11%	14%	22%
	$30,000	24%	23%	22%	22%	7%	36%
	$40,000	20%	26%	19%	31%	9%	31%
	$62,500	22%	27%	20%	32%	8%	34%
	$87,500	20%	31%	20%	34%	7%	30%
	$125,000	14%	29%	15%	34%	16%	26%
	$150,000	21%	41%	21%	41%	10%	31%

Available purchasing budget

Within the hypothetical purchasing scenario, each respondent was assigned a budget for purchasing all new electronic products, half of the population was given a high budget ($2,500) with which they could potentially purchase 11 of the 12 products and the other half given a low ($1,500) budget. Further, each product had a set price, which was displayed and updated for the respondent as they made choices, and all product prices were kept constant, with the exception of the digital camera and the laptop, which were varied between higher and lower prices in an effort to simulate higher and lower quality products (i.e. an entry level DSLR camera versus point-and-shoot). As might be expected, those respondents with more money available to spend (either due to a higher initial budget, or lower product prices), selected on average more products for purchase. While product prices and available budget for product purchases impacted the total number of products purchased, the distribution of types of products purchased was the same across pricing and budget groups. The flat screen television, smartphone, and laptop were the most frequently selected product across all budget and price combinations, in addition to being most commonly selected first when respondents answered this question, suggesting that these three products are most among the key products in the electronics product community. As shown in Figure 21, results suggest that the tablet is primarily budget dependent, the smartphone, basic mobile, and flat screen are largely independent of budget and product price, the laptop is price dependent only in the lower budget scenario, and the digital camera is both price and budget dependent. Full results for all products are shown in Table 7.

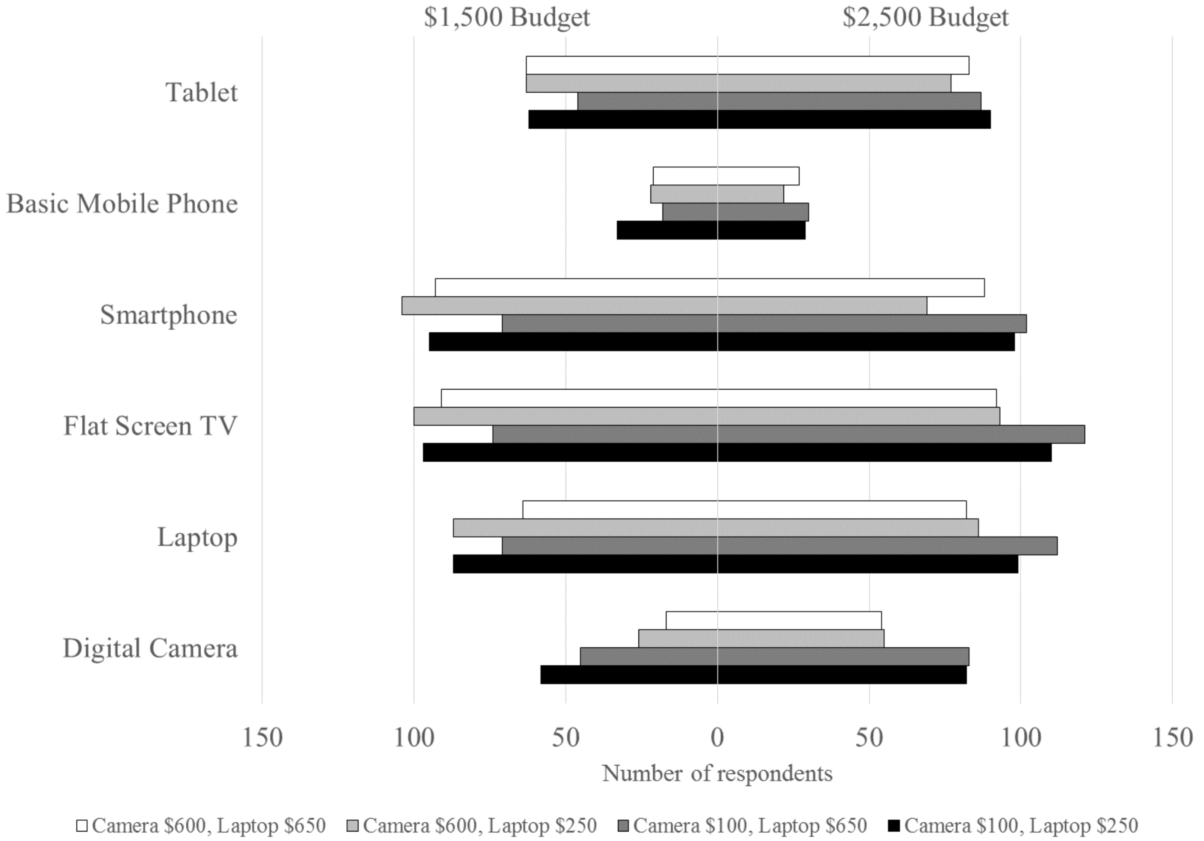


Figure 21: Product selection comparison across hypothetical purchasing scenario budget and product cost variations. Varying total budget available for replacing products and price of digital camera / laptop produced similar trends, and when more money was available (either due to larger initial budget or lower product costs), more products were selected for purchase. Results suggest that tablet selection is primarily budget dependent, the smartphone, basic mobile phone, and flat screen TV selection are independent of price and budget, although a higher price laptop inhibits selection in the $1,500 budget scenario, the laptop is price dependent in the $1,500 budget scenario, but less so in the $2,500 budget scenario, and the digital camera is both price and budget dependent.

Table 7: Results for complete product set for product selection comparison across hypothetical purchasing scenario budget and product cost variations

	Number of respondents selecting product, by budget group and product price								
	Global Population	$1,500 Budget				$2,500 Budget			
		Camera $100, Laptop $250	Camera $100, Laptop $650	Camera $600, Laptop $250	Camera $600, Laptop $650	Camera $100, Laptop $250	Camera $100, Laptop $650	Camera $600, Laptop $250	Camera $600, Laptop $650
	n=1011	n=133	n=113	n=135	n=133	n=126	n=138	n=111	n=122
Digital Camera	420	58	45	26	17	82	83	55	54
Laptop	688	32	22	26	30	99	112	86	82
Digital Camcorder	289	97	74	100	91	60	44	39	36
Flat Screen TV	778	51	32	41	40	110	121	93	92
DVD Player	367	48	37	71	53	60	59	36	48
Blu-Ray Player	460	43	29	50	29	66	74	52	59
Gaming Console	377	95	71	104	93	61	61	49	55
Smartphone	720	33	18	22	21	98	102	69	88
Basic Mobile Phone	202	45	30	51	47	29	30	22	27
MP3 Player	370	62	46	63	63	50	52	38	57
Tablet	571	87	71	87	64	90	87	77	83
Desktop	514	70	46	57	58	77	77	71	58
Average number of products selected	5.7	5.4	4.6	5.2	4.6	7.0	6.5	6.2	6.1

Limitations of results and data interpretation

Although the results suggest that future consumption would be homogenous across demographic indicators, these results are limited by several factors. First, all products included in the survey were relatively mature. In other words, all had been on the market through multiple product generations and were widely recognized. As a result, information availability for these products makes them accessible, while at the same time, technological innovation makes them affordable. Next, research has shown that attitudes impact prediction of behavior (Ajzen 2001) and self-prediction of behavior is generally optimistic (Vietri et al. 2009). Therefore, a respondent’s attitudes or aspirations may bias their selections. Finally, the scenario presented (replacing all products at once) versus the likely reality (replacing each product individually) is unlikely for most consumers. Therefore, further research is necessary to understand the impacts of each of these points and how they might affect consumption patterns across the survey population.

4.3.3 Multifunction generalist products are occupying specialized niches

Researchers have shown that some products are, or are perceived to be, optimized for particular activities. This occurs both with multifunctional products that seem to be optimized for specific activities, as the tablet is well suited for entertainment (Li 2014), and as multi-functional products drive single function specialists into extinction, as the smartphone did with the point and shoot camera (Shu 2016). As a result, those products are used either more commonly, or exclusively, for a smaller subset of activities and functions than they are capable of conducting, and begin to occupy a specialty niche. As a result, products with redundant functionality are consumed, creating a larger material demand within the community.

A similar phenomenon occurs in biological ecology. Each organism is capable of surviving under a range of conditions (its fundamental niche). However, many organisms instead occupy realized niches to enhance survival. Realized niches develop when a species occupies a position within a community or ecosystem that is smaller than its fundamental niche, based on the organisms' interactions with other organisms within the same habitat (Smith and Smith 2009).

The survey results suggest that products are, in fact, occupying realized niches, smaller than their fundamental niche. Within a habitat defined as the subset of the survey population with each of three key products (the smartphone, tablet, and laptop) available (n=388), when asked which products had been used in the past month to perform activities, the smartphone dominated for activities that required little to no keyboard interaction but benefited from mobility, while the laptop dominated for activities that required little to no mobility, but a larger degree of keyboard entry or accuracy (Figure 22). Not only were these products most frequently used for these types of activities, but they were also exclusively used for these same activities by a large proportion of the respondents. More than half of respondents who indicated that they made voice or video phone calls or got directions using one of the three products did so exclusively using the smartphone. Almost one half of those respondents who typed or edited documents or performed other productivity tasks and almost one third of those respondents who made online purchases or performed other e-commerce transactions did so exclusively with the laptop. The tablet beat out the smartphone and laptop by a small margin when respondents were asked about entertainment activities, such as playing games and watching movies or television programs. This may be due to the availability of a larger screen size combined with lightweight portability.

Additionally, leisure activities, including social media usage, surfing or browsing the internet, and playing games, were both the most frequently performed activity across all platforms and also performed with similar frequency across all platforms. This result suggests an evolution of the functions themselves, as activities are emerging and coevolving with the product; i.e. the viewing activity evolves and becomes more common across all platforms as products and content become available to support that activity.

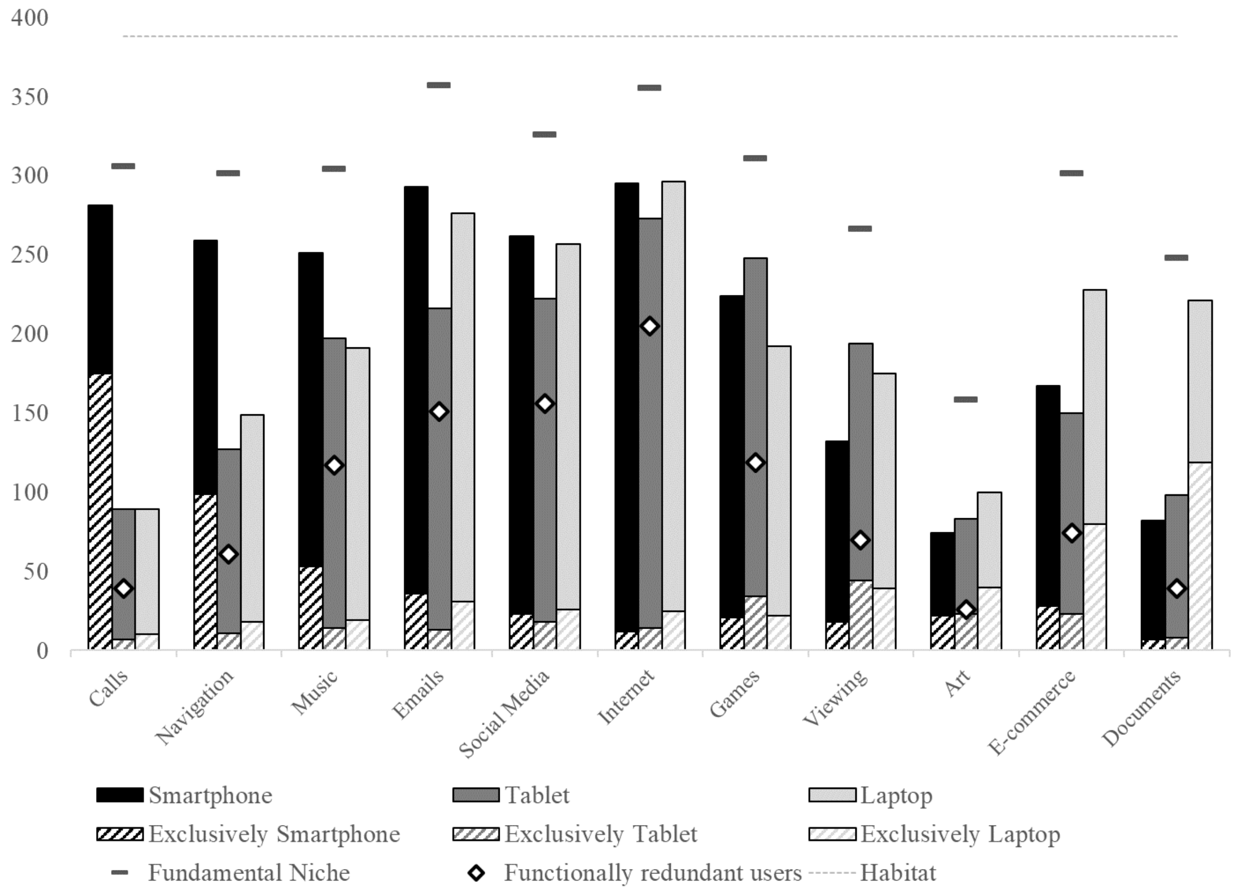


Figure 22: Realized niche for the smartphone, tablet, and laptop.
Habitat population comprised of those respondents who have all three products available (n = 388; shown by dashed line at top of figure), suggests that products occupy realized niches smaller than their fundamental niche. The fundamental niche is comprised of all users who perform an activity, shown as the dark gray horizontal marker, the realized niche for each product is the group of users who use the product for the activity, shown as columns. Smartphones are used more frequently for activities benefiting from convenience and mobility, laptops are used more frequently for activities requiring more detail, and entertainment activities are accomplished on all three devices. Dark gray diamonds indicate functionally redundant users who indicate that they perform the function on all three of the devices. *Texting and digital photographs were offered as functions for the tablet and smartphone in the survey, however, were not included here because they were not offered as functions for the laptop.

Within the same habitat, when asked which product had been used most frequently in the months preceding the survey to perform specific activities, similar trends emerged (Figure 23). For example, more than 60% use the laptop most frequently to write or edit documents. More than 40% indicated that they had used a laptop most frequently for surfing the Internet and writing or sending emails and although over 80% of the subpopulation will use a smartphone to browse the internet or to write or send emails, only about 25% use the smartphone most frequently. Finally, although this habitat has three multifunction products available with which to conduct each of the activities, many use a different product altogether, increasing the functional redundancy within the habitat. Over half use a flat screen television to watch television or movies, approximately 20%

use the desktop computer to write or edit documents and to send email, and more than 15% use the desktop computer to surf or browse the internet.

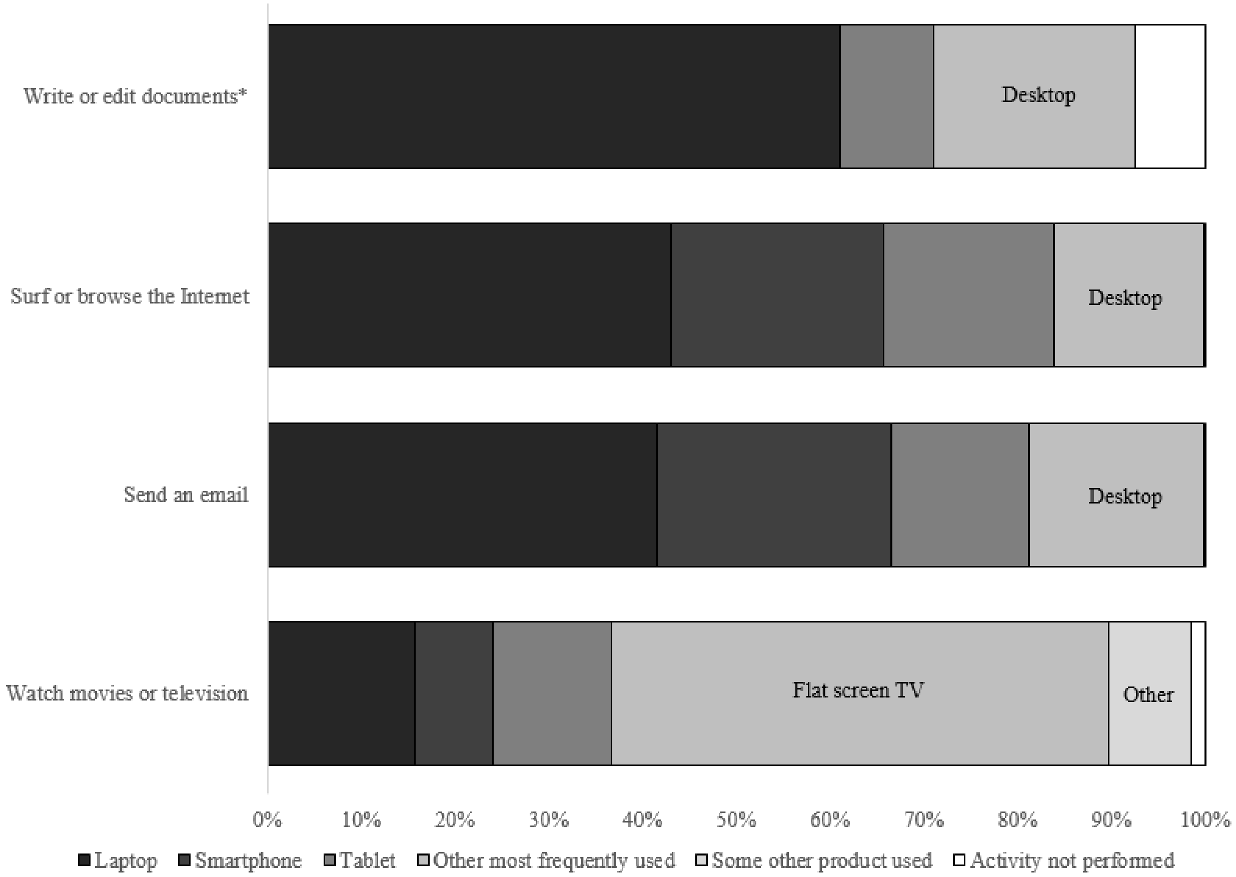


Figure 23: Percentage of respondents who used a product for the listed activity most frequently in the months preceding the survey.
Although all respondents had the three products available to perform the activity, between 16% and 62% preferred another product most frequently to perform the given activity. Sample sub-population comprised of those respondents who have all three products available (n=388). *Smartphone not offered as an option for write or edit documents.

These results align with previous research suggesting that these three devices are optimized for and emphasize different functions, and as a result, are used more often for different purposes (Li 2014), and support the theory behind the task-technology fit model (Goodhue and Thompson 1995), in that compatibility between technology and task is critical to the adoption of technology. Just as biological species occupy realized niches smaller than the functional niche that they are capable of occupying, product species are used for a smaller group of functions than they are capable of conducting. Unfortunately, because functional use is not maximized, multiple products are consumed, creating a larger material demand. These results call into question previous research suggesting that more sustainable communities could be achieved through a shift to smaller multifunctional products (Kasulaitis et al. 2015) or to a minimally redundant community (Ryen et al. 2015), because little is known about whether consumers would adopt a fundamentally different product set.

4.3.4 Product interactions and technological innovations drive a community shift

Although multifunctional generalists aren't being functionally maximized, technological progress is driving a natural community evolution as newer, lighter, more multifunctional technologies are developed and outcompete existing products or are marketed to be consumed as a suite of products. This mirrors biological ecology, in which interspecific interactions may impact species distribution by complementing or modulating the effects of abiotic conditions. These interspecific interactions may act as inhibitors, slowing down species range expansion rates, or as facilitators, speeding up expansion rates (Svenning, et al. 2014).

Outside of biological ecology, interspecific competition may be the most familiar type of species interaction. When interspecific competition occurs, members of different species compete for the same limited resource. Species compete when they have overlapping niches – overlapping ecological roles and requirements for survival and reproduction (Smith and Smith 2009). In the consumer electronics industry, this competition became especially apparent when the flat screen television was introduced and drove the CRT television to extinction, an example of competitive exclusion. On the other hand, competition can be minimized if two species with overlapping niches evolve by natural selection to utilize less similar resources, resulting in resource partitioning (Smith and Smith 2009). As shown in section 4.3.3, this occurs with the tablet and laptop. Although in its early days the tablet was expected to outcompete and drive the laptop to extinction (OConnell 2013), instead the tablet is more often used for entertainment and leisure purposes, while the laptop still dominates for productivity tasks.

Other types of interspecific interactions include commensalism and mutualism, in which two species have a long term interaction that is beneficial to one (commensalism) or both (mutualism) species. Although some relationships may appear to be strictly commensalism, there may actually be benefits on both sides and the relationship may be slightly mutualistic (Smith and Smith 2009). This occurs in the consumer electronics industry with televisions and their auxiliary devices. Blu-Ray and DVD players cannot be used without an associated television for audio and visual output, therefore both types of players rely on consumption of a television. However, there is some benefit to the television, as well, because with the addition of the Blu-Ray or DVD player, the television offers additional functionality. Therefore, both devices benefit from the relationship.

A natural shift due to these interspecific interactions occurs within the consumer electronics product ecosystem as technology continues to evolve. As shown by Figure 24, more than half of the respondents indicate a preference for one of four key products (the flat screen television, the smartphone, the laptop, and the tablet) in the hypothetical replacement scenario question (Q300), suggesting that these products may realize increasing expansion rates into new demographic habitats. At the same time, however, almost 20% of respondents would remove these products from their community under the circumstances. Conversely, expansion rates are slowed or reversed as products are "removed", those that are available (in survey question 100) and not selected for consumption in the hypothetical replacement scenario (survey question 300) from the community.

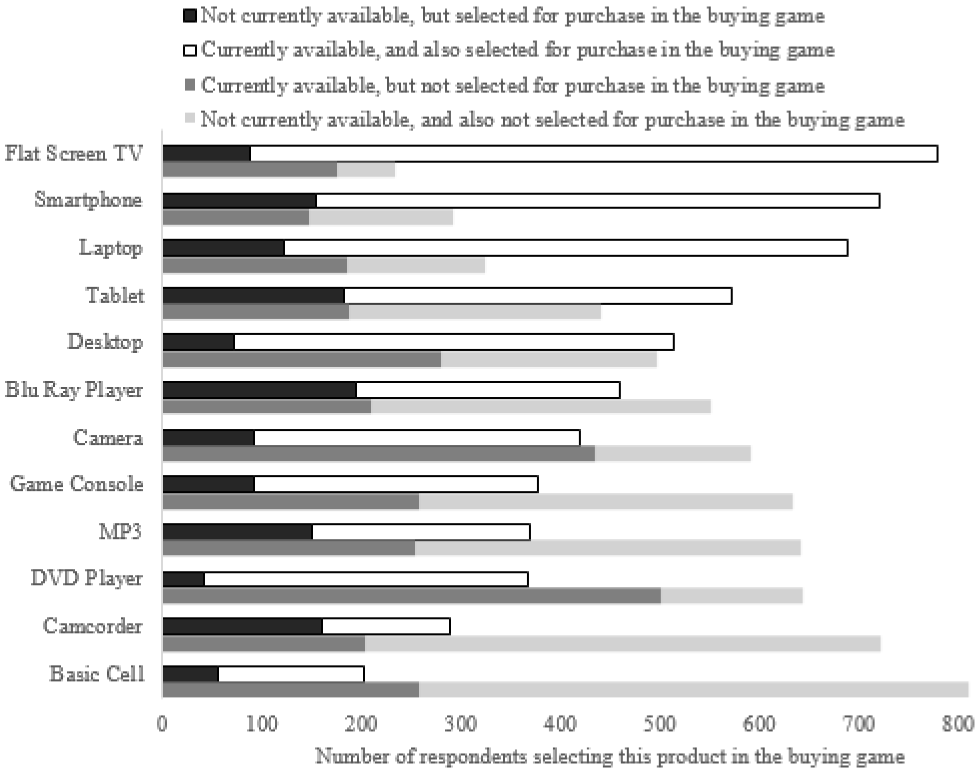


Figure 24: Total consumption of products in the hypothetical purchasing scenario.
Results show a natural shift towards digital, multifunctional, and predominately mobile (with the exception of flat screen television) technologies. Blue shows products that exist in the hypothetical community (dark blue indicates that the product was added, light blue indicates that the product was preexisting), while maroon shows the products that were removed from the hypothetical community (n=1011).

Interspecific interactions may impact consumption decisions. When acting as inhibitors, multi-functional generalists drive single function products into small specialty niches or into extinction. For example, the smartphone is expected to drive the digital camera into a specialty niche. Interestingly, the percentage of respondents with smartphone available that also have a digital camera available is slightly higher than the percentage of all respondents who have a digital camera available (79% compared to 75%). Further, the percentage of respondents without a smartphone available who do have a digital camera available is actually lower (at 67%). A similar trend appeared in the buying game (43%, 42%, and 37% respectively). This result suggests that the relationship between smartphones and digital cameras is impacted by factors other than strictly interspecific competition. For example, relatively low cost of point and shoot digital cameras or differences in functionality and picture quality between smartphones and DLSR cameras may encourage redundant consumption. CRT televisions have effectively been driven to extinction by flat screen televisions. Although the percentage of respondents who have a flat screen available that also have a CRT television available is approximately equal to the percent of all respondents with a CRT television available (23% and 24% respectively), the percentage of those respondents who do not have a flat screen available but do have a CRT available is higher at 30%.

When acting as facilitators: interconnected products encourage the adoption of other related products. 86% of all respondents have flat screen televisions available, however, 89% of respondents who have a DVD player available have a flat screen television available, and 96% of respondents who have Blu-Ray players available have flat screen televisions available, suggesting that consumption of these types of ancillary products enhance features or services provided by the primary product, encouraging increased consumption. 31% of those respondents who indicated that they purchased their tablet and smartphone at the same time (n=26) indicated that the ability to use the two products together was the driving factor behind the decision. Almost one-third of respondents who owned a tablet indicated that the presence of a smartphone in their community increased their decision to purchase the tablet, and almost one-quarter of respondents who owned a tablet indicated that the presence of a laptop or flat screen in their community increased their decision to purchase the tablet.

A similar trend emerged when surveying consumption trends among smartphone and tablet owners. Of those who had a smartphone, the presence of a tablet increased the decision to purchase for approximately one-third and presence of laptop increased the decision to purchase for approximately one quarter. This result suggests that these species exhibit a mutualistic relationship, in which both species have a long term interaction that is beneficial to both. Only 14% of those who have a smartphone but not a tablet (n=248) and 10% of those who have a tablet but not a smartphone (n= 96) indicate that the presence of the other product in their community would prevent them from accepting a free tablet or smartphone, respectively, while 57% and 24% indicate that nothing would prevent them from accepting a free tablet or smartphone respectively.

The question remains whether it is possible to leverage these interactions to intentionally shift community structure to reduce or minimize total material consumption. Using the product adoption-interaction framework described in the methodology section, total respondent consumption was simulated assuming that perceived quality and task-technology fit are the primary drivers of consumption. Based on this assumption, the simulation selected the product offering the highest perceived quality to meet the user's needs. In a situation where multiple products offered the same level of quality, the simulation selected a single product randomly from those offering the highest perceived quality to fulfill each activity need. As the model selects only a single product, the resultant community will be the minimally redundant community. Selection based on quality alone most accurately estimated consumption rates of the tablet, (0.6 tablets per community among survey respondents, the "survey population", versus 0.7 tablets per community among the population simulated by the model, the "simulated population") and least accurately estimated consumption rates of the smartphone (0.7 smartphones per community among the survey population versus only 0.1 smartphones per community among the simulated population) as shown in Figure 25. One reason for the discrepancy with smartphones is that they are increasingly becoming an integral part of smart communities of products, including wearable and home technologies (CTA 2017). Their high mobility and convenience drives their consumption, despite rarely being a first choice based on quality alone.

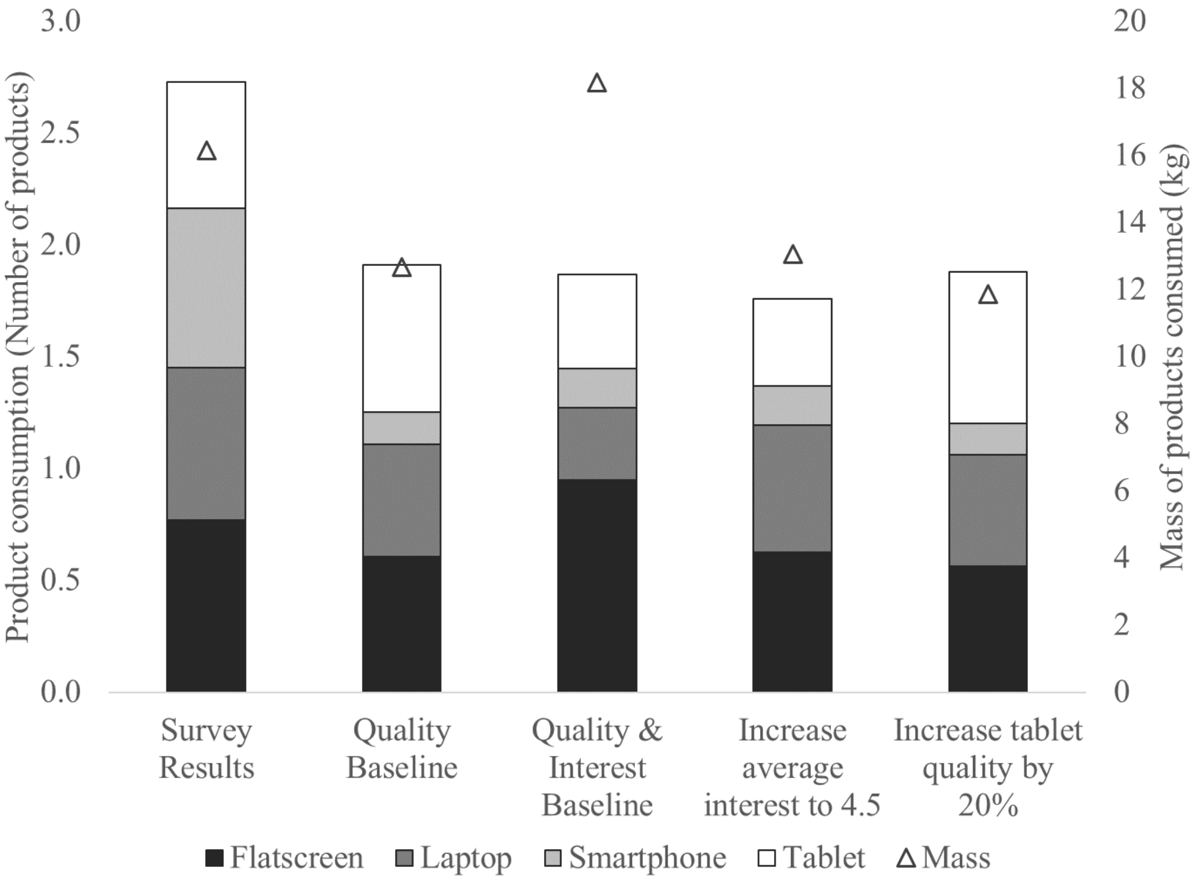


Figure 25: Product consumption and resultant material consumption under each scenario.

The simulated population consumed approximately 0.2 fewer laptop computers and flat screen television than the survey population. This result, in tandem with 0.6 fewer total products consumed by the simulated population, suggests that a single product is not selected at random from those offering the highest quality of experience. Instead, consumers may select all products that meet their needs, or may select multiple products to meet their needs in different scenarios. For example, flat screen televisions are both widely known and expected to be best suited to watching movies or television, and as a result are often selected for watching movies and television over other products with similar perceived quality scores. However, their lack of mobility may encourage consumers to select an additional product for watching movies and television while traveling or under other circumstances.

Later iterations of the model incorporated consumer interest in technology and knowledge about technology. Incorporating these factors, the model accurately predicted tablet consumption rates, suggesting tablet consumption may be influenced by both perceived quality and consumer interest in technology. Sensitivity analysis showed that design improvement or increased consumer interest may cause a shift in community structure, but also a corresponding increase in total material demand, as shown by the Quality & Interest Baseline column (Figure 25).

Model results indicate that incremental changes in consumer interest, such as might be achieved through a marketing or educational campaign informing consumers of new or underutilized functionality, or product perceived quality, due to a product improvement, may shift consumption to newer technologies, yet minimal material reduction is achieved, as shown by the tablet quality increase scenario in Figure 25. The largest reduction in material consumption occurred as a result of the forced decision for a single product to accomplish each activity, creating a minimally redundant community. As previously discussed, this minimally redundant community is challenged by the differing needs of consumers for activities in differing circumstances, and further research is necessary to understand the potential for achieving minimally redundant communities.

4.4 Implications

As electronic products mature in the market, the general impact of demographic characteristics (such as age, education, interest) on consumption is lessened. Although particular groups of products may be more likely to be adopted by particular demographic groups, consumption on the whole is statistically similar for all groups except those who are the most and least interested in technology. This result lessens the effectiveness of leveraging marketing and interventions geared towards particular demographic groups when attempting to reduce the material consumption of the industry as a whole. Further, products are optimized for performing particular activities, or are perceived to be optimized for those activities, so interventions to affect consumption behaviors may be more effective when aimed at informing consumers of product capabilities.

A natural shift in community structure is occurring, as technological progress enables products that provide multiple functions, higher quality, or interconnected functionalities. As interest in technology products and knowledge of product capabilities increases, and product design is improved to make multifunctional generalists more competitive with specialized products, community structure will continue to experience a natural shift toward newer technologies, which may be accompanied by a net reduction in material demand. Conversely, the natural shift may result in increased product consumption, causing a net increase in material demand.

The rapid pace of technological evolution in the consumer electronics industry and the movement towards an Internet of Things (Xia et al. 2012) challenges intentional community restructuring to reduce the total number of products in a community, and thus the net material demand. Further, redesigning specific products to more effectively outcompete existing products and educating consumers to improve adoption intention for particular products are challenged by the relatively slower pace of those processes. These types of system interventions are often limited by effects demonstrated in this work including form factor lock-in (Chapter II) and behavioral response (Chapter III), which may minimize improvements in material consumption and challenge the vitality of efforts to reduce material consumption via focused efforts to shift community structure.

These results suggest that focused efforts to develop a closed loop, circular economy may have more success reducing ecosystem impacts than piece meal efforts. Planning for material recovery in the design and development stages and developing both improved material recycling infrastructures and secondary markets are vital steps in improving the sustainability of the consumer electronics industry as a whole. Further, efforts toward encouraging sustainable behavior (such as educating consumers to consume minimally redundant product communities) should not be ignored. Policies and educational campaigns to inform and encourage this type of behavior, in addition to more basic educational campaigns teaching consumers where, how, and why to make products available for collection and recycling must all be improved.

V. Conclusions

This dissertation demonstrates the utility of adapting ecological concepts of community and ecosystem ecology to understand the evolution of material flows through a product ecosystem. Although this research has focused on the consumer electronics product ecosystem, the methodologies in Chapter II, III, and IV can be applied to other product groupings with similar characteristics. As computing technologies are embedded further into non-traditional products, such as connected household appliances and ‘wearable’ electronics, products and components are increasingly miniaturized and product consumption continues to shift towards these smaller products. This shift introduces new challenges in the form of increasingly diverse waste streams, complex materials integration, and a shift away from legacy value streams of bulk materials and precious metals, and reduces the efficacy of existing strategies for reducing community material impacts.

As noted in Chapter II, relying on dematerialization as a strategy for primary material consumption reduction is challenged by behavioral response, both on the part of manufacturers, who trade technological innovation for improved product performance, and on the part of consumers who, as shown in Chapter III, consume increasing numbers of products despite overlapping functionality. Finally, Chapter IV suggests that, although product ecosystems might naturally evolve towards more energy efficient products thereby reducing one aspect of environmental impact, efforts to manipulate that evolution may not achieve a significant net material reduction. Therefore, efforts to reduce primary material consumption of the consumer electronics product ecosystem may lag behind the growth of the system and may not achieve the desired magnitude of change.

Instead, efforts to reduce net material consumption of the consumer electronics product ecosystem must focus on recovery of material and development of secondary markets, in order to minimize primary material consumption. Current electronics waste recycling regulations and infrastructures are focused on the recovery of base metals that occur in large quantities and precious metals that have high economic value. Significant improvements to the e-waste recycling infrastructures must be made, specifically in the collection of products, the recovery of materials, and the development of secondary markets. Efforts to improve these infrastructures must be evaluated based on their ability to reduce primary production (Zink and Geyer 2018).

Unfortunately, adapting recycling infrastructure to recover new materials is challenged by complex product design and incorporation of critical metals. Currently, recycling efficiency and the associated electronics recycling regulations are focused on weight (Oguchi et al. 2011), with the goal of optimizing recovery of base metals, such as copper and ferrous metal, and precious metals, such as gold and silver (Wäger et al. 2011, Cui and Forssberg 2003, Cui and Zhang 2008). This optimization is because the greatest economic value in electronics recycling is in the recovery of precious metals with high value and recovery of base metals which occur in relatively large quantities (Kang and Schoenung 2005). Due to the lack of infrastructure, social behavior, product design, and thermodynamic limits of separation, the recovery of critical metals, such as indium, and rare earth metals, is less than 1% (Graedel et al. 2011, Chancerel et al. 2013, Reck and Graedel 2012). Significant progress in recovery of rare earth and critical metals is necessary to develop a successful closed loop system in electronics. In parallel, e-waste recycling policies and incentives must similarly evolve with the changing product landscape, with additional research needed to evaluate the feasibility or benefit of adding targets for number of products recycled or critical material recovery rates to current mass-based approaches.

The increasing quantity and diversity of material usage combined with the difficulty of product and material recovery highlights a critical need for a three pronged approach to encourage the development of a circular economy. First, evolving product and material flows provide new opportunities for manufacturers and e-waste recyclers alike. While current business models are predicated on continued growth and growing sales volumes (Allwood et al. 2011), this type of model neglects the end of life consequences associated with the product. Therefore, e-waste regulations must be formulated to both encourage adaptation of product design to favor recycling while also making recovery of additional materials economically appealing.

Second, collection of products must be increased. Recently, retailers and new businesses have begun offering trade-in credits or cash in return for smartphones, tablets, netbooks and other small devices (e.g. Verizonwireless 2016 Gazelle 2016). The devices are then refurbished and reused or, in cases where renewal is not possible, are recycled. This type of business model may provide the incentive necessary to 1) accelerate the naturally occurring evolution toward newer, more efficient products, and 2) reduce the likelihood of a product ending up in storage, instead making it available for recovery. Such an expansion of the business model is beneficial both due to the extension of the service life of the device in the secondhand market and the availability of materials for recovery and recycling.

Finally, increasing consumption and the accumulation of in-use stocks is a barrier to circularity that cannot be overcome by recycling alone (Haas et al. 2015). Sustainable consumption must be incorporated in evaluations of circular economy potential. In the case study presented in Chapter III, supply of a material in the waste stream only met or exceeded demand by new products when consumption of the new product, in this case the CRT television, had ceased. This result supports the idea that there is the potential to close material loops, provided that net additions to stock are also reduced (Haas et al. 2015).

Considering consumer electronics as a community and the associated material flows as part of an ecosystem provides greater understanding of the potential achievements and limitations of existing sustainability strategies. Dematerialization as a standalone strategy to achieve net material reduction is challenged by increasing and evolving product, and by association, material consumption. Therefore, there is a critical need to develop and encourage a circular economy for consumer electronics, in which manufacturers design and build products with an eye towards material recovery and recycling, e-waste recyclers expand business models to accommodate evolving material flows, and policy and design supports the development of secondary markets, for both refurbished products and recycled materials. Efforts to address these challenges are likely to be more effective upstream (Zink and Geyer 2018), thus further research is needed to understand and encourage the development of adaptive methodologies for designing products for material recovery and developing infrastructure that maintains relevancy in the face of rapidly evolving technologies.

Appendix A

This appendix provides bill of materials data for laptop computers included in the analysis presented in Chapter III, additional benchmarking and analysis not included in the main text.

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Product Level Dematerialization

Bill of materials data from the disassembled Dell laptop computers (Table A-1) and Hewlett Packard laptop computers (Table A-2) show that the relative contribution of each material to the overall product weight is relatively constant both over time and over changing screen size. This supports the possibility of development of a representative bill of materials that could be used to estimate the relative concentration of materials in a product based on the product’s weight.

The results of the study were benchmarked against recent trends towards lightweight or thin laptops and towards smaller products like smartphones and tablets, through a survey of manufacturer specifications for a variety of products (Figure A-1) . Benchmarking against lightweight laptops in the same product line (Table A-3) showed a significant weight reduction (17%) with the 2011 model, but minimal product dematerialization in the following years. Further investigation revealed that this weight reduction was achieved through the removal of a standard installed optical drive. Benchmarking against smaller products that provide similar functionality, such as netbook computers (Table A-4), tablet computers (Table A-5), and smartphones (Table A-6), show that significant product level dematerialization can be achieved through a shift to a smaller product. These results support the conclusion that significant product level dematerialization is only achieved through a technological leap to a smaller product or by the removal of functionality.

Bill of Materials Data

Year Model	1999 CPiR 14.1	2000 CPX H5005T PPX 14.1	2001 C600 14.1	2002 C510/ 610 14.1	2003 D600 14.1	2005 D610 14.1	2006 D620 14.1	2007 D630 14.1
Aluminum	367 (12%)	311 (10%)	293 (11%)	449 (16%)	543 (22%)	285 (12%)	235 (9%)	307 (12%)
Magnesium	- (0%)	- (0%)	- (0%)	- (0%)	69 (3%)	- (0%)	406 (15%)	388 (15%)
Copper	22 (1%)	95 (3%)	18 (1%)	26 (1%)	45 (2%)	71 (3%)	67 (3%)	59 (2%)
Ferrous	391 (13%)	404 (13%)	444 (16%)	285 (10%)	110 (5%)	177 (7%)	304 (11%)	202 (8%)
PC + ABS	645 (22%)	708 (23%)	598 (22%)	619 (22%)	414 (17%)	702 (29%)	250 (9%)	241 (9%)
Other Plastic	145 (5%)	57 (2%)	89 (3%)	118 (4%)	178 (7%)	107 (4%)	137 (5%)	190 (7%)
Battery Cell	369 (12%)	344 (11%)	362 (13%)	359 (13%)	275 (11%)	265 (11%)	413 (16%)	407 (15%)
PWB Material	396 (13%)	474 (16%)	351 (13%)	393 (14%)	357 (15%)	337 (14%)	338 (13%)	361 (14%)
LCD Materials	566 (19%)	598 (20%)	504 (19%)	539 (19%)	364 (15%)	442 (18%)	431 (16%)	425 (16%)
Others	87 (3%)	55 (2%)	49 (2%)	26 (1%)	81 (3%)	64 (3%)	64 (2%)	61 (2%)
Total	2,988	3,046	2,707	2,815	2,437	2,449	2,645	2,641

Table A- 1: Bill of materials data for disassembled Dell Latitude laptop computers (grams)

Screen Size Model	12.1 2530P 2008	14.1 6930P 2008	17 8730P 2008
Aluminum	210 (12%)	343 (14%)	563 (16%)
Magnesium	214 (12%)	337 (14%)	494 (14%)
Copper	36 (2%)	29 (1%)	74 (2%)
Ferrous	250 (14%)	278 (12%)	326 (9%)
PC + ABS	305 (18%)	265 (11%)	287 (8%)
Other Plastic	- (0%)	118 (5%)	240 (7%)
Battery Cell	274 (16%)	274 (11%)	374 (11%)
PWB Material	211 (12%)	337 (14%)	373 (11%)
LCD Materials	223 (13%)	413 (17%)	684 (20%)
Others	18 (1%)	21 (1%)	30 (1%)
Total	1,742	2,414	3,445

Table A- 2: Bill of materials data for disassembled Hewlett Packard EliteBook laptop computers (grams)

Benchmarking against recent trends

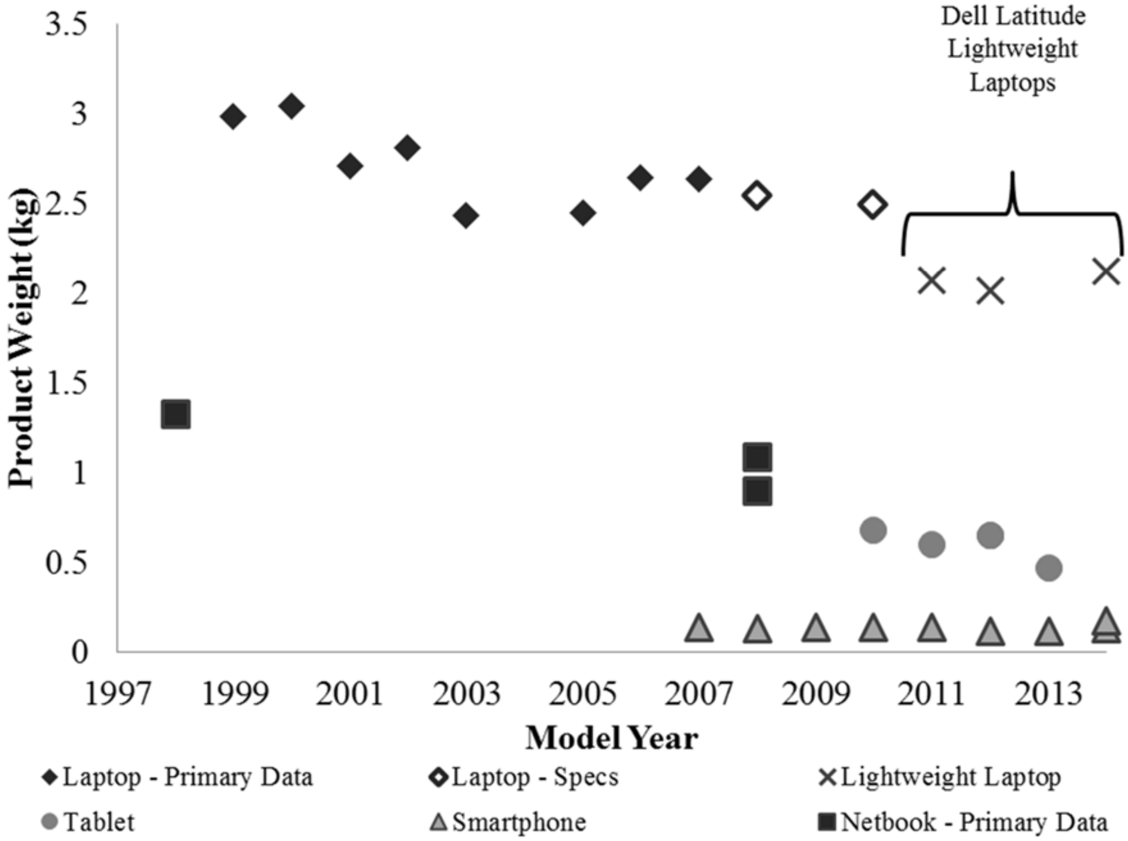

Figure A- 1: Results from benchmarking case study against recent trends in product characteristics shows that dematerialization can be achieved by "lightweighting" which is achieved through the removal of a standard functionality (such as the optical drive), or by a switch to a smaller product. These results support the conclusion that significant product level dematerialization is only achieved through a technological leap to a smaller product or by the removal of functionality. Data sources for each product beyond the primary Dell and HP laptop set are described in tables below.

Release Year	Product	Weight (kg)	% change over previous year*
1999	Dell Latitude Cpi R-Series PPX	2.99	N/A
2000	DELL CPX H5005T PPX	3.05	2%
2001	Dell Latitude C600	2.71	-11%
2002	Dell Latitude C610	2.81	4%
2003	Dell Latitude D600	2.44	-13%
2005	Dell Latitude D610	2.45	1%
2006	Dell Latitude D620	2.64	8%
2007	Dell Latitude D630	2.64	0%
2008	Dell Latitude E6400	2.54	-4%
2010	Dell Latitude E6410	2.50	-2%
2011	Dell Latitude E6420	2.07	17%
2012	Dell Latitude E6430	2.01	3%
2014	Dell Latitude E6440	2.12	-5%

Table A- 3: Product mass data as determined by a combination of primary research and manufacturer's specifications showing recent trends in product dematerialization for Dell Latitude business class laptops. Data for 1999 through 2007 is from the case study completed for this study. Data for 2008 through 2014 is from product specifications published by Dell at http://www.dell.com/us/business/p/latitude-laptops?~ck=bt

Release Year	Product	Weight (kg)	% change over previous year*
1998	Sony Vaio PCG-505FX	1.32	N/A
2008	Acer One Aspire	1.09	2%
2008	Asus EEE PC	0.90	3%

Table A- 4: Product mass data determined by primary research showing trends in product dematerialization for a sample of netbook computers. Weight data for netbook computers is from primary research conducted by the authors.

Release Year	Product	Weight (kg)	% change over previous year*
2010	Apple iPad 1st Generation	0.68	N/A
2011	Apple iPad 2nd Generation	0.60	12%
2012	Apple iPad 3rd Generation	0.65	-8%
2012	Apple iPad 4th Generation	0.65	0%
2013	Apple iPad Air	0.47	28%

Table A- 5: Product mass data determined by survey of manufacturer specifications showing recent trends in product dematerialization for Apple iPad tablet computers. Weight data for Apple iPad computers is from Apple technical support for products available at http://support.apple.com/specs/#ipad.

Release Year	Product	Weight (kg)	% change over previous year*
2007	Apple iPhone 1st Generation	0.14	N/A
2008	Apple iPhone 3G	0.13	-1%
2009	Apple iPhone 3GS	0.14	2%
2010	Apple iPhone 4	0.14	1%
2011	Apple iPhone 4S	0.14	2%
2012	Apple iPhone 5	0.11	-20%
2013	Apple iPhone 5C / 5S	0.11	0%
2014	Apple iPhone 6	0.13	15%
2014	Apple iPhone 6 Plus	0.17	33%

Table A- 6: Product mass data determined by survey of manufacturer specifications showing recent trends in product dematerialization for Apple iPhones. Weight data for Apple iPhone is from Apple technical support for products available at http://support.apple.com/specs/#iphone.

Functional Dematerialization

As the case with the bill of materials data and lack of product level dematerialization, the bill of assemblies data (Figure A-2, Tables A-7 and A-8) show relatively little change in the component assembly weight and relative contribution to the overall product. Yet, technological improvements are occurring, such as those described by Moore's Law, suggesting that manufacturers are capitalizing on these technological improvements in order to improve performance within an established form factor.

To this end, several of the component assemblies were analyzed for total mass and other key characteristics to identify trends in functional dematerialization. Product displays assemblies (Figure A-5, Tables A-13 and A-14) shows some dematerialization with display resolution improves. Interestingly, the display assemblies show slight increases in component mass which correspond with improvements in display resolution, followed by periods of continued dematerialization. Battery assemblies (Figure A-3, Tables A-9 and A-10), hard disk drive (HDD) (Figure A-4, Tables A-11 and A-12), silicon characteristics (Figure A-6, Tables A-15 and A-16) and chassis assemblies (Figure A-7, Tables A-17 and A-18) show similar trends in minimal component level dematerialization corresponding to increasing functional capacity or performance.

Analysis of the silicon characteristics (Figure A-6, Tables A-15 and A-16) indicate that total die area on the board roughly follows motherboard area over time and for increasing laptop size, with a correlation coefficient of 0.65 for all 14.1" laptops motherboards. Figure A-6 and Tables A-15 and A-16 show trends in total motherboard area and the silicon die present on each laptop's motherboard, not including the processor or DRAM. A step increase was observed between model year 2000 and 2001 as the main board became larger and a separate sound and graphics card was added. This increase correlates with a shift from available CD-ROM to DVD-ROM modules, and we suggest that the materialization of the boards was required to support the new function of the product. Additionally, we observed that in some cases of year-to-year comparisons (1999 and 2000, 2001 and 2002, 2006 and 2007) the board shape stayed the same from one year to the next, but the amount of silicon die per board stepped down from one year to the next. While the motherboard area and the die area-to-motherboard area ratio are roughly constant for a typical product over time, averaging 35,000 mm^2 and 0.015 respectively the results show significant variability around these averages. Most notably, as the laptop size increases to 17.1”, the additional size enabled use of a much larger motherboard, with significantly higher die area, presumably to provide functional improvement.

Bill of Component Assemblies

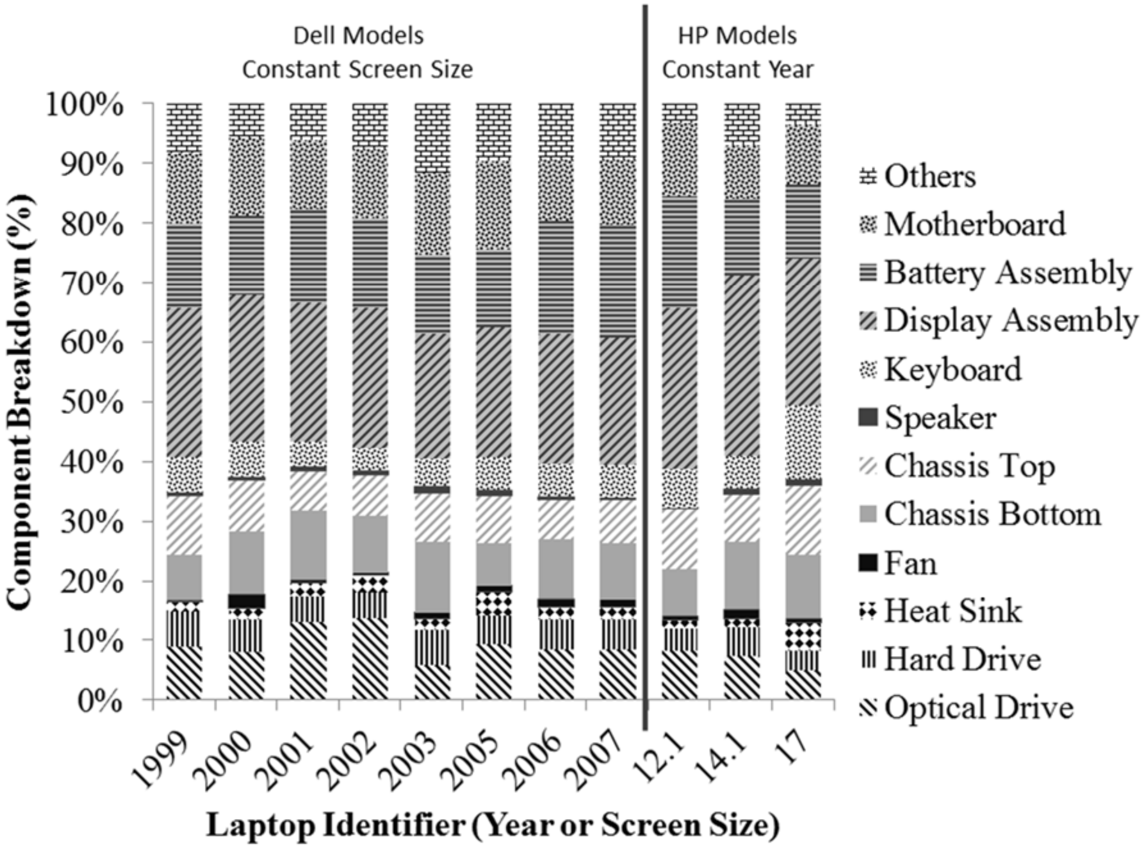

Figure A- 2: Laptop subassembly composition shows relatively constant percentage contributions by each component to the overall product mass, suggesting that technological improvements realized by manufacturers are being traded for improved performance within an established form factor These results also suggest that the proposed representative BOM may be adjusted for more accurate results when estimating laptop computers with magnesium or aluminum chassis (casings) vice plastic, or when estimating newer "thin" or "lightweight" laptop computers, which are manufactured without a standard optical drive.

Year	1999	2000	2001	2002	2003	2005	2006	2007
Model	CPiR	CPX H5005T PPX	C600	C510/ 610	D600	D610	D620	D630
Screen Size	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1
Battery Assembly	426 (14%)	406 (13%)	424 (16%)	426 (15%)	319 (13%)	319 (13%)	505 (19%)	500 (19%)
Chassis Bottom	231 (8%)	321 (11%)	312 (12%)	267 (9%)	290 (12%)	175 (7%)	264 (10%)	252 (10%)
Chassis Top	297 (10%)	258 (8%)	184 (7%)	194 (7%)	200 (8%)	196 (8%)	179 (7%)	191 (7%)
Display Assembly	747 (25%)	752 (25%)	629 (23%)	657 (23%)	514 (21%)	536 (22%)	577 (22%)	561 (21%)
Optical Drive	264 (9%)	247 (8%)	355 (13%)	388 (14%)	144 (6%)	231 (9%)	226 (9%)	225 (9%)
Fan	8 (<1%)	77 (3%)	15 (1%)	12 (<1%)	23 (1%)	23 (1%)	36 (1%)	32 (1%)
Hard Drive	176 (6%)	161 (5%)	115 (4%)	121 (4%)	140 (6%)	118 (5%)	128 (5%)	131 (5%)
Heat Sink	52 (2%)	59 (2%)	62 (2%)	81 (3%)	49 (2%)	98 (4%)	58 (2%)	55 (2%)
Keyboard	175 (6%)	182 (6%)	114 (4%)	108 (4%)	112 (5%)	134 (5%)	142 (5%)	146 (6%)
Motherboard	350 (12%)	393 (13%)	311 (11%)	322 (11%)	335 (14%)	362 (15%)	270 (10%)	288 (11%)
Speaker	16 (1%)	16 (1%)	20 (1%)	22 (1%)	28 (1%)	21 (1%)	12 (<1%)	12 (<1%)
Others	246 (8%)	176 (6%)	168 (6%)	218 (8%)	284 (12%)	235 (10%)	247 (9%)	248 (9%)
Total	2,988	3,046	2,707	2,815	2,437	2,449	2,645	2,641

Table A- 7: Bill of component assemblies for disassembled Dell Latitude laptop computers (grams)

Screen Size **Model**	**12.1** **2530P** **2008**	**14.1** **6930P** **2008**	**17** **8730P** **2008**
Battery Assembly	**324** **(19%)**	**315** **(13%)**	**430** **(12%)**
Chassis Bottom	**139** **(8%)**	**277** **(11%)**	**370** **(11%)**
Chassis Top	**173** **(10%)**	**191** **(8%)**	**400** **(12%)**
Display Assembly	**473** **(27%)**	**730** **(30%)**	**846** **(25%)**
Optical Drive	**145** **(8%)**	**176** **(7%)**	**174** **(5%)**
Fan	**12** **(1%)**	**35** **(1%)**	**27** **(1%)**
Hard Drive	**63** **(4%)**	**117** **(5%)**	**109** **(3%)**
Heat Sink	**26** **(2%)**	**37** **(2%)**	**161** **(5%)**
Keyboard	**111** **(6%)**	**132** **(5%)**	**424** **(12%)**
Motherboard	**215** **(12%)**	**212** **(9%)**	**345** **(10%)**
Speaker	**5** **(<1%)**	**22** **(1%)**	**37** **(1%)**
Others	**56** **(3%)**	**170** **(7%)**	**122** **(4%)**
Total	**1,742**	**2,414**	**3,445**

Table A- 8: Bill of component assemblies for disassembled Hewlett Packard EliteBook laptop computers (grams)

Summary of Battery Characteristics

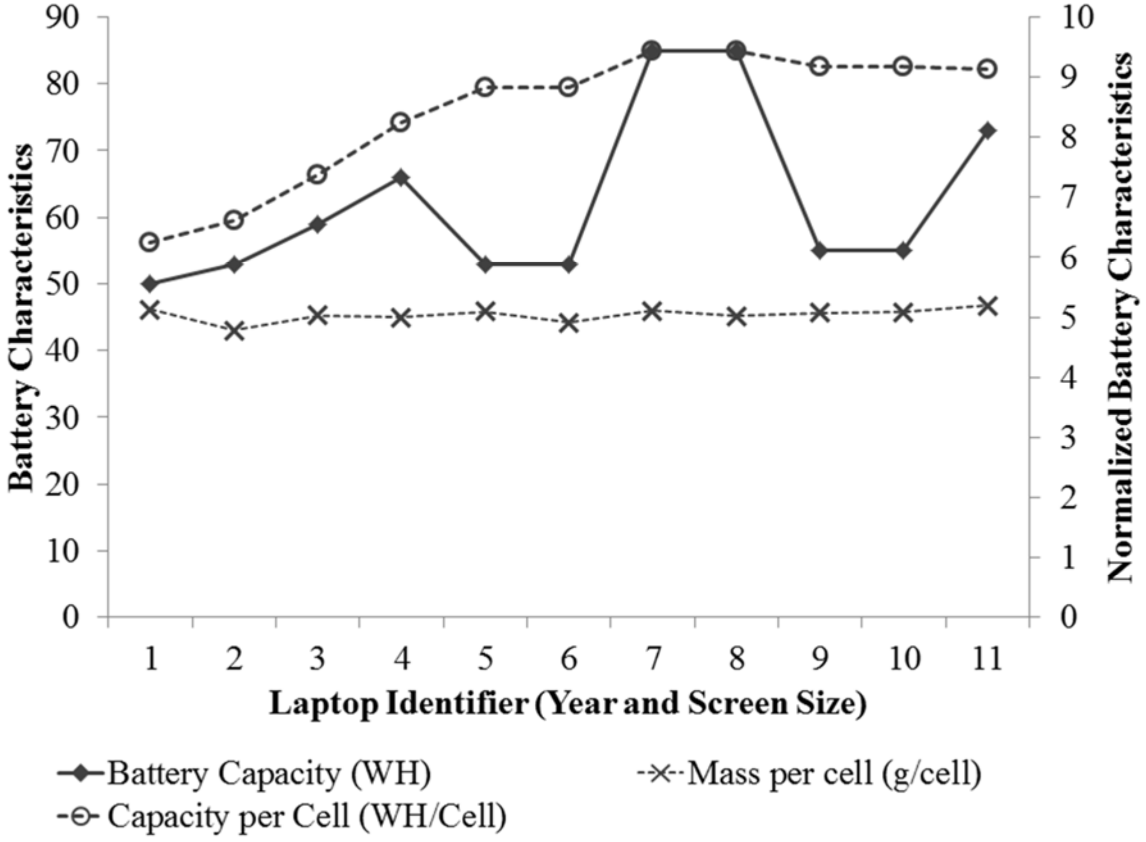

Figure A- 3: Summary of battery assembly characteristics showing that dematerialization within an established form factor is occurring.

Year	**1999**	**2000**	**2001**	**2002**	**2003**	**2005**	**2006**	**2007**
Battery Assembly (g)	426	406	424	426	319	319	505	500
Assembly Contribution (%)	14%	13%	16%	15%	13%	13%	19%	19%
Battery Cell (g)	369	344	362	359	275	265	413	407
Cell Contribution (%)	12%	11%	13%	13%	11%	11%	16%	15%
Mass per cell (g/cell)	46	43	45	45	46	44	46	45
Battery Capacity (WH)	50	53	59	66	53	53	85	85
Capacity per Cell (WH/Cell)	6.25	6.63	7.38	8.25	8.83	8.83	9.44	9.44
Mass per Capacity (g/WH)	7.37	6.48	6.13	5.45	5.19	5.00	4.86	4.78

Table A- 9: Summary of battery characteristics for the disassembled Dell laptop computers. Battery capacity was determined through a survey of Dell Latitude technical specifications available at http://www.dell.com/us/business/p/latitude-laptops?~ck=bt

Screen Size	**12.1**	**14.1**	**17**
Battery Assembly (g)	324	315	430
Assembly Contribution (%)	19%	13%	12%
Battery Cell (g)	274	274	374
Cell Contribution (%)	16%	11%	11%
Mass per cell (g/cell)	46	46	47
Battery Capacity (WH)	55	55	73
Capacity per Cell (WH/Cell)	9.17	9.17	9.13
Mass per Capacity (g/WH)	4.98	4.98	5.12

Table A- 10: Summary of battery characteristics for the disassembled Hewlett Packard computers. Battery capacity was determined through a survey of HP EliteBook technical specifications available at the HP Support Center at http://h20565.www2.hp.com/portal/site/hpsc?ac.admitted=1419102363080.876444892.492883150

Summary of Hard Disk Drive Characteristics

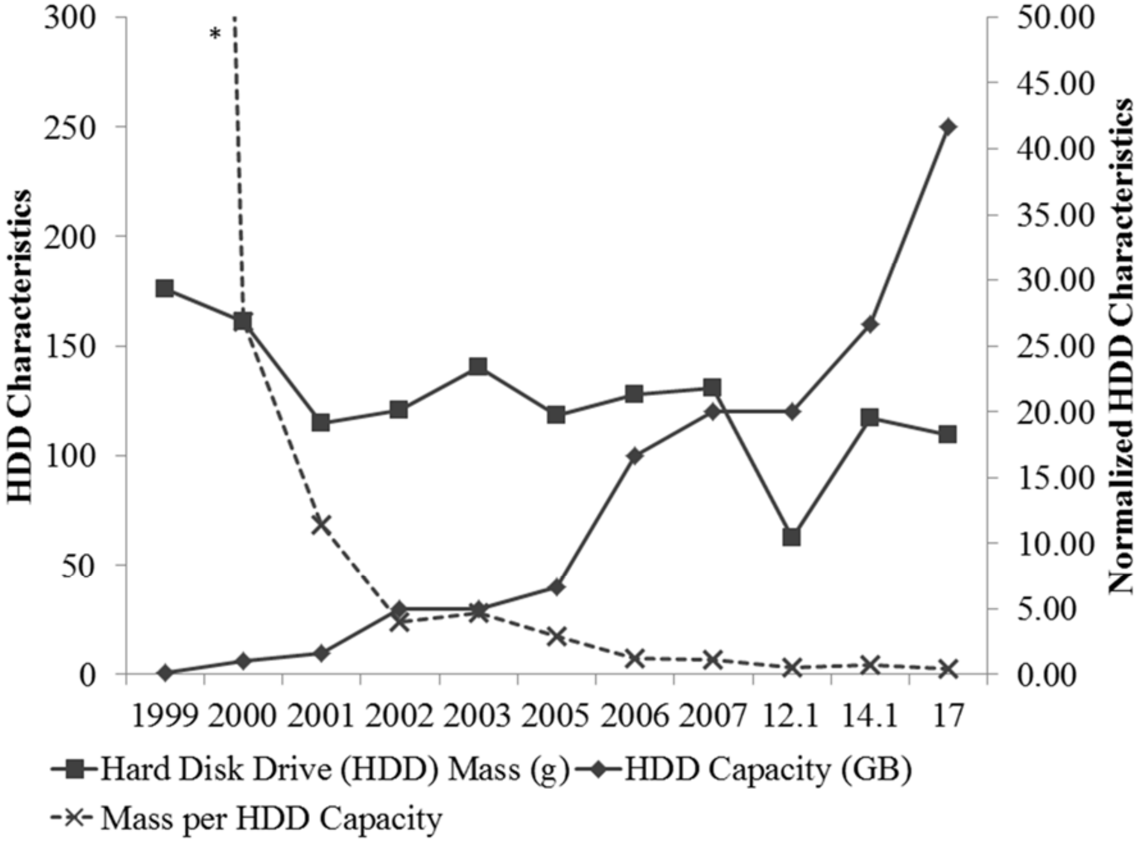

Figure A- 4: Analysis of the hard drive disk (HDD) assembly shows that the hard drive component shows some dematerialization, while at the same time increasing capacity. As a result, the capacity per gram has increased in the longitudinal study. *The axis for normalized HDD characteristics was truncated for visibility – the 1999 value for mass per HDD capacity is 234 g/GB.

Year	1999	2000	2001	2002	2003	2005	2006	2007
HDD Mass (g)	176	161	115	121	140	118	128	131
HDD Contribution (%)	6%	5%	4%	4%	6%	5%	5%	5%
HDD Capacity	750MB	6GB	10GB	30GB	30GB	40GB	100GB	120GB
Mass per HDD Capacity	234.32	26.82	11.46	4.02	4.67	2.96	1.28	1.09

Table A- 11: Summary of hard disk drive (HDD) characteristics of the disassembled Dell laptop computers. HDD Capacity is listed as labeled on the disassembled drive.

Screen Size	12.1	14.1	17
HDD Mass (g)	63	117	109
HDD Contribution (%)	4%	5%	3%
HDD Capacity	120GB	160 GB	250GB
Mass per HDD Capacity	0.52	0.73	0.44

Table A- 12: Summary of HDD characteristics of the disassembled Hewlett Packard laptop computers. HDD Capacity is listed as labeled on the disassembled drive.

Summary of display assembly characteristics

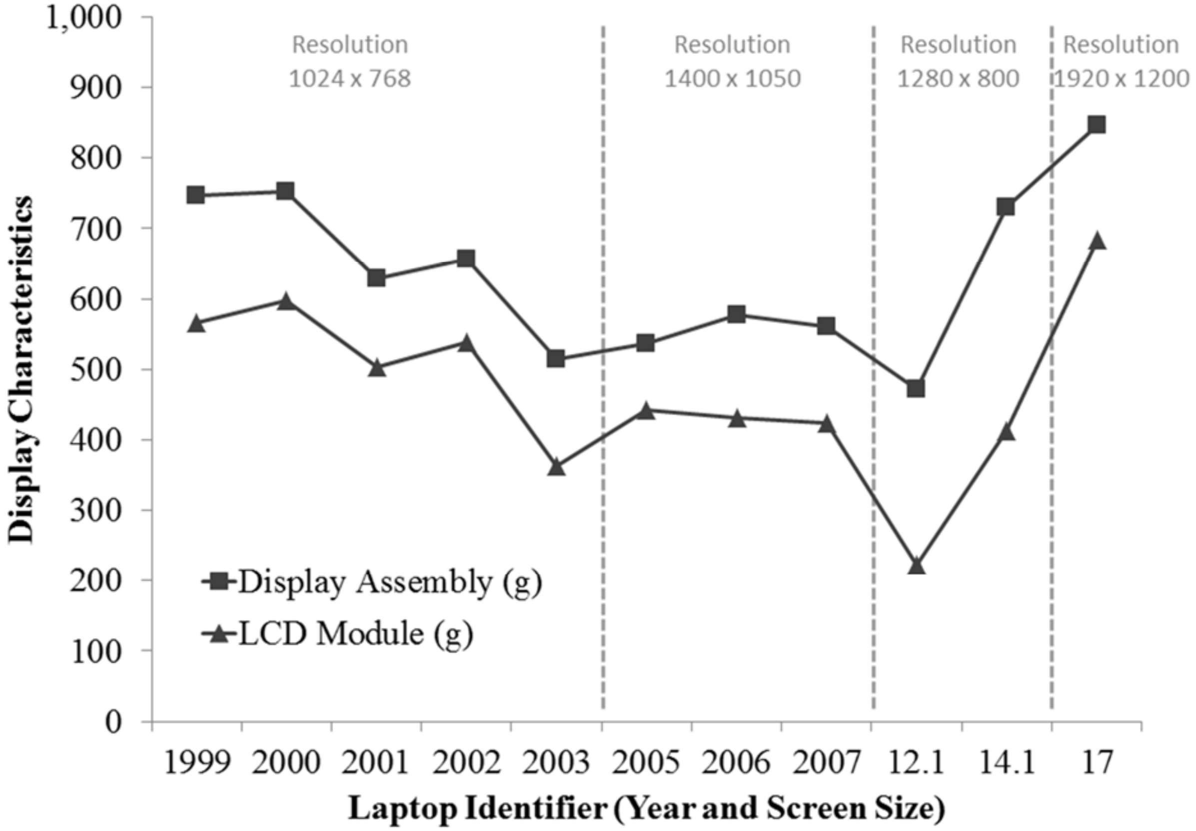

Figure A- 5: Display characteristics show functional dematerialization as LCD modules decrease in mass for the same display resolution, which is shown in light gray at the top of the figure. Mass increases when resolution increases with the 2005 model, with the dematerialization trend continuing in following years. Logically, there is a clear display dematerialization from the 17 inch to 14.1 inch to 12.1 inch screen.

Year	1999	2000	2001	2002	2003	2005	2006	2007
Display Assembly (g)	747	752	629	657	514	536	577	561
LCD Module (g)	566	598	504	539	364	442	431	425
Display Resolution	1024 x 768	1024 x 768	1024 x 768	1024 x 768	1024 x 768	1400 x 1050	1440 x 900	1440 x 900

Table A- 13: Summary of display assembly characteristics of the disassembled Dell laptop computers. Display resolution was determined through a survey of Dell Latitude technical specifications available at http://www.dell.com/us/business/p/latitude-laptops?~ck=bt

Screen Size	12.1	14.1	17
Display Assembly (g)	473	730	846
LCD Module (g)	223	413	684
Display Resolution	1280 x 800	1280 x 800	1920 x 1200

Table A- 14: Summary of display assembly characteristics of the disassembled 2008 Hewlett Packard laptop computers. Display resolution was determined through a survey of HP EliteBook technical specifications available at the HP Support Center at http://h20565.www2.hp.com/portal/site/hpsc?ac.admitted=1419102363080.876444892.492883150

Summary of silicon die area characteristics

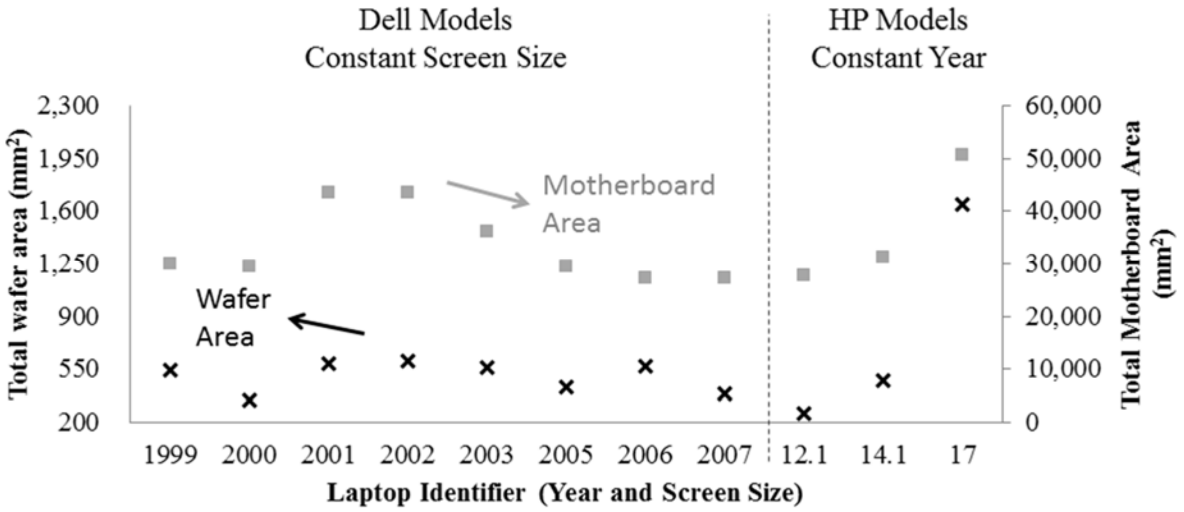

Figure A- 6: Total wafer area on each motherboard (left axis) not including CPU or DRAM, compared with total motherboard area (right axis) shows a correlation factor of 0.65 when considering the correlation between the total motherboard area and inner wafer area on the 14-inch motherboards.

Year	1999	2000	2001	2002	2003	2005	2006	2007
Total area of mainboard PCB (mm^2)	29,948	29,456	43,400	43,400	36,055	29,569	27,243	27,243
Total area of IC outer packaging (mm^2) on mainboard	3,920	4,402	5,404	5,064	3,274	2,997	3,088	3,028
Total area of IC silicon wafer (mm^2) on mainboard	544	343	589	606	559	432	568	390
Total area of processor (mm^2)	170	841	88	86	80	88	147	154
Total area of memory (mm^2)	256	1,856	1,660	1,484	1,024	1,596	1,320	2,136

Table A- 15: Summary of silicon characteristics for motherboard, processor and memory for the disassembled Dell laptop computers

Screen Size	12.1	14.1	17
Total area of mainboard PCB (mm^2)	31,840	31,323	50,690
Total area of IC outer packaging (mm^2) on mainboard	1,766	3,483	13,032
Total area of IC silicon wafer (mm^2) on mainboard	262	477	1,650
Total area of processor (mm^2)	100	117	113
Total area of memory (mm^2)	2,136	2,736	Not Available

Table A- 16: Summary of silicon characteristics for motherboard, processor and memory for the disassembled Hewlett Packard laptop computers

Summary of chassis assembly characteristics

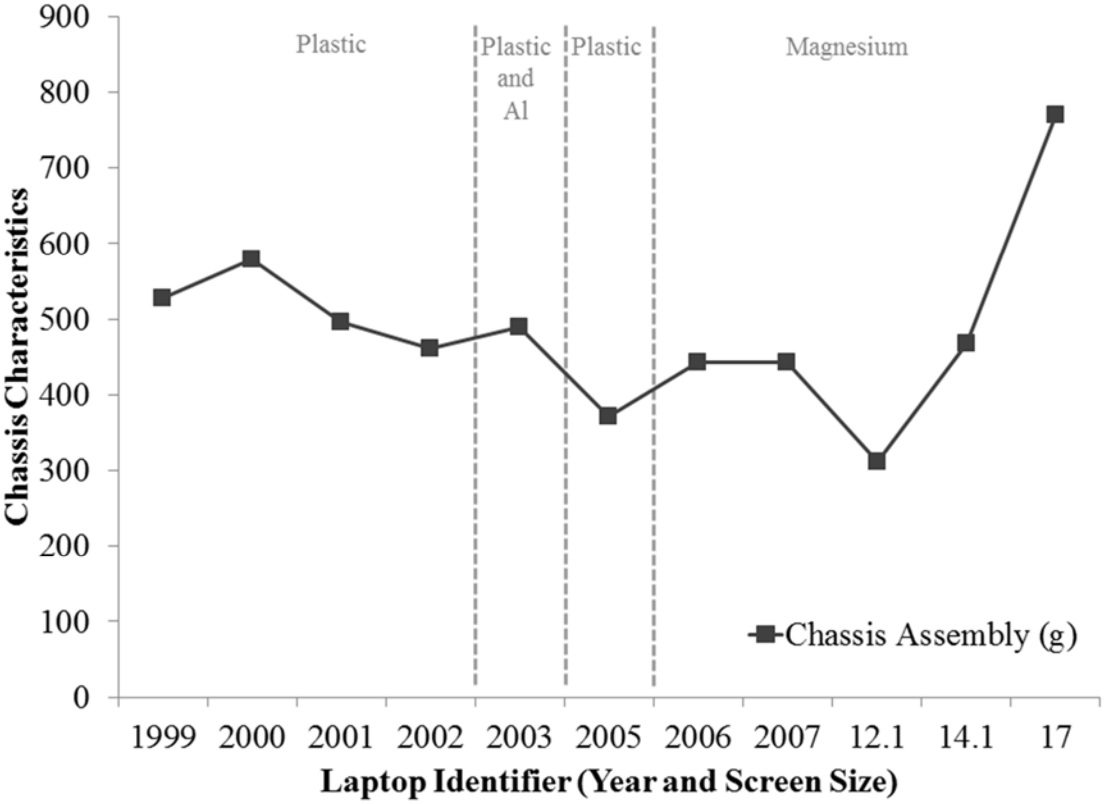

Figure A- 7: Analysis of the chassis assembly shows that the chassis shows some dematerialization, however the shift from plastic to magnesium result in significant chassis dematerialization. As expected, chassis dematerialization occurs as the result of a shift from the 17 to 14.1 to 12.1 inch laptop.

Year	1999	2000	2001	2002	2003	2005	2006	2007
Chassis Material	P	P	P	P	P / Al	P	Mg	Mg
Chassis Mass (g)	528	578	496	461	490	372	443	443
Chassis Contribution (%)	18%	19%	18%	16%	20%	15%	17%	17%

Table A- 17: Summary of chassis characteristics of disassembled 14.1 inch Dell laptop computers. P indicates that the chassis material is plastic, Al indicates aluminum and Mg indicates magnesium.

Screen Size	12.1	14.1	17
Chassis Material	Mg	Mg	Mg
Chassis Mass (g)	312	468	770
Chassis Contribution (%)	18%	19%	22%

Table A- 18: Summary of chassis characteristics of disassembled 2008 Hewlett Packard laptop computers. Mg indicates that the chassis material is magnesium.

Motherboard Analysis and Estimation

The motherboards included in the dataset represented a wide variety of chip types and sizes. As shown in the main text, figure 7, the distribution of combinations of silicon die area to packaging area shows no obvious trends and R-squared value for the larger figure is relatively low at 0.3995. Further analysis shows that the most common chip sizes are those equal to 20 mm^2 and those 100 mm^2 or larger (Figure A-8). While the 20 mm^2 chips represented the most frequently occurring chip size, those chips represent no more than approximately 1/3 of the total silicon die area, and in some cases, less than 10%. Chips at least 100 mm^2 or larger, on the other hand, represent anywhere from approximately 25% to 65% of the total silicon die area (Figure A-9).

After disassembly, motherboard area is one of the most easily measured characteristics, followed by counting the number of chips present on the board then measuring the outer packaging area of the IC chips. Measurement of the inner silicon die area is difficult because of the necessity to remove the outer packaging, which is time consuming and destructive, or measure the inner area with expensive x-ray equipment.

Based on chip and associated silicon die characteristics, as well as ease of measurement of specific motherboard and chip characteristics, several methods of varying complexity were developed for estimating silicon die area. Method 1 was based upon average silicon die area per chip, method 2 was based upon the ratio of silicon to motherboard area, method 3 was based upon the ratio between silicon die area and packaging area, and method 4 used a combination of measuring and estimating using methods 1 – 3. In each method, the 14.1 inch boards were used as the training set to develop and calculate each estimation using the methods described, and any silicon dies that are unpackaged are assumed to be directly measured rather than estimated.

Following estimation, the methods were evaluated and ranked using RMS error. The full list of method descriptions and the associated RMS errors, ranked smallest to largest error, are shown in Table A-19. A summary of the results of each estimation method are shown in Tables A-20, A-21, A-22 and A-23.

Summary of chip distributions and contributions

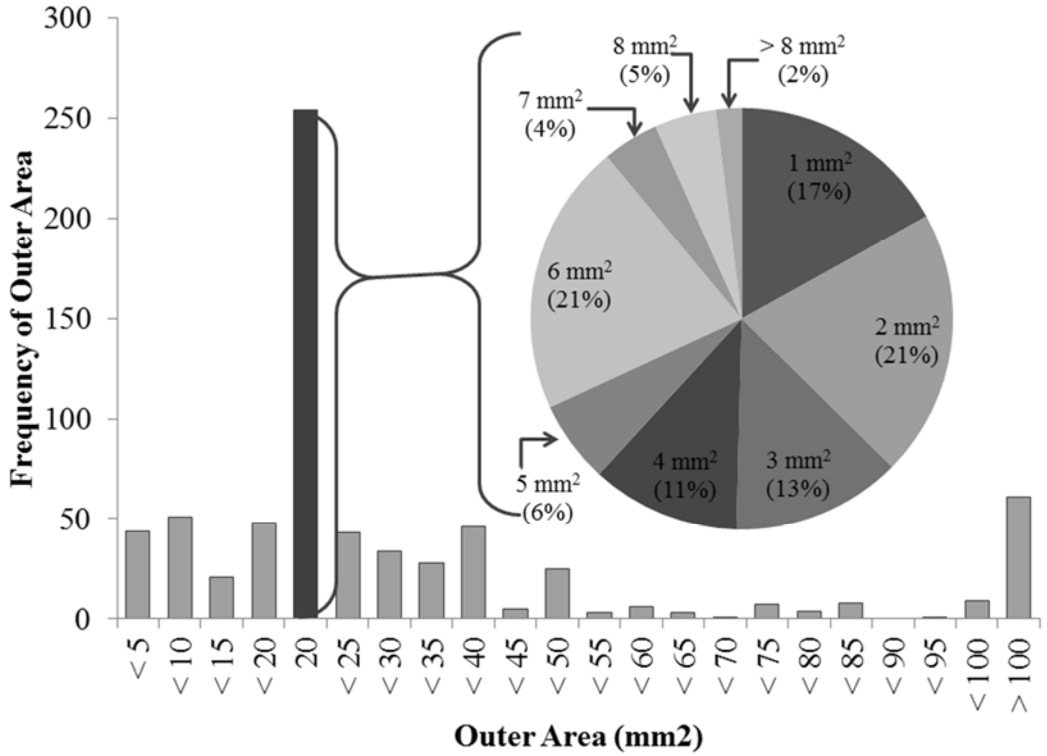

Figure A- 8: Histogram of all semiconductor chips on all boards shows a concentration of chips with outer packaging area of 20 mm^2 (column chart), while the pie chart shows that the inner wafer areas appearing in the 20 mm^2 chips are more evenly distributed.

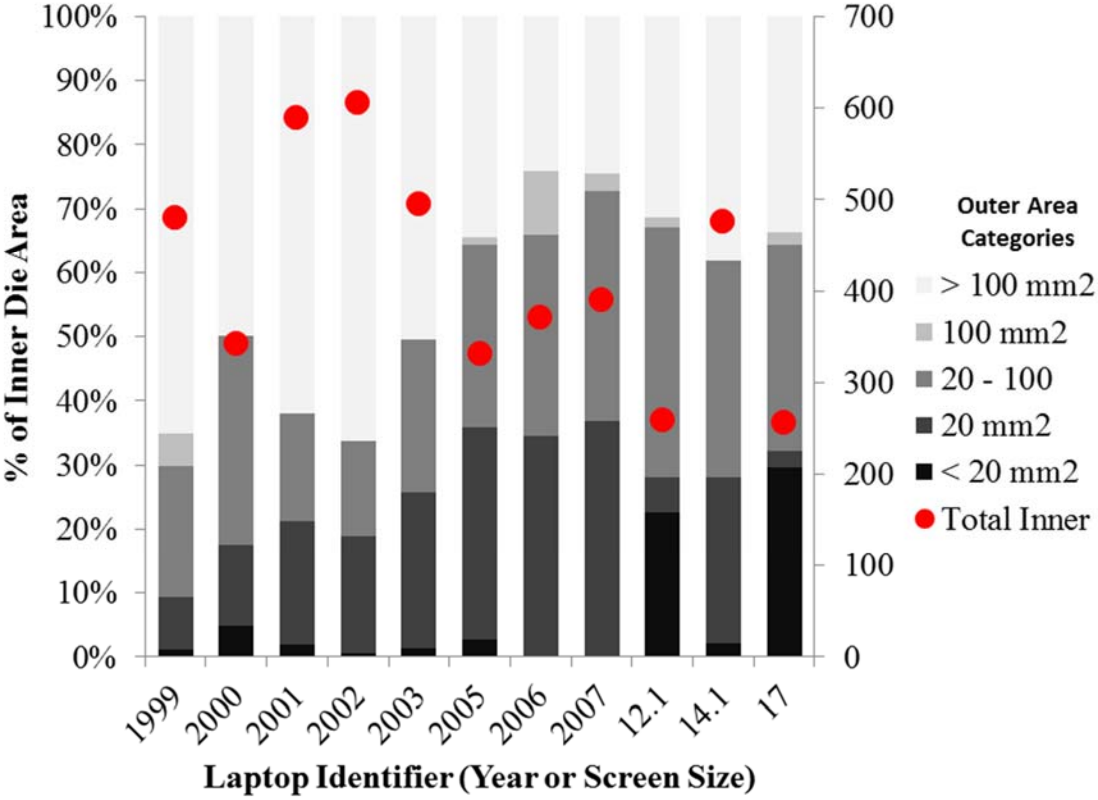

Figure A- 9: Percentage of inner die area covered by each size of semiconductor outer packaging (left axis) and the total wafer area on each board (red circle on right axis).

Summary of silicon estimation results and rankings

	Method	**RMS Error**
4b	Estimate greater than 100mm^2, estimate contribution by other chips	76.8
1c	Average area per chip for chips smaller than 20 mm^2, chips equal to 20 mm^2, and chips larger than 20 mm^2	80.5
1b	Average area per chip for 20 mm^2 chips and average area per chip for non 20 mm^2 chips	85.6
4d	Estimate greater than 15 mm one dimension, estimate contribution by other chips	85.9
1d	Average area per chip for chips smaller than 20 mm^2, chips equal to 20 mm^2, chips between 20 and 100 mm^2 and chips larger than 100 mm^2	88.4
1a	Average area per chip of all chips on 14.1 inch boards	95.6
3b	Average of (Sum of silicon on board / Sum of packaging on board) for 14.1 Boards	97.6
4c	Measure greater than 15 mm one dimension, estimate contribution by other chips	113.8
4a	Measure greater than 100mm^2, estimate contribution by other chips	115.3
2	Ratio of silicon die to motherboard area	123.1
4h	Estimate greater than 15 mm one dimension, estimate contribution by 20 mm^2 chips, estimate contribution by other chips	130.6
4g	Measure greater than 15 mm one dimension, estimate contribution by 20 mm^2 chips, estimate contribution by other chips	152.5
3c	Average ratio of silicon die to package for chips smaller than 20 mm^2, equal to 20 mm^2, greater than 20 mm^2 for 14.1 inch boards	153.8
4e	Measure greater than 100mm^2, estimate contribution by 20 mm^2 chips, estimate contribution by other chips	165.2
4f	Estimate contribution by greater than 100mm^2, estimate contribution by 20 mm^2 chips, estimate contribution by other chips	165.2
3a	Average of board averages ratio silicon die to package for 14.1 inch boards	197.1

Table A- 19: Summary of RMS Error for estimation methods. All methods begin with measuring the actual area of any unpackaged chips. All variations of Method 4 estimate area based on the average die area per chip for the selection of chips indicated.

Year		1999	2000	2001	2002	2003	2005	2006	2007	2008
	Actual Area	544	343	589	606	559	432	568	390	477
1a	Average area per chip of all chips on 14.1 inch boards	400	406	616	445	509	521	666	484	460
1b	Average area per chip for 20 mm^2 chips and average area per chip for non 20 mm^2 chips	446	461	630	433	490	515	619	421	471
1c	Average area per chip for chips smaller than 20 mm^2, chips equal to 20 mm^2, and chips larger than 20 mm^2	480	436	565	457	488	513	661	462	444
1d	Average area per chip for chips smaller than 20 mm^2, chips equal to 20 mm^2, chips between 20 and 100 mm^2 and chips larger than 100 mm^2	460	416	545	535	528	558	656	464	378

Table A- 20: Summary of estimation methods and results for Method 1 - use of average die area per chip, based on the 14.1 inch motherboard training set. All variations of Method 1 include the direct measurement of any unpackaged chips. Average die area per chip of all chips on 14.1 inch boards is 7.8 mm^2. Average die area per chip for all chips with packaging area smaller than 20 mm^2 is 1.4 mm^2. Average die area per chip for all chips with packaging area equal to 20 mm^2 is 3.8 mm^2. Average die area per chip for all chips with packaging area larger than 20 mm^2 is 13.4 mm^2. Average die area per chip for all chips with packaging area that is not 20 mm^2 is 11.4 mm^2. Average die area per chip for all chips with packaging area that is between 20 mm^2 and 100 mm^2 is 5.9 mm^2. Average die area per chip for chips with packaging area equal to or greater than 100 mm^2 is 36.1 mm^2.

Year		1999	2000	2001	2002	2003	2005	2006	2007	2008
	Actual Area	544	343	589	606	559	432	568	390	477
2	Ratio of silicon die to motherboard area	410	403	594	594	494	405	373	373	429

Table A- 21: Summary of estimation results for Method 2 - use of silicon area to motherboard ratio. The average ratio of silicon die area to motherboard area based on the 14.1 inch motherboards is 0.014.

Year		1999	2000	2001	2002	2003	2005	2006	2007	2008
	Actual Area	544	343	589	606	559	432	568	390	477
3a	Average of board averages ratio silicon die to package for 14.1 inch boards	737	755	926	844	615	597	676	481	598
3b	Average of (Sum of silicon on board / Sum of packaging on board) for 14.1 Boards	547	543	665	606	460	457	542	346	430
3c	Average ratio of silicon die to package for chips smaller than 20 mm^2, equal to 20 mm^2, greater than 20 mm^2 for 14.1 inch boards	644	656	814	735	553	542	626	432	529

Table A- 22: Summary of estimation methods and results for Method 3 - use of silicon die area to packaging area ratios. All variations of Method 3 include measurement of the actual dimensions of any unpackaged chips. Average of board averages of silicon die area to packaging area ratios for all chips on boards is 0.172. Average of board ratios of total silicon area to total packaging area is 0.126. Average silicon die area to packaging area ratio for chips with packaging area smaller than 20 mm^2 is 0.217. Average silicon die area to packaging area ratio for chips with packaging area equal to 20 mm^2 is 0.178. Average silicon die area to packaging area ratio for chips with packaging area greater than 20 mm^2 is 0.145.

Year		1999	2000	2001	2002	2003	2005	2006	2007	2008
	Actual Area	544	343	589	606	559	432	568	390	477
4a	Measure greater than 100mm^2, estimate contribution by other chips	632	460	783	662	585	486	605	391	504
4b	Estimate greater than 100mm^2, estimate contribution by other chips	509	503	668	580	585	582	693	499	465
4c	Measure greater than 15 mm one dimension, estimate contribution by other chips	615	443	770	641	454	484	570	383	495
4d	Estimate greater than 15 mm one dimension, estimate contribution by other chips	516	510	646	642	563	623	595	401	423
4e	Measure greater than 100mm^2, estimate contribution by 20 mm^2 chips, estimate contribution by other chips	714	563	915	733	660	564	676	459	607
4f	Estimate contribution by greater than 100mm^2, estimate contribution by 20 mm^2 chips, estimate contribution by other chips	591	607	800	652	660	660	764	567	569
4g	Measure greater than 15 mm one dimension, estimate contribution by 20 mm^2 chips, estimate contribution by other chips	701	550	910	712	536	563	655	465	606
4h	Estimate greater than 15 mm one dimension, estimate contribution by 20 mm^2 chips, estimate contribution by other chips	601	617	786	714	645	702	681	483	534

Table A- 23: Summary of estimation methods and results for Method 4 – combination of measuring die area and estimating using the techniques of Method 1. All variations of method 4 include measuring any unpackaged chips. Estimation techniques for the variations of Method 4 use the average die area per chip for the appropriate chip size. Average die area per chip of all chips on 14.1 inch boards is 7.8 mm^2. Average die area per chip for all chips with packaging area smaller than 20 mm^2 is 1.4 mm^2. Average die area per chip for all chips with packaging area equal to 20 mm^2 is 3.8 mm^2. Average die area per chip for all chips with packaging area larger than 20 mm^2 is 13.4 mm^2. Average die area per chip for all chips with packaging area that is not 20 mm^2 is 11.4 mm^2. Average die area per chip for all chips with packaging area that is between 20 mm^2 and 100 mm^2 is 5.9 mm^2. Average die area per chip for chips with packaging area equal to or greater than 100 mm^2 is 36.1 mm^2.

Appendix B

This appendix provides tables of the material composition data for household consumer electronic products included in the analysis presented in Chapter IV, average material composition data used for model inputs, and additional model outputs not included in the main text.

List of Tables

List of Figures

Sales and stock data

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Desktop	0.33	0.36	0.40	0.44	0.49	0.56	0.63	0.72	0.84	0.98	1.11	1.21	1.31	1.41	1.50	1.57	1.63	1.67	1.69	1.69	1.65
Laptop	0.00	0.00	0.01	0.02	0.04	0.05	0.08	0.10	0.12	0.14	0.17	0.19	0.22	0.25	0.29	0.34	0.40	0.45	0.50	0.58	0.59
Tablet	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.15	0.23	0.27
Netbook	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.11
E-Reader	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.05	0.09
LCD Monitor	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.08	0.08	0.10	0.12	0.16	0.23	0.31	0.44	0.60	0.75	0.91	1.00	1.08
CRT Monitor	0.30	0.33	0.37	0.43	0.48	0.55	0.62	0.69	0.79	0.90	0.99	1.04	1.06	1.03	0.98	0.90	0.80	0.69	0.57	0.46	0.35
CRT TV Small	1.85	2.00	2.15	2.30	2.47	2.59	2.70	2.78	2.86	2.96	3.05	3.09	3.17	3.20	3.22	3.18	3.12	2.94	2.72	2.50	2.27
Plasma TV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.07	0.11	0.17	0.22	0.25
LCD TV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.03	0.07	0.16	0.30	0.50	0.73	0.98
DVD	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.13	0.21	0.35	0.50	0.70	0.75	0.82	0.83	0.84	0.80	0.79
VCR	0.63	0.60	0.57	0.56	0.60	0.70	0.83	0.98	1.14	1.35	1.56	1.68	1.79	1.83	1.84	1.82	1.82	1.81	1.80	1.79	1.77
Blu-Ray	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.13	0.23
MP3 Player	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.06	0.06	0.07	0.07	0.11	0.14	0.20	0.33	0.45	0.48	0.50
Gaming Console	0.12	0.14	0.15	0.17	0.19	0.21	0.22	0.24	0.26	0.28	0.29	0.31	0.33	0.34	0.35	0.39	0.41	0.38	0.40	0.44	0.46
Printer	0.15	0.16	0.18	0.21	0.23	0.27	0.32	0.37	0.44	0.53	0.62	0.69	0.77	0.83	0.90	0.96	1.02	1.08	1.12	1.13	1.13
Digital Camera	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.07	0.16	0.24	0.36	0.52	0.69	0.85	1.00	1.13	1.35	1.56	1.76
Digital Camcorder	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.05	0.08	0.10	0.12	0.13	0.14	0.15	0.15	0.17	0.19	0.23	0.27	0.32
Basic Cell	0.06	0.08	0.11	0.17	0.25	0.33	0.38	0.50	0.69	0.90	1.12	1.36	1.61	1.82	2.07	2.34	2.65	2.88	3.02	3.24	3.48
Smart Phone	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.08	0.16	0.26	0.38	0.58	0.80	1.03

Table B-1: U.S. average household stock data

Source: Ryen et al. (2014).

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Desktop	4,553	4,571	4,757	6,251	7,342	9,187	10,762	12,848	15,612	18,954	19,595
Laptop	0	0	888	1,213	1,536	1,711	2,376	2,880	3,076	3,778	4,619
Tablet	0	0	0	0	0	0	0	0	0	0	0
Netbook	0	0	0	0	0	0	0	0	0	0	0
E-Reader	0	0	0	0	0	0	0	0	0	0	0
LCD Monitor	424	720	829	883	1,342	1,424	1,088	455	705	1,358	2,289
CRT Monitor	4,511	5,028	6,431	8,322	8,671	10,673	11,070	12,760	15,636	17,730	17,984
CRT TV	20,808	20,136	21,992	24,634	26,732	25,436	24,582	23,605	25,353	27,658	29,288
Plasma TV	0	0	0	0	0	0	0	0	0	0	0
LCD TV	0	0	0	0	0	0	0	0	0	2	7
DVD	0	0	0	0	0	0	0	315	1,089	4,019	8,499
VCR	11,857	12,714	13,571	14,429	15,286	16,143	17,000	17,000	18,000	23,000	24,000
Blu-Ray	0	0	0	0	0	0	0	0	0	0	0
MP3 Player	0	0	0	0	0	0	0	0	3,802	4,109	4,386
Gaming	21	33	52	82	128	201	316	496	777	1,219	1,913
Printer	2,390	2,400	2,964	3,919	4,661	5,721	7,168	7,797	10,800	13,202	13,760
Digital Camera	0	0	0	0	0	11	12	518	1,545	4,735	10,500
Digital Camcorder	0	0	0	0	0	0	1,900	1,680	2,050	2,740	3,160
Basic Cell	2,577	3,366	5,387	7,873	12,430	14,500	14,794	23,869	32,943	42,017	51,091
Smart Phone	0	0	0	0	0	0	0	0	0	0	0

Table B-2: U.S. sales data (1990 – 2000, sales in thousands)

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Desktop	16,844	16,839	17,740	18,889	18,263	17,001	16,422	14,640	12,629	11,280
Laptop	4,596	5,224	6,628	7,979	9,417	11,664	11,038	11,924	15,375	10,571
Tablet	0	0	0	0	0	0	7,960	9,656	11,870	10,800
Netbook	0	0	0	0	0	0	0	819	4,458	8,098
E-Reader	0	0	0	0	0	100	1,100	1,920	2,920	5,990
LCD Monitor	3,167	5,594	8,663	10,880	15,841	18,508	17,764	19,958	13,051	13,176
CRT Monitor	13,076	11,182	7,564	6,696	3,723	1,673	489	0	0	0
CRT TV	26,157	28,686	25,866	24,780	22,170	16,872	6,298	1,324	476	175
Plasma TV	10	19	205	870	2,084	4,204	5,381	6,150	5,533	4,485
LCD TV	530	172	751	1,842	4,282	10,286	16,069	22,910	26,567	29,205
DVD	12,707	17,090	21,994	20,000	16,148	19,788	15,886	21,276	20,937	18,677
VCR	15,000	14,000	6,000	2,000	1,000	1,000	6	6	5	5
Blu-Ray	0	0	0	0	0	0	3,469	4,561	7,070	11,500
MP3 Player	4,540	4,335	3,100	7,126	24,812	35,949	47,087	33,985	30,119	33,179
Gaming	3,000	8,420	6,320	4,630	6,147	10,387	17,428	16,666	15,333	14,224
Printer	12,841	13,797	14,719	15,456	15,906	16,472	17,718	15,883	14,165	14,126
Digital Camera	9,300	14,900	23,100	28,300	34,800	35,732	40,041	40,400	35,000	29,600
Digital Camcorder	2,740	3,330	4,081	4,344	4,520	4,846	5,171	5,497	5,823	6,148
Basic Cell	60,166	69,240	74,600	85,600	99,500	112,400	117,500	116,400	132,760	141,834
Smart Phone	0	11	2,300	4,500	9,800	14,000	20,700	33,020	40,148	52,000

Table B-3: U.S. Sales data (2001 – 2010, sales in thousands)

	Summary of data sources
Desktop	U.S. sales data from U.S. EPA (2011), adjusted for residential market share (U.S. EPA 2011)
Laptop	U.S. sales data from U.S. EPA (2011), adjusted for netbook and tablet market share (Jeffries 2010), adjusted for residential market share (U.S. EPA 2011)
Tablet	U.S. sales data from U.S. EPA (2011), adjusted for laptop and netbook market share (Jeffries 2010), adjusted for residential market share (U.S. EPA 2011)
Netbook	U.S. sales data from U.S. EPA (2011), adjusted for laptop and tablet market share (Jeffries 2010), adjusted for residential market share (U.S. EPA 2011)
E-Reader	2006, 2009, 2010 sales data from Das (2011), additional years interpolated
LCD Monitor	U.S. sales data from U.S. EPA (2011), adjusted for residential market share (U.S. EPA 2011), which is assumed to be equal to the residential market share for desktop computers
CRT Monitor	U.S. sales data from U.S. EPA (2011), adjusted for residential market share (U.S. EPA 2011), which is assumed to be equal to the residential market share for desktop computers
CRT TV	U.S. sales data from U.S. EPA (2011), combined small and large CRT television
Plasma TV	U.S. sales data from U.S. EPA (2011), adjusted for market share of LCD versus plasma televisions (CEA, 2011)
LCD TV	U.S. sales data from U.S. EPA (2011), adjusted for market share of LCD versus plasma televisions (CEA, 2011)
DVD	Digital Bits (2007)
VCR	U.S. EPA (2011)
Blu-Ray	CEA 2009, 2010
MP3 Player	Eskelsen et al. (2009)
Gaming	Statista (2015)
Printer	U.S. EPA (2011)
Digital Camera	CIPA (2013)
Digital Camcorder	Eskelsen et al. (2009)
Basic Cell	Eskelsen et al. (2009)
Smart Phone	Eskelsen et al. (2009)

Table B-4: U.S. sales data sources

Year	Number of Households	Source
1990	91,946,280	1
1991	93,183,208	1
1992	94,645,987	1
1993	95,337,831	1
1994	95,955,720	1
1995	97,340,921	1
1996	98,706,019	1
1997	99,883,746	1
1998	101,041,243	1
1999	103,874,000	2
2000	105,480,101	3
2001	106,848,114	4
2002	107,740,595	4
2003	108,633,076	4
2004	109,525,557	4
2005	111,090,617	5
2006	111,617,402	5
2007	112,377,977	5
2008	113,101,329	5
2009	113,616,229	5
2010	114,235,996	5

Table B-5: U.S. households

Sources: (1) U.S. Census Bureau 2015a, (2) U.S. Census Bureau 2015b, (3) U.S. Census Bureau 2015c, (4) Ryen et al. 2014, and (5) U.S. Census Bureau 2016

Material composition data

Material composition data included characterization of bulk materials (e.g., copper, plastics, steel) and composite components (e.g., battery cell, printed circuit board, liquid crystal display (LCD) module), all of which was primarily collected through product disassembly by the authors. Each product, not including power adaptors, was weighed and then disassembled to a level where each piece was comprised of a single material (if feasible). Material composition data for those products that were disassembled by the authors represents data for pieces that were weighed individually on a scale with 1200 gram capacity and 0.1 g resolution. Where primary disassembly was not possible, either due to lack of product availability or safety concerns (e.g., exposure to lead during CRT disassembly), published product data (e.g., Oguchi et al. 2011, Teehan and Kandlikar 2013) was used to establish a representative suite of material compositions for the remaining products. Published data was provided in a variety of formats and selected based on the following order of preference: 1) disaggregated data (including disaggregated metal content) accounting for 100% of the product mass, 2) partially disaggregated data (including aggregated metal content) accounting for 100% of the product mass and 3) partially or wholly disaggregated data accounting for less than 100% of the product mass. The decision making process used to determine whether data would be included is outlined in Figure B-1.

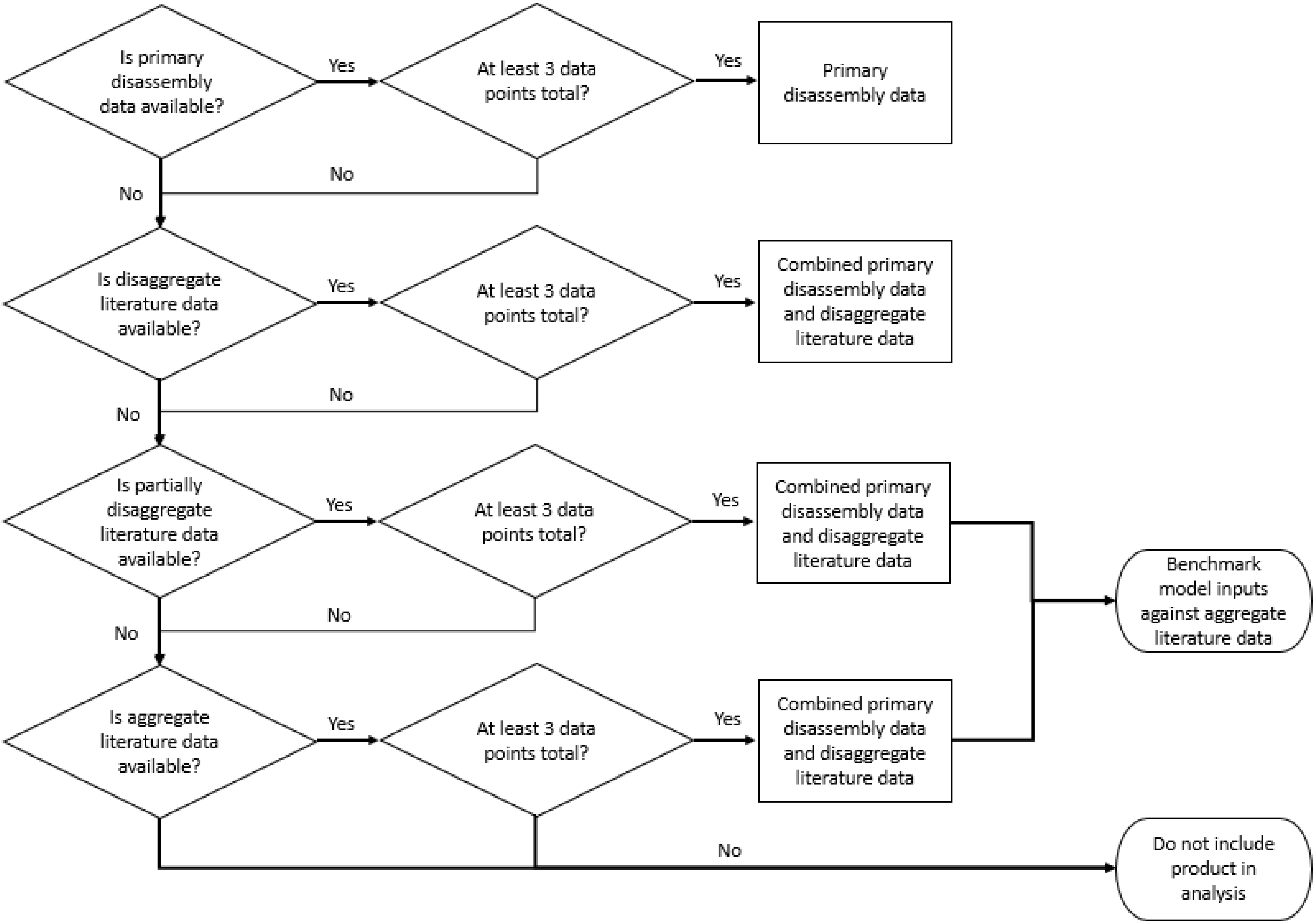

Figure B-1: Decision tree for product material composition data usage

Desktop Computer Material Composition and Weights

Description			ABA Model (1)	(2)	(2)	Average of literature data
Model Year			1997			
Metals	Ferrous	(g)	6355.02	5720	986.15	4354
		(%)	64.0%	65.4%	21.8%	50%
	Aluminum	(g)	1439.29	1230	713.25	1128
		(%)	14.5%	14.1%	15.7%	15%
	Copper	(g)	329.807	181	272	261
		(%)	3.3%	2.1%	6.0%	4%
	Total Metal Content	(g)	8124	7131	1971	5742
		(%)	81.8%	81.6%	43.5%	69.0%
Plastic		(g)	614.905	472	1121.85	736
		(%)	6.2%	5.4%	24.8%	12%
PWB		(g)	1185.52	1137	1141.08	1155
		(%)	11.9%	13.0%	25.2%	17%
Other		(g)	5.316	0	294.85	100
		(%)	0.1%	0.0%	6.5%	2%
Total Weight (g)			**9929.86**	**8740**	**4529.18**	**7733**

Table B-6: Material composition data for desktop computers included in the study.

Sources: (1) Hikwama 2005, (2) Eugster 2007

Laptop Computer Material Composition and Weights

Description			Dell Latitude CPiR 14 inch (2)	Dell CPX H5005T PPX 14 inch (2)	Dell Latitude C600 (2)	Dell Inspiron 4100 14 inch (1)	Dell Latitude C510/610 (2)	Dell Inspiron 5100 14 inch (1)	Dell Latitude D600 14 inch (2)	Dell Latitude D610 14 inch (2)	Dell Latitude D620 14 inch (2)	Dell Latitude D630 14 inch (2)	HP EliteBook 2530P 12 inch (2)	HP EliteBook 6930P 14 inch (2)	HP EliteBook 8730p (2)	Average of disassembly data
Model Year			1999	2000	2001	2001	2002	2003	2003	2005	2006	2007	2008	2008	2008	
Metals	Ferrous	(g)	391.2	403.7	443.6	296.9	284.9	58.6	109.9	176.9	303.7	202.3	250.4	277.9	326.5	271.3
		(%)	13.1%	13.5%	14.8%	9.9%	9.5%	2.0%	3.7%	5.9%	10.2%	6.8%	8.4%	9.3%	10.9%	10.0%
	Aluminum	(g)	367.0	311.3	293.4	369.5	449.1	570.5	543.2	284.9	235.3	306.5	210.3	342.7	563.0	372.8
		(%)	12.3%	10.4%	9.8%	12.4%	15.0%	19.1%	18.2%	9.5%	7.9%	10.3%	7.0%	11.5%	18.8%	13.7%
	Copper	(g)	22.3	95.2	17.8	23.3	25.5	85.4	45.3	70.7	66.6	59.5	36.1	29.2	73.7	50.0
		(%)	0.7%	3.2%	0.6%	0.8%	0.9%	2.9%	1.5%	2.4%	2.2%	2.0%	1.2%	1.0%	2.5%	1.8%
	Magnesium	(g)	0.0	0.0	0.0	0.0	0.0	40.7	69.4	0.0	406.1	388.3	214.4	337.2	493.7	150.0
		(%)	0.0%	0.0%	0.0%	0.0%	0.0%	1.4%	2.3%	0.0%	13.6%	13.0%	7.2%	11.3%	16.5%	5.5%
	Total Metal Content	(g)	780.6	810.1	754.8	689.6	759.6	755.1	767.7	532.5	1011.6	956.6	711.2	987.0	1456.9	844.1
		(%)	26.1%	27.1%	25.3%	23.1%	25.4%	25.3%	25.7%	17.8%	33.9%	32.0%	23.8%	33.0%	48.8%	31.1%
Plastics		(g)	790.6	764.5	686.6	708.2	737.4	932.6	592.3	809.3	387.3	431.3	304.9	382.9	526.9	619.6
		(%)	26.5%	25.6%	23.0%	23.7%	24.7%	31.2%	19.8%	27.1%	13.0%	14.4%	10.2%	12.8%	17.6%	22.8%
PWB		(g)	395.8	474.4	351.2	425.5	392.9	383.2	357.0	336.9	337.8	361.0	211.3	336.9	373.4	364.4
		(%)	13.2%	15.9%	11.8%	14.2%	13.1%	12.8%	11.9%	11.3%	11.3%	12.1%	7.1%	11.3%	12.5%	13.4%
LCD Module		(g)	565.5	597.6	503.6	506.3	539.2	605.7	363.6	441.6	431.0	424.7	223.0	412.5	683.6	484.5
		(%)	18.9%	20.0%	16.9%	16.9%	18.0%	20.3%	12.2%	14.8%	14.4%	14.2%	7.5%	13.8%	22.9%	17.8%
Battery Cell		(g)	368.6	343.7	361.8	359.1	359.5	543.8	274.9	265.2	413.2	406.5	273.9	274.1	373.7	355.2
		(%)	12.3%	11.5%	12.1%	12.0%	12.0%	18.2%	9.2%	8.9%	13.8%	13.6%	9.2%	9.2%	12.5%	13.1%
Other		(g)	86.9	55.5	48.5	47.3	26.0	42.7	81.1	63.5	63.9	60.6	17.6	21.0	30.5	49.6
		(%)	2.9%	1.9%	1.6%	1.6%	0.9%	1.4%	2.7%	2.1%	2.1%	2.0%	0.6%	0.7%	1.0%	1.8%
Total Weight (g)			**2987.9**	**3045.8**	**2706.5**	**2736.1**	**2814.5**	**3263.1**	**2436.7**	**2448.9**	**2644.8**	**2640.7**	**1741.9**	**2414.4**	**3445.1**	**2717.4**

Table B-7: Material composition data for laptop computers included in the study.

Sources (1) disassembled by authors, (2) Kasulaitis et al. 2015

E-Reader and Tablet Material Composition and Weights

Description			Amazon Kindle (1)	RCA REB 1100	Apple iPad 8Gb WIFI 1st Gen	Amazon Kindle 3rd Generation WiFi	Average of available data
Ereader / Tablet			Ereader	Ereader	Tablet	Ereader	
Model Year			2010	2001	2009	2010	
Metals	Ferrous	(g)	24.7	28.6	3.1	1.5	11.1
		(%)	11.1%	4.8%	0.5%	0.7%	2%
	Aluminum	(g)	13.5	0.0	137.2	34.0	57.1
		(%)	6.1%	0.0%	20.0%	15.2%	12%
	Copper	(g)	2.4	30.4	1.1	0.0	10.5
		(%)	1.1%	5.1%	0.2%	0.0%	2%
	Total Metal Content	(g)	40.6	59.0	141.4	35.5	78.6
		(%)	18.3%	9.9%	20.6%	15.9%	15%
Plastic		(g)	70.4	236.6	36.4	76.3	116.4
		(%)	31.7%	39.6%	5.3%	34.1%	26%
PWB		(g)	25.7	82.3	31.1	25.9	46.4
		(%)	11.6%	13.8%	4.5%	11.6%	10%
Battery		(g)	53.1	91.9	129.0	51.0	90.6
		(%)	23.9%	15.4%	18.8%	22.8%	19%
LCD Module		(g)	31.3	125.6	188.0	34.0	115.9
		(%)	14.1%	21.0%	27.3%	15.2%	21%
Other		(g)	1.1	2.0	161.5	1.0	54.8
		(%)	0.5%	0.3%	23.5%	0.4%	8%
Total Weight (g)			**222.2**	**597.4**	**687.4**	**223.7**	**432.69**

Table B-8: Material composition data for electronic book readers (e-readers) and tablets included in the study.

E-Reader and tablet data were combined based on similarity size, function, and material composition.

Sources (1) disassembled by the authors, (2) Kozak 2003, (3) Teehan and Kandlikar 2013

Netbook Computer Material Composition and Weights

Description			Sony Vaio (1)	Acer Aspire (1)	HP Mini 110 - 1030CA (1)	Average of disassembly data
Model Year			1998	2010	2010	
Metals	Ferrous	(g)	120	23	26	56.4
		(%)	9.1%	2.2%	2.5%	4.6%
	Aluminum	(g)	78	124	89	97.0
		(%)	5.9%	11.4%	8.6%	8.6%
	Copper	(g)	12	6	33	16.9
		(%)	0.9%	0.5%	3.2%	1.5%
	Magnesium	(g)	324	0	0	108.1
		(%)	24.7%	0.0%	0.0%	8.2%
	Other metal	(g)	0	4	0	2.1
		(%)	0.0%	0.4%	0.0%	0.1%
	Total Metal Content	(g)	534	157	148	279.9
		(%)	40.6%	14.5%	14.2%	23.1%
Plastic		(g)	115	369	344	276.1
		(%)	8.8%	34.0%	33.0%	25.3%
PWB		(g)	185	187	148	173.1
		(%)	14.1%	17.2%	14.2%	15.1%
Glass		(g)	0	0	0	0.0
		(%)	0.0%	0.0%	0.0%	0.0%
Battery		(g)	102	129	178	136.4
		(%)	7.7%	11.9%	17.1%	12.2%
LCD Module		(g)	342	233	199	257.9
		(%)	26.0%	21.4%	19.1%	22.2%
Other		(g)	37	11	24	24.3
		(%)	2.8%	1.0%	2.3%	2.1%
Total Weight (g)			**1315.4**	**1086.3**	**1041.1**	**1147.6**

Table B-9: Material composition data for netbook computers included in the study.

Source (1) disassembled by the authors

LCD Monitors Material Composition and Weights

Description			Samsung Syncmaster 2243 21.5" (1)	(2)	Average of disaggregate literature data	NEC Multi Sync LCD 1810 XtraView (3)	Mitsubishi LXA565W (3)	Mitsubishi LXA565W (3)	Sony SDM-M81 (3)	Sony CPD-M151 (3)	Sony SOM-X52 (3)	Sony SOM-HJ53 (3)	Average of aggregate literature data
Model Year			2009										
Metals	Ferrous	(g)	1003.5	1771	1387								
		(%)	19.8%	33.5%	26.7%								
	Aluminum	(g)	18	130	74								
		(%)	0.4%	2.5%	1.4%								
	Copper	(g)	455.7	230	343								
		(%)	9.0%	4.4%	6.7%								
	Total Metal Content	(g)	1477	2131	1804	2378	2591	2660	3362	2440	2504	1848	2540
		(%)	29.1%	40.4%	34.8%	46.0%	54.8%	53.2%	48.8%	49.2%	54.7%	51.4%	51.2%
Plastics		(g)	1153	1,981	1567	1,379	1,023	1,010	1,682	1,286	994	804	1168
		(%)	22.7%	37.5%	30.1%	26.7%	21.6%	20.2%	24.4%	25.9%	21.7%	22.4%	23.3%
PWB		(g)	53.4	410	232	598	352	346	66	290	236	243	304
		(%)	1.1%	7.8%	4.4%	11.6%	7.4%	6.9%	1.0%	5.9%	5.2%	6.8%	6.4%
LCD Module		(g)	2350	647	1498	809	765	781	1783	940	751	695	932
		(%)	46.4%	12.3%	29.3%	15.7%	16.2%	15.6%	25.9%	19.0%	16.4%	19.3%	18.3%
Other		(g)	36.4	110	73								
		(%)	0.7%	2.1%	1.4%								
Total Weight (g)			**5070**	**5279**	**5175**	**5165**	**4731**	**4997**	**6892**	**4956**	**4576**	**3596**	**5024**

Table B-10: Material composition data for LCD monitors included in the study.

Sources (1) Teehan and Kandlikar 2013, (2) Huisman et al. 2007, and (3) California 2004

CRT Televisions Material Composition and Weights

Description			14-inch model (1)	14-inch model (1)	14-inch model (1)	29-inch model (1)	29-inch model (1)	29-inch model (1)	Average of several samples (1)	21-inch or smaller models, average of 3 samples (1)	28-inch or larger models, average of 6 samples (1)	CRT Television (2)	Average CRT television
Model Year			1992	1995-1997	1996	1990	1991	1996	1996	2002	2002		
Metals	Ferrous	(g)											
		(%)		10.9%	9.8%	17.6%	17.2%	17.3%	9.7%	11.1%	12.7%	0.0%	11.8%
	Aluminum	(g)										122	122
		(%)		0.0%	0.1%	0.0%	0.0%	0.0%	0.3%	0.2%	0.1%	0.5%	0.1%
	Copper	(g)										1283	1283
		(%)		6.7%	3.8%	3.9%	4.6%	4.6%	1.5%	3.4%	2.5%	4.8%	4.0%
	Other Metals	(g)											
		(%)		0.0%	0.0%	0.0%	0.0%	0.0%	1.4%	1.8%	1.0%	0.1%	0.5%
	Total Metal Content	(g)										1438	1438
		(%)	5%	18%	14%	22%	22%	22%	13%	17%	16%	5.4%	15.3%
Plastic		(g)										4039	4039
		(%)	19.4%	18.5%	20.7%	17.2%	13.2%	13.3%	16.1%	17.9%	13.6%	15.1%	16.5%
PWB		(g)										1644	1644
		(%)	10.7%	10.2%	10.5%	4.8%	4.7%	4.2%	8.1%	7.0%	6.6%	6.2%	7.3%
CRT Glass	Panel Glass	(g)										11857	11857
		(%)	23.3%	22.6%	23.1%	23.4%	24.4%	24.5%	25.0%	23.7%	25.1%	44.5%	26.0%
	Funnel Glass	(g)										5928	5928
		(%)	12.6%	12.1%	12.4%	12.6%	13.1%	13.2%	13.4%	12.8%	13.5%	22.2%	13.8%
Other		(g)										1,765	1765
		(%)	28.7%	19.0%	19.6%	20.5%	22.8%	22.9%	24.5%	22.1%	24.9%	6.6%	20.1%
Total Weight (g)												**26671**	**26671**

Table B-11: Material composition data for CRT televisions included in the study.

Sources: (1) Oguchi et al. 2011, (2) Huisman et al. 2007, (3) Huisman 2003, and (4) Hikawama 2005

CRT Monitors Material Composition and Weights

Description			CRT Monitor (1)	17 inch monitor (2)	Compaq Monitor (3)	Average CRT Monitor
Model Year					1997	
Metals	Ferrous	(g)	770	1324	836	977
		(%)	5.3%	9.0%	6.4%	6.9%
	Aluminum	(g)	238	49	342	210
		(%)	1.6%	0.3%	2.6%	1.5%
	Copper	(g)	839	892	571	767
		(%)	5.7%	6.1%	4.4%	5.4%
	Other Metals	(g)	713	0	0	238
		(%)	4.9%	0.0%	0.0%	1.6%
	Total Metal Content	(g)	2560	2265	1750	2155
		(%)	17.5%	15%	13.4%	15.4%
Plastic		(g)	1913	2607	2909.732	2476
		(%)	13.1%	17.8%	22.2%	17.7%
PWB		(g)	1385	0	659.33	1022
		(%)	9.5%	0.0%	5.0%	4.8%
CRT Glass	Panel Glass	(g)	5647	9393	7749	7596
		(%)	38.5%	64.1%	59.2%	53.9%
	Funnel Glass	(g)	2781	0	0	2781
		(%)	19.0%	0.0%	0.0%	6.3%
Other		(g)	366	385	30.564	261
		(%)	2.5%	2.6%	0.2%	1.8%
Total Weight (g)			**14653**	**14649**	**13098**	**14134**

Table B-12: Material composition data for CRT monitors included in the study.

Sources: (1) Oguchi et al. 2011, (2) Huisman et al. 2007, (3) Huisman 2003, and (4) Hikawama 2005

Plasma (PDP) Televisions Material Composition and Weights

Description			35-43-inch models, average of 5 samples	Weighted average of several samples	Average of 2 samples	Sony PFM0C1	Sony PFM-50C1	Samsung SPN4235	Average of all available data
Model Year			2002	2002	na				
Metals	Ferrous	(g)							
		(%)	23.0%	na	44.2%				34%
	Aluminum	(g)							
		(%)	19.9%	na	10.3%				15%
	Copper	(g)							
		(%)	0.8%	na	1.5%				1%
	Total Metal Content	(g)				15,514	16,292	17,090	16299
		(%)	44.6%	41.9%	56.0%	39.0%	45.7%	44.5%	45.3%
Plastics		(g)				1,710	570	2,636	1639
		(%)	13.2%	9.9%	10.1%	4.3%	1.6%	6.9%	8%
PWB		(g)				2,830	4,755	4,277	3954
		(%)	4.9%	12.3%	7.8%	7.1%	13.4%	11.1%	9%
Display Module		(g)				19278	13200	13300	15259
		(%)				48.5%	37.1%	34.6%	40.1%
Other		(g)				412	799	1137	783
		(%)				1.0%	2.2%	3.0%	2%
Total Weight (g)						39745	35615	38440	37933
Source			1	1	1	2	2	2	

Table B-13: Material composition data for plasma display panel (PDP) televisions included in the study.

Sources (1) Oguchi et al. 2011 and (2) California 2004

LCD Televisions Material Composition and Weights													
Description			13-15-inch models, average of 4 samples (1)	Weighted average of several samples (1)	32-inch model (1)	32-inch model (1)	Average of 2 samples (1)	JVC LT-26WX84 (2)	JVC LT-26WX85 (2)	Gateway GTW-L30M103 (2)	Sharp LC37HV4U (2)	Not Available (3)	Average of all available data
Model Year			2002	2002	2008	2007	na	2003	2003	2004	2003		
Metals	Ferrous	(g)										9772	9772
		(%)	26.9%		49.8%	48.2%	37.8%					34.5%	39%
	Aluminum	(g)										1511	1511
		(%)	4.4%		1.4%	0.0%	3.8%					5.3%	3%
	Copper	(g)										441	441
		(%)	1.4%		0.0%	0.8%	0.8%					1.6%	1%
	Total Metal Content	(g)						11,400	11,400	9,600	16,556	11724	12136
		(%)	68.4%		51.2%	49.0%	42.4%	60.3%	60.3%	60.2%	55.2%	41.4%	54.3%
Plastics		(g)						4,006	3,994	2,754	7,711	8446.36	5382
		(%)	43.5%	39.5%	24.9%	26.2%	31.8%	21.2%	21.1%	17.3%	25.7%	29.8%	28%
PWB		(g)						1,095	1,157	781	1,682	1780	1299
		(%)	16.1%	9.7%	9.7%	11.6%	11.7%	5.8%	6.1%	4.9%	5.6%	6.3%	9%
LCD Module		(g)						1775	1778	2281	3356	6323	3103
		(%)						9.4%	9.4%	14.3%	11.2%	22.3%	13%
Other		(g)						638	591	665	678	26.7	520
		(%)					6%	3.4%	3.1%	4.2%	2.3%	0.1%	3%
Total Weight (g)								**18914**	**18920**	**15938**	**29985**	**28300**	**22411**

Table B-14: Material composition data for LCD televisions included in the study.

Sources (1) Oguchi et al. 2011, (2) California 2004, and (3) Huisman et al. 2007

Blu Ray and DVD Player Material Composition and Weights

Description			DVD Sony SLV-D360P (1)	BluRay Samsung BD-P1400 (1)	BluRay Samsung BD-P1000 (1)	Average of disassembly data
DVD/			DVD	BluRay	BluRay	
Model Year			2005	2007	2006	
Metals	Ferrous	(g)	1777.7	2692.3	2606.8	2359.0
		(%)	49.7%	67.2%	58.5%	58.5%
	Aluminum	(g)	86.6	0.0	26.5	37.7
		(%)	2.4%	0.0%	0.6%	1.0%
	Copper	(g)	143.2	120.0	161.4	141.5
		(%)	4.0%	3.0%	3.6%	3.5%
	Total Metal Content	(g)	2007.5	2812.3	2794.7	2538.2
		(%)	56.1%	70.2%	62.7%	63.0%
Plastics		(g)	890.9	501.6	549.6	647.3
		(%)	24.9%	12.5%	12.3%	16.6%
PWB		(g)	658.3	610.2	1037.3	768.6
		(%)	18.4%	15.2%	23.3%	19.0%
Other		(g)	19.4	83.5	77.4	60.1
		(%)	0.5%	2.1%	1.7%	1.5%
Total Weight (g)			**3576.1**	**4007.5**	**4459.0**	**4014.2**

Table B-15: Material composition data for BluRay and DVD players included in the study.

BluRay and DVD player data were combined based on similarity size, function, and material composition.

Source (1) disassembled by the authors

VCR Material Composition and Weights

Model Year			1986	1990	1995	1996	1996	2002	Average of available data
Metals	Ferrous	(%)	49.8%	59.9%	55.4%	58.0%	44.3%	49.5%	53%
	Aluminum	(%)	6.2%	0.0%	0.0%	0.0%	4.4%	4.5%	3%
	Copper	(%)	4.3%	3.6%	2.3%	2.8%	2.4%	1.6%	3%
	Total Metal Content	(%)	60.3%	63.5%	59.5%	60.8%	53.6%	57.0%	59.1%
Plastic		(%)	24.1%	19.9%	24.9%	22.4%	25.4%	24.5%	24%
PWB		(%)	13.1%	14.0%	14.5%	13.1%	19.3%	17.0%	15%
Other		(%)	2.5%	2.6%	1.1%	3.7%	1.7%	1.5%	2%
Source			1	1	1	1	1	1	

Table B-16: Material composition data for all VCRs included in the study.

Source (1) Oguchi et al. 2011

MP3 Player Material Composition and Weights						
Description			Mini iPod (1)	Dell MP3 (1)	Philips Rush Player (1)	Average of disassembly data
Model Year						
Metals	Ferrous	(g)	20.8	1.3	1.2	7.8
		(%)	21%	0%	2%	8%
	Aluminum	(g)	31.4	92.4	0.0	41.3
		(%)	32%	33%	0%	22%
	Copper	(g)	2.0	6.4	0.0	2.8
		(%)	2%	2%	0%	1%
	Total Metal Content	(g)	54.2	100.1	1.2	51.8
		(%)	55%	35%	2%	31%
Plastic		(g)	6.2	32.1	27.1	21.8
		(%)	6%	11%	52%	23%
PWB		(g)	16.1	79.4	18.9	38.1
		(%)	16%	28%	36%	27%
Battery		(g)	12.4	34.7	0.0	15.7
		(%)	13%	12%	0%	8%
Display Module		(g)	3.6	8.7	4.2	5.5
		(%)	4%	3%	8%	5%
Other		(g)	5.7	27.7	0.6	11.3
		(%)	6%	10%	1%	6%
Total Weight (g)			**98.2**	**282.7**	**52.0**	**144.3**

Table B-17: Material composition data for MP3 players included in the study.

Source (1) disassembled by the authors

Printers Material Composition and Weights								
Description			HP DeskJet 932c (1)	Dell A940 (1)	Dell 720 (1)	Kodak ESP7 (1)	HP 8000 (1)	Average of disassembly data
Model Year			2000	2004	2004	2008	2009	
Metals	Ferrous	(g)	3054.8	1276.5	533.4	1645.8	2422.4	1786.6
		(%)	51.2%	20.0%	29.6%	19.8%	29.5%	30.0%
	Aluminum	(g)	69.8	2.5	0.0	4.2	0.0	15.3
		(%)	1.2%	0.0%	0.0%	0.1%	0.0%	0.3%
	Copper	(g)	40.6	0.0	9.9	51.7	57.2	31.9
		(%)	0.7%	0.0%	0.5%	0.6%	0.7%	0.5%
	Total Metal Content	(g)	3165.2	1279.0	543.3	1701.7	2479.6	1833.7
		(%)	53.1%	20.0%	30.1%	20.4%	30.2%	30.8%
Plastic		(g)	2513.5	4058.2	1185.7	5499.9	5448.1	3741.1
		(%)	42.1%	63.6%	65.7%	66.0%	66.4%	60.8%
PWB		(g)	252.9	205.8	46.5	282.2	184.1	194.3
		(%)	4.2%	3.2%	2.6%	3.4%	2.2%	3.1%
Glass		(g)	0.0	721.4	0.0	661.1	0.0	276.5
		(%)	0.0%	11.3%	0.0%	7.9%	0.0%	3.8%
Other		(g)	32.7	119.2	25.0	184.3	98.7	92.0
		(%)	0.5%	1.9%	1.4%	2.2%	1.2%	1.4%
Total Weight (g)			**5964.3**	**6383.5**	**1805.0**	**8329.1**	**8210.5**	**6138.5**

Table B-18: Material composition data for printers included in the study.

Source (1) disassembled by the authors

Digital Camera Material Composition and Weights					
Description			Kodak Easy Share[a]	Kodak Easy Share[a]	Average of disassembly data
Model Year			2008	2002	
Metals	Ferrous	(g)	1.1	5.2	3.2
		(%)	0.9%	4.0%	2.4%
	Aluminum	(g)	9	31.6	20.3
		(%)	7.1%	24.1%	15.6%
	Copper	(g)	10.8	2.9	6.9
		(%)	8.5%	2.2%	5.3%
	Total Metal Content	(g)	21	40	30.3
		(%)	16.4%	30.3%	23.3%
Plastic		(g)	68.8	63.1	66.0
		(%)	54.0%	48.1%	51.0%
PWB		(g)	21.5	1.7	11.6
		(%)	16.9%	1.3%	9.1%
Battery		(g)	0	0	0.0
		(%)	0.0%	0.0%	0.0%
Other		(g)	16.2	26.7	21.5
		(%)	12.7%	20.4%	16.5%
Total Weight (g)			**127.4**	**131.2**	**129.3**
Source			1	1	

Table B-19: Material composition data for digital cameras included in the study.

Source (1) disassembled by the authors

Digital Camcorder Material Composition and Weights				
Description			Sony HandyCam	Average of disassembly data
Model Year			1998	
Metals	Ferrous	(g)	252.1	252.1
		(%)	29.7%	29.7%
	Aluminum	(g)	29.5	29.5
		(%)	3.5%	3.5%
	Copper	(g)	23.25	23.3
		(%)	2.7%	2.7%
	Total Metal Content	(g)	305	304.9
		(%)	35.9%	35.9%
Plastic		(g)	352.25	352.3
		(%)	41.5%	41.5%
PWB		(g)	97.3	97.3
		(%)	11.5%	11.5%
Battery		(g)	64.6	64.6
		(%)	7.6%	7.6%
Other		(g)	29.2	29.2
		(%)	3.4%	3.4%
Total Weight (g)			848.2	848.2
Source			1	

Table B-20: Material composition data for digital camcorders included in the study.

Source (1) disassembled by the authors

Basic Cell Phone Material Composition and Weights

Description			Nokia 5165 (1)	Sanyo SCP-4000 (1)	LG VX 3200 (1)	Motorola RAZR V3c (1)	LG VX5200 (1)	LG VX5300 (1)	LG enV VX9100 (1)	LG VX8360 (1)	Average of disassembly data
Model Year			1998	1999	2004	2005	2005	2006	2008	2009	
Metals	Ferrous	(g)	2.2	2.9	0.4	0.6	0.3	0.5	0.7	0.3	1.0
		(%)	1.3%	2.3%	0.4%	0.6%	0.3%	0.5%	0.6%	0.3%	0.8%
	Aluminum	(g)	0.0	0.0	0.0	27.6	0.5	0.0	13.1	3.0	5.5
		(%)	0.0%	0.0%	0.0%	27.5%	0.5%	0.0%	10.5%	3.1%	5.2%
	Copper	(g)	0.0	0.0	6.5	0.0	5.0	2.2	0.0	1.7	1.9
		(%)	0.0%	0.0%	6.8%	0.0%	5.1%	2.4%	0.0%	1.8%	2.0%
	Magnesium	(g)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		(%)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Total Metal Content	(g)	2.2	2.9	6.9	28.2	5.8	2.7	13.8	5.0	8.4
		(%)	1.3%	2.3%	7.2%	28.1%	5.9%	3.0%	11.1%	5.2%	8.0%
Plastics		(g)	45.7	33.7	34.8	16.7	32.7	31.2	41.7	34.7	33.9
		(%)	26.4%	26.3%	36.5%	16.7%	33.2%	34.2%	33.4%	36.4%	30.4%
LCD Module		(g)	8.1	5.7	5.7	15.2	11.5	9.3	13.7	10.4	10.0
		(%)	4.7%	4.5%	6.0%	15.2%	11.7%	10.2%	11.0%	10.9%	9.3%
PWB		(g)	42.6	30.6	17.6	11.6	13.4	11.4	24.2	14.4	20.7
		(%)	24.6%	23.9%	18.4%	11.6%	13.6%	12.5%	19.4%	15.1%	17.4%
Battery		(g)	73.3	47.6	22.7	19.6	21.6	22.4	23.7	20.5	31.4
		(%)	42.4%	37.2%	23.8%	19.6%	21.9%	24.6%	19.0%	21.5%	26.2%
Other		(g)	1.1	7.5	7.7	8.9	13.5	14.2	7.6	10.4	8.9
		(%)	0.6%	5.9%	8.1%	8.9%	13.7%	15.6%	6.1%	10.9%	8.7%
Total weight (g)			**173.0**	**128.0**	**95.4**	**100.2**	**98.5**	**91.2**	**124.7**	**95.4**	**113.3**

Table B-21: Material composition data for basic cell phones included in the study.

Source (1) disassembled by the authors

Smart Phone Material Composition and Weights

Description			Palm Treo 650 (1)	iPhone 8gb A1203 (1)	Blackberry Curve 8900 (1)	Samsung Epic 4G Galaxy S D700 (1)	PalmTreo 700 (1)	iPhone 3G (1)	Average of disassembly data
Model Year			2005	2007	2009	2010			
Metals	Ferrous	(g)	1.0	14.9	4.5	0.9	4.5	0.4	4.4
		(%)	0.6%	10.3%	4.2%	0.6%	2.4%	0.3%	3.0%
	Aluminum	(g)	5.5	29.8	0.0	0.0	24.5	37.3	16.2
		(%)	3.1%	20.7%	0.0%	0.0%	13.0%	28.0%	10.8%
	Copper	(g)	2.2	0.5	0.0	5.2	2.5	2.3	2.1
		(%)	1.2%	0.3%	0.0%	3.3%	1.3%	1.7%	1.3%
	Magnesium	(g)	0.0	0.0	13.5	27.0	0.0		8.1
		(%)	0.0%	0.0%	12.5%	17.3%	0.0%	0.0%	5.0%
	Total Metal Content	(g)	8.7	45.2	18.0	33.1	31.5	39.9	29.4
		(%)	4.8%	31.3%	16.7%	21.2%	16.6%	30.0%	20.1%
Plastics		(g)	37.9	16.7	22.4	46.2	49.8	20.1	32.2
		(%)	21.1%	11.5%	20.7%	29.6%	26.3%	15.1%	20.7%
LCD Module		(g)	30.1	34.2	15.7	17.3	0.0	11.7	18.2
		(%)	16.7%	23.7%	14.5%	11.1%	0.0%	8.8%	12.5%
PWB		(g)	48.3	14.6	17.9	14.1	47.8	15.1	26.3
		(%)	26.9%	10.1%	16.6%	9.0%	25.3%	11.3%	16.5%
Battery		(g)	41.5	26.1	29.7	32.1	41.6	20.7	32.0
		(%)	23.1%	18.1%	27.5%	20.6%	22.0%	15.6%	21.1%
Other		(g)	13.3	7.6	4.4	13.1	18.4	25.6	13.7
		(%)	7.4%	5.3%	4.1%	8.4%	9.7%	19.2%	9.0%
Total weight (g)			**179.8**	**144.3**	**108.1**	**155.9**	**189.05**	**133.1**	**151.7**

Table B-22: Material composition data for smartphones included in the study.

Source (1) disassembled by the authors.

Gaming Console Material Composition and Weights

Description			Playstation 3	Wii	XBOX 360	Average of disassembly data
Model Year			2007			
Metals	Ferrous	(g)	1237.73	461.6	1453.22	1051
		(%)	29.3%	39.2%	38.6%	36%
	Aluminum	(g)	650.63	68.6	511.1	410
		(%)	15.4%	5.8%	13.6%	12%
	Copper	(g)	211.68	18.58	17.98	83
		(%)	5.0%	1.6%	0.5%	2%
	Total Metal Content	(g)	2100	549	1982	1544
		(%)	49.7%	46.6%	52.6%	49.6%
Plastic		(g)	1380.717	403.1	1348.07	1044
		(%)	32.7%	34.2%	35.8%	34%
PWB		(g)	714.74	215.72	433.93	455
		(%)	16.9%	18.3%	11.5%	16%
Other		(g)	32.45	10.8	4.9	16
		(%)	0.8%	0.9%	0.1%	1%
Total Weight (g)			**4228**	**1178**	**3769**	**3059**
Source			1	1	1	

Table B-23: Material composition data for gaming console included in the study.

Source (1) disassembled by the authors

Model Inputs

Material composition data as shown in the previous section was averaged to a single material composition for each product. These material compositions were used as model inputs. Average mass for each product was determined via literature review or study of disassembled products and the baseline run held product mass constant over time. Sensitivity analysis was conducted with variable product mass as shown in Table B-18. Variable mass was limited to products that exhibited product level dematerialization (as in the case of the DVD and Blu-Ray players) or a combination of product level dematerialization and increasing size (as in the case of the LCD television).

	Fe (%)	Al (%)	Cu (%)	Other Metals (%)	Plastic (%)	PWB (%)	Display Module (%)	CRT Panel Glass (%)	CRT Funnel Glass (%)	Battery (%)	Other (%)
Desktop	50.4%	14.8%	3.8%		12.1%	16.7%					2.2%
Laptop	10.0%	13.7%	1.8%	5.5%	22.8%	13.4%	17.8%			13.1%	1.8%
Tablet / E-Reader	2.0%	11.7%	1.7%		26.3%	10.0%	21.2%			19.0%	8.1%
Netbook	4.6%	8.6%	1.5%	8.4%	25.3%	15.1%	22.2%			12.2%	2.1%
LCD Monitor	26.7%	1.4%	6.7%		30.1%	4.4%	29.3%				1.4%
CRT TV	11.8%	0.1%	4.0%	0.5%	16.5%	7.3%		26.0%	13.8%		20.1%
CRT Monitor	6.9%	1.5%	5.4%	1.6%	17.7%	4.8%		53.9%	6.3%		1.8%
Plasma TV	33.6%	15.1%	1.2%		7.7%	9.4%	33.1%				0.0%
LCD TV	39.4%	3.0%	0.9%		28.1%	8.8%	13.3%				6.5%
DVD / BluRay	58.5%	1.0%	3.5%		16.6%	19.0%					1.5%
VCR	52.8%	2.5%	2.8%	1.0%	23.5%	15.2%					2.2%
MP3 Player	8.0%	21.5%	1.4%		23.3%	26.9%	4.9%			8.3%	5.6%
Gaming Console	35.7%	11.6%	2.4%		34.2%	15.6%					0.6%
Printer	30.0%	0.3%	0.5%		60.8%	3.1%					5.3%
Digital Camera	2.4%	15.6%	5.3%		51.0%	9.1%				0.0%	16.5%
Digital Camcorder	29.7%	3.5%	2.7%		41.5%	11.5%				7.6%	3.4%
Basic Cell	0.8%	5.2%	2.0%		30.4%	17.4%	9.3%			26.2%	8.7%
Smart Phone	3.0%	10.8%	1.3%	5.0%	20.7%	16.5%	12.5%			21.1%	9.0%

Table B-24: Model inputs - average material composition data for bulk materials.

Average material composition data is based on the individual product composition data presented in the material composition tables.

Categories	Metals	Mean wt%
Base Metals	Copper	18.6684%
	Aluminum	4.1300%
	Iron	3.8103%
	Tin	2.9220%
Precious Metals	Silver	0.1304%
	Gold	0.0359%
	Palladium	0.0117%
	Platinum	0.0022%
Hazardous	Lead	2.0441%
	Zinc	1.2213%
	Nickel	1.2585%
	Antimony	0.3380%
	Manganese	0.1250%
	Magnesium	0.1555%
	Bismuth	0.0865%
	Chromium	0.0340%
	Cadmium	0.0216%
	Barium	0.0200%
	Arsenic	0.0070%
	Beryllium	0.0038%
	Mercury	0.0006%
Rare	Gallium	0.0035%
	Tantalum	0.0172%

Table B-25: Representative composition of selected materials from printed wiring board (PWB) (Wang and Gaustad 2012)

Metals	Mean wt%
Aluminum	6.975%
Copper	9.650%
Ferrous	22.213%
Cobalt	16.725%

Table B-26: Representative composition of selected materials in LiOH battery (Oguchi et al. 2011)

Metals	Mean wt% Panel Glass	Mean wt% Funnel Glass
Aluminum	1.400%	1.425%
Ferrous	0.073%	0.040%
Lead	0.009%	21.625%
Zinc	0.340%	0.106%
Barium	7.867%	0.400%
Strontium	7.433%	0.420%

Table B-27: Representative composition of selected materials in CRT glass (Oguchi et al. 2011)

Metals	Mean wt%
Indium (g/t)	0.0174%
Yttrium	0.1831%
Europium	0.0134%
Lanthanum	0.0113%
Cerium	0.0076%
Gadolinium	0.0011%
Terbium	0.0038%
Praseodymium	<0.0002%

Table B-28: Representative composition of selected materials in LCD display module (Buchert et al. 2012)

Product Mass (kg)	Average	High	Low
Desktop	9.77	10.95	4.53
Laptop	2.79	3.45	1.74
Tablet	0.60	0.78	0.22
Netbook	1.13	1.32	1.04
E-Reader	0.62	0.78	0.22
LCD Monitor	5.03	6.89	3.60
CRT Monitor	18.58	23.59	11.16
CRT TV	31.38	31.60	26.67
Plasma TV	41.35	42.20	35.62
LCD TV	17.89	29.99	15.94
DVD	4.83	5.00	3.58
VCR	5.00	5.00	5.00
Blu-Ray	4.58	5.00	3.58
MP3 Player	0.49	0.57	0.05
Gaming	3.01	4.23	1.18
Printer	7.51	8.89	1.81
Digital Camera	0.31	0.34	0.13
Digital Camcorder	0.90	0.91	0.85
Basic Cell	0.31	0.53	0.09
Smart Phone	0.21	0.33	0.11

Table B-29: Sensitivity analysis model inputs – average, high, and low values for product mass data in kilograms.

	Summary of data sources
Desktop	US EPA 2008, Hikwama 2005, Eugster 2007
Laptop	Disassembled by authors, Kasulaitis et al. 2015
Tablet	Disassembled by authors, Kozak 2003, Teehan and Kandlikar 2013
Netbook	Disassembled by authors
E-Reader	Disassembled by authors, Kozak 2003, Teehan and Kandlikar 2013
LCD Monitor	Teehan and Kandlikar 2013, Huisman et al. 2007, California 2004
CRT Monitor	Oguchi et al. 2011, Huisman et al. 2007, Huisman 2003, Hikwama 2005
CRT TV	Oguchi et al. 2011, Huisman et al. 2007, Huisman 2003, Hikwama 2005
Plasma TV	Oguchi et al. 2011, California 2004
LCD TV	Oguchi et al. 2011, California 2004, Huisman et al. 2007
DVD	Disassembled by authors
VCR	Huisman et al. 2007
Blu-Ray	Disassembled by authors
MP3 Player	Disassembled by authors
Gaming	Disassembled by authors, Huisman et al. 2007
Printer	Disassembled by authors
Digital Camera	Disassembled by authors
Digital Camcorder	Disassembled by authors
Basic Cell	Disassembled by authors
Smart Phone	Disassembled by authors

Table B-30: Summary of mass data sources.

Material Flow Analysis Results

The model was evaluated using the average product masses as a baseline evaluation, and the high and low values of product masses. The material flows by product and by materials are shown below.

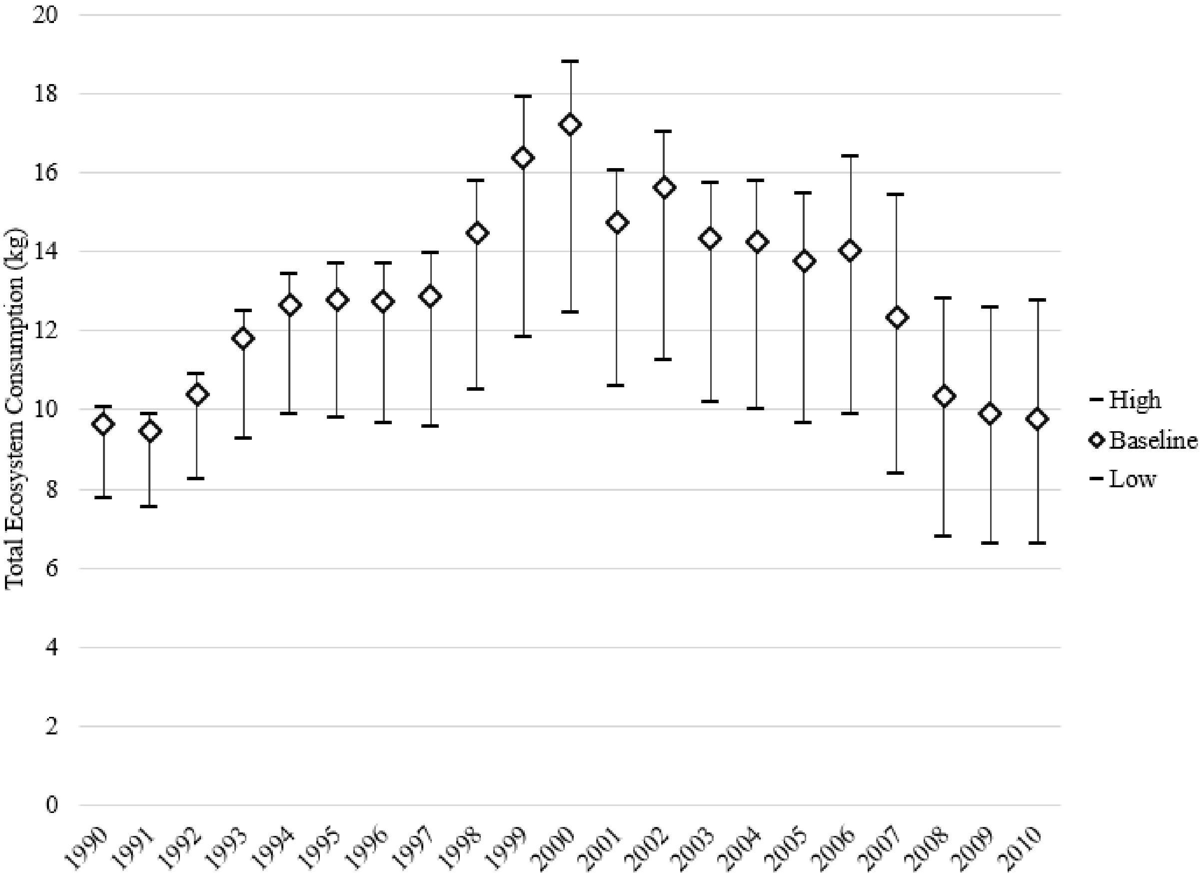

Figure B-2: Baseline, high and low ecosystem total consumption.

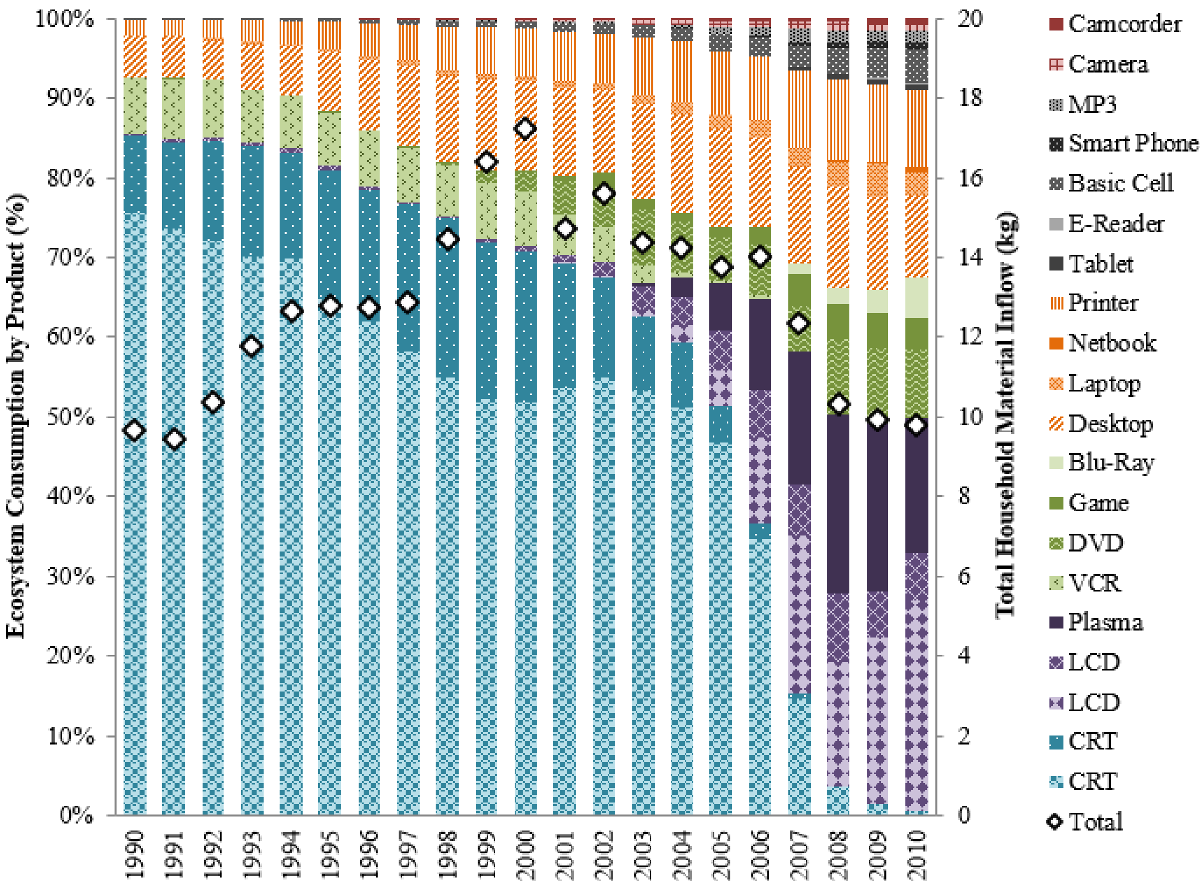

Figure B-3: Baseline ecosystem consumption by product.

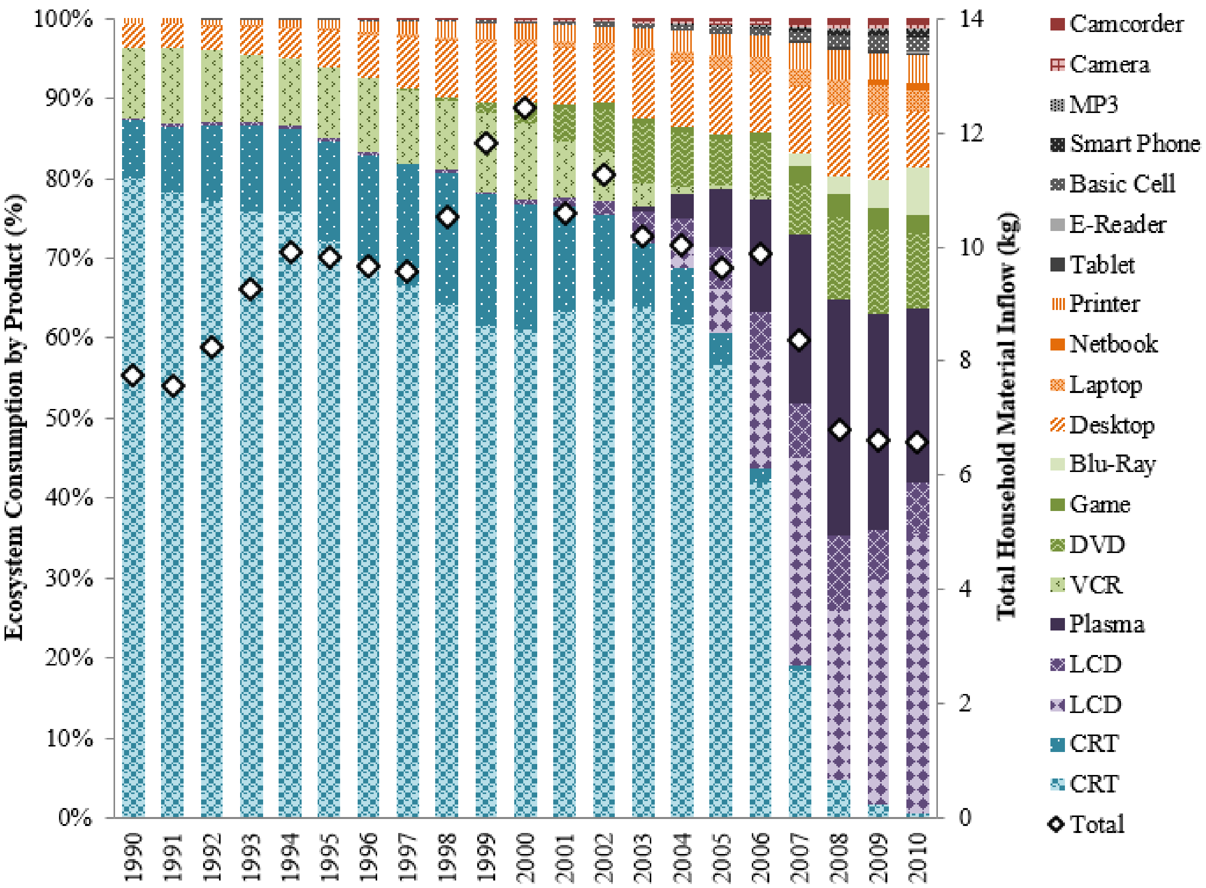

Figure B-4: Low ecosystem consumption by product.

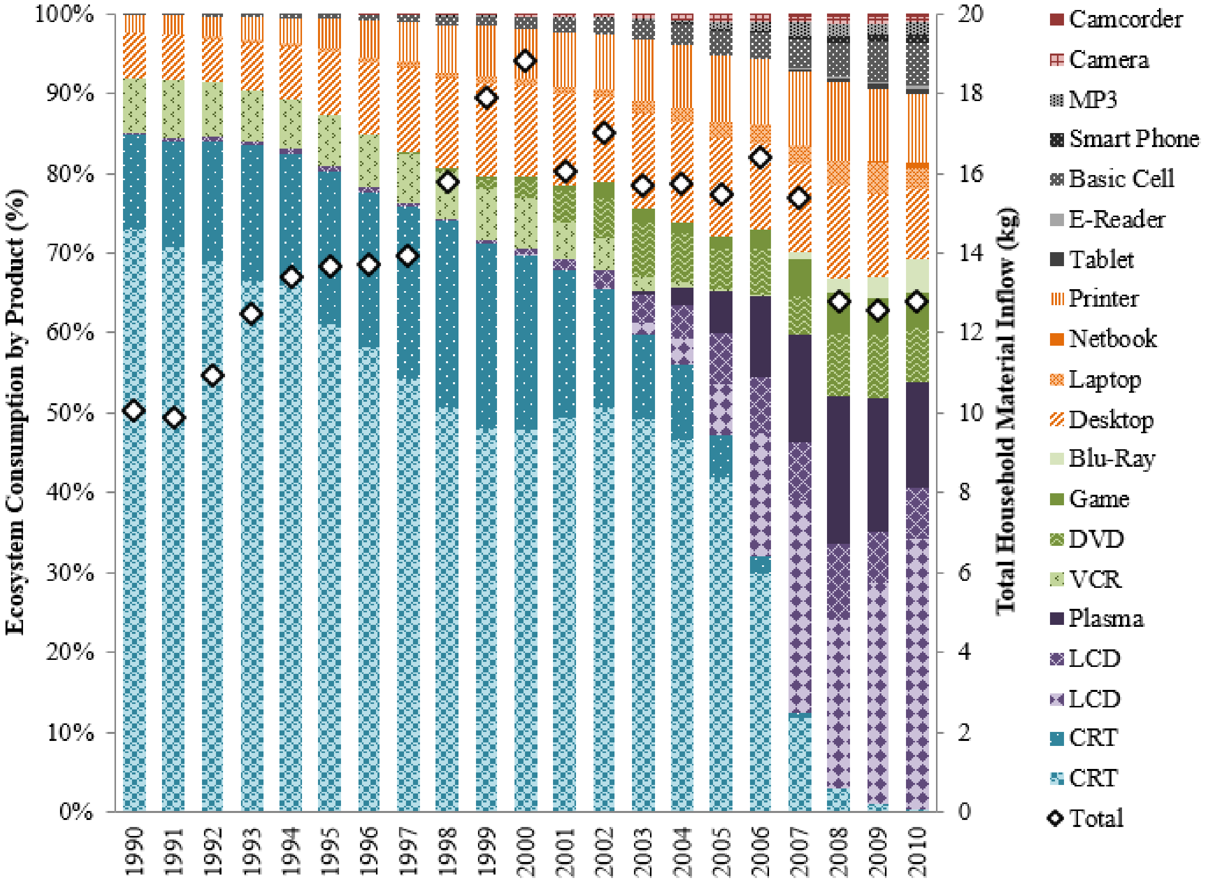

Figure B-5: High ecosystem consumption by product.

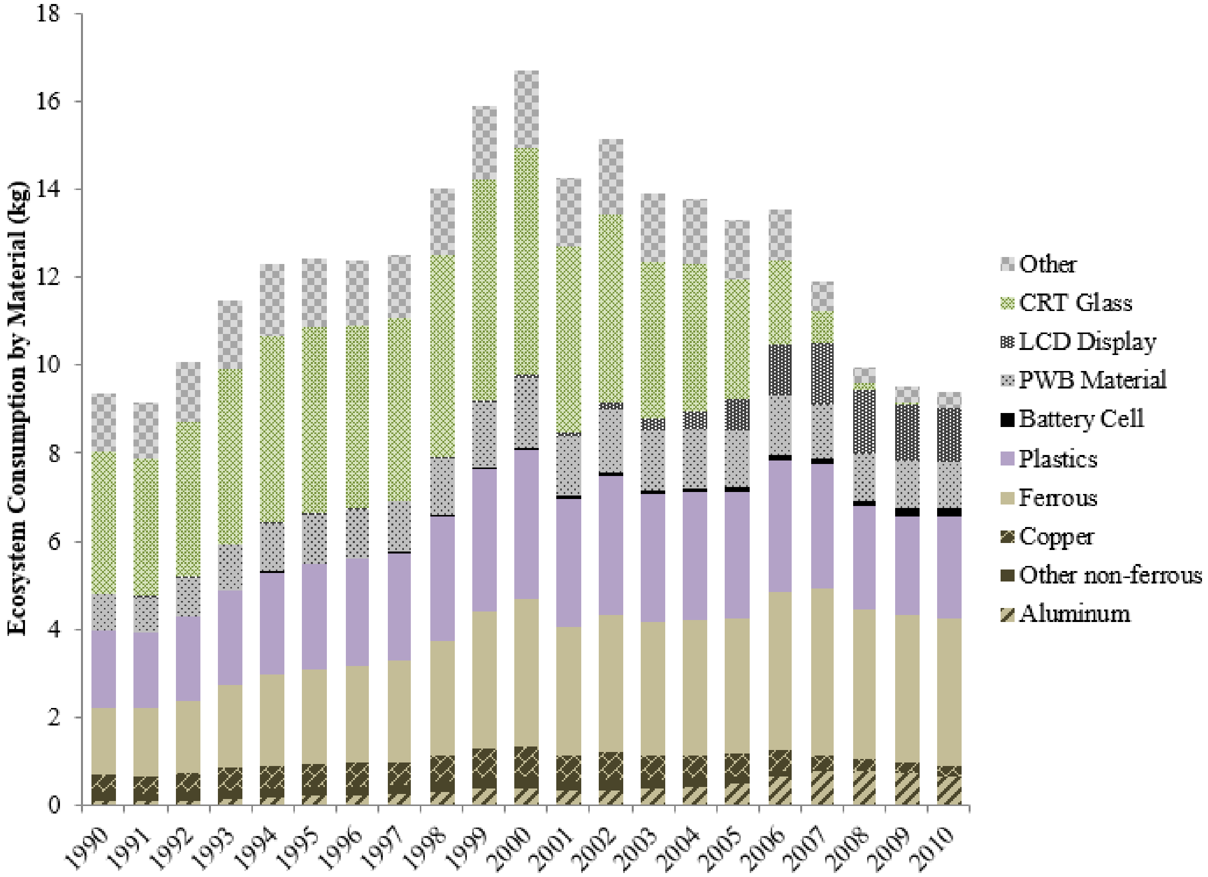

Figure B-6: Baseline ecosystem consumption by material.

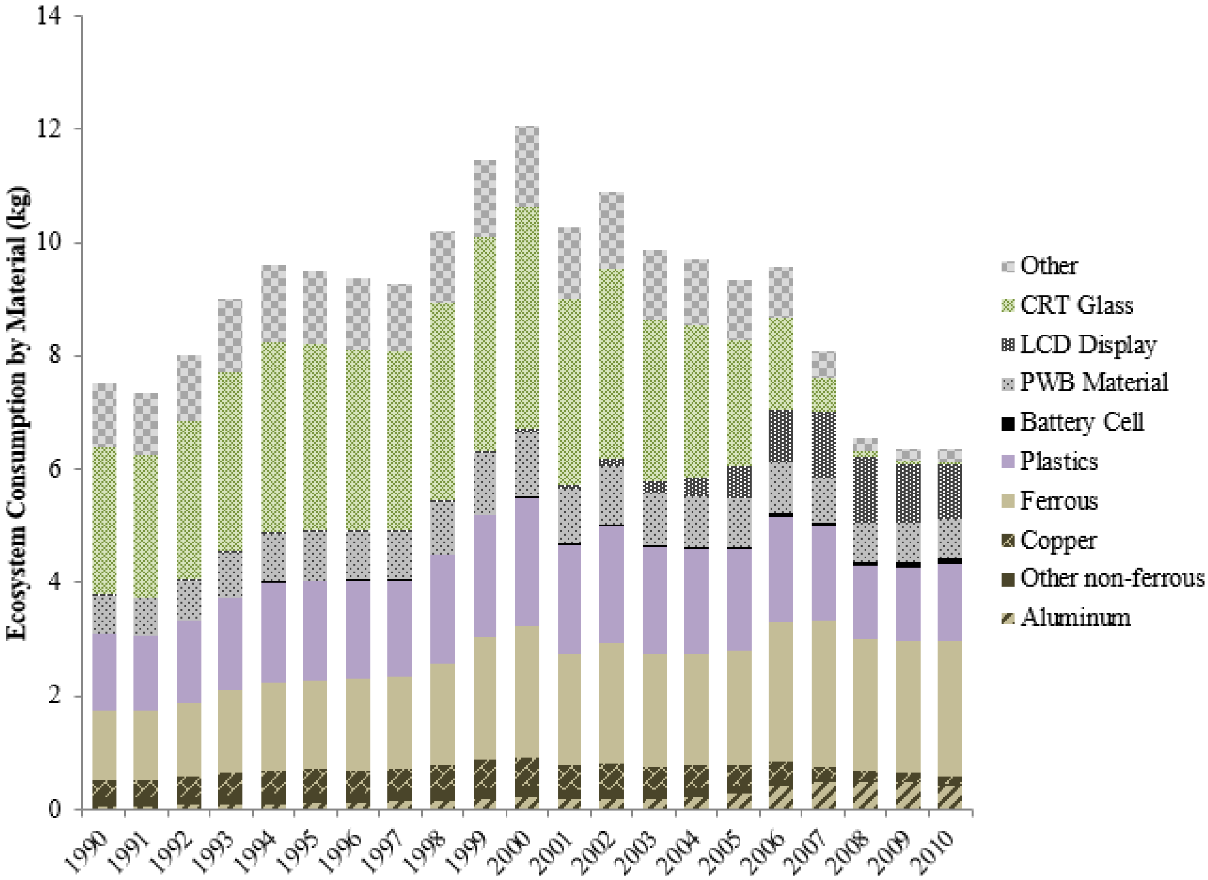

Figure B-7: Low ecosystem consumption by material.

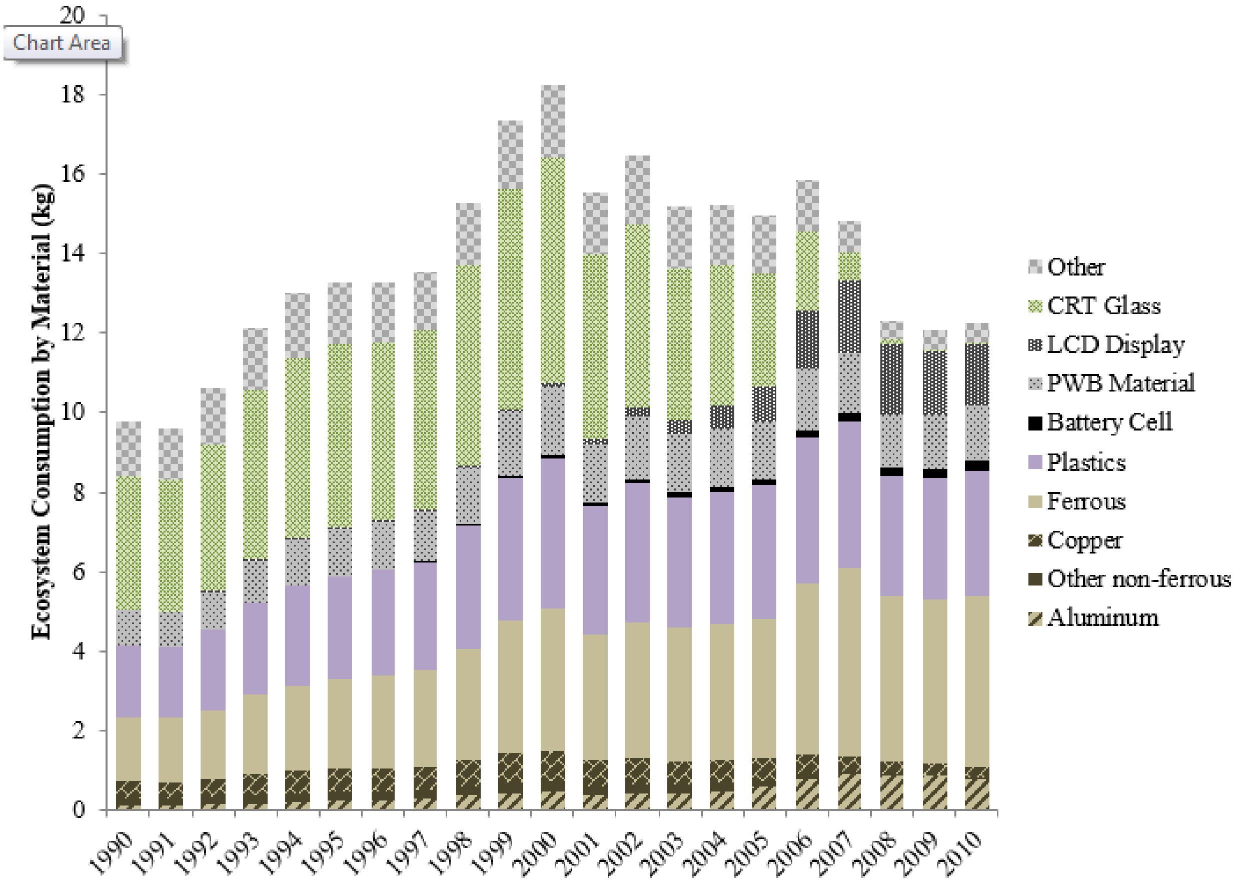

Figure B-8: High ecosystem consumption by material.

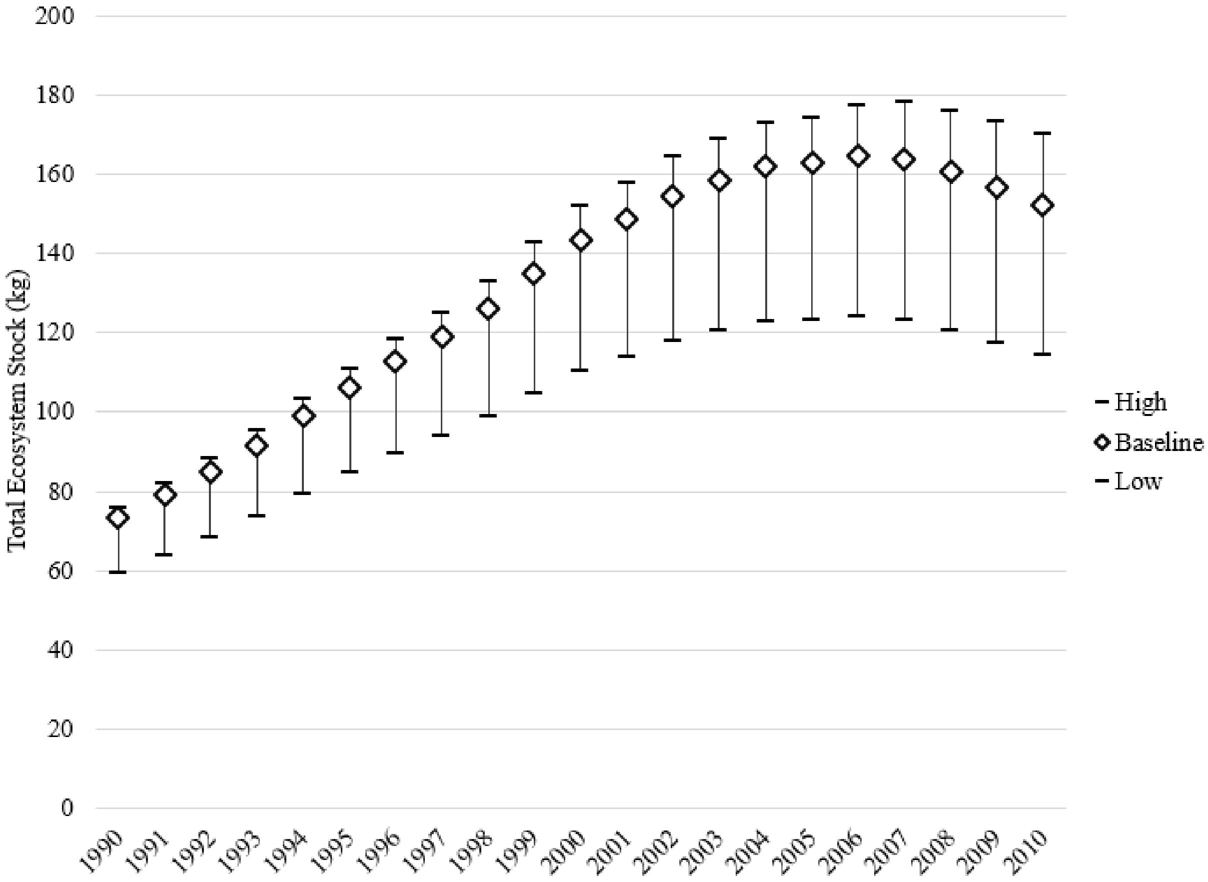

Figure B-9: Baseline, high, and low total ecosystem stock.

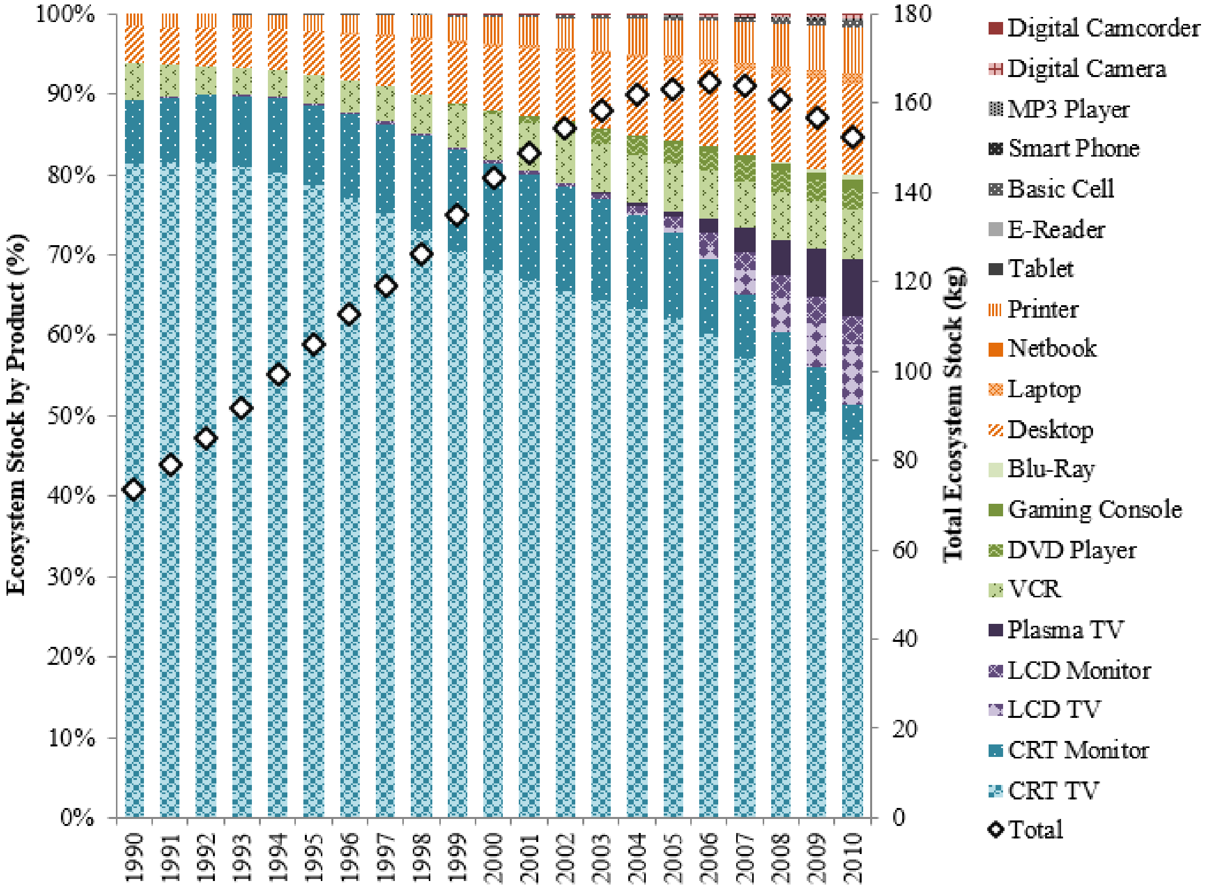

Figure B-10: Baseline ecosystem stock by product.

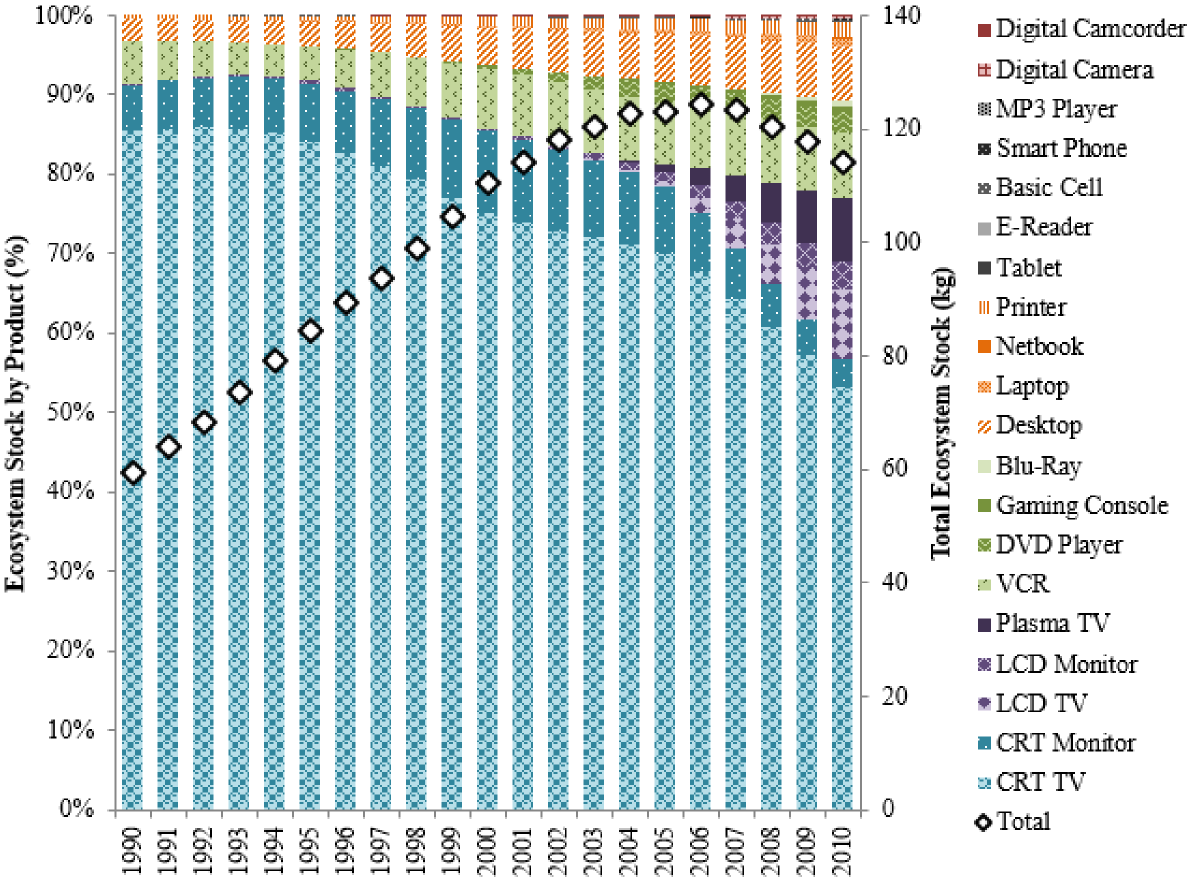

Figure B-11: Low ecosystem stock by product.

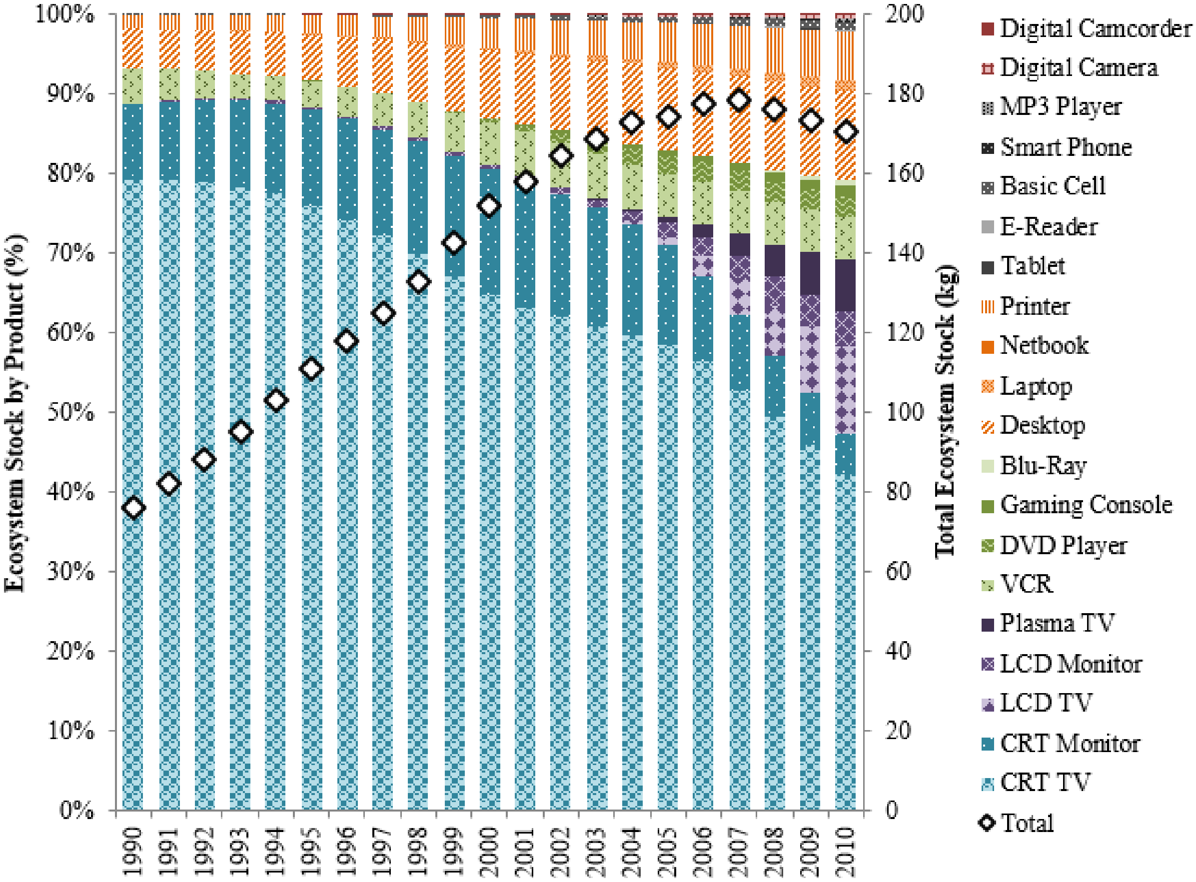

Figure B-12: High ecosystem waste by product.

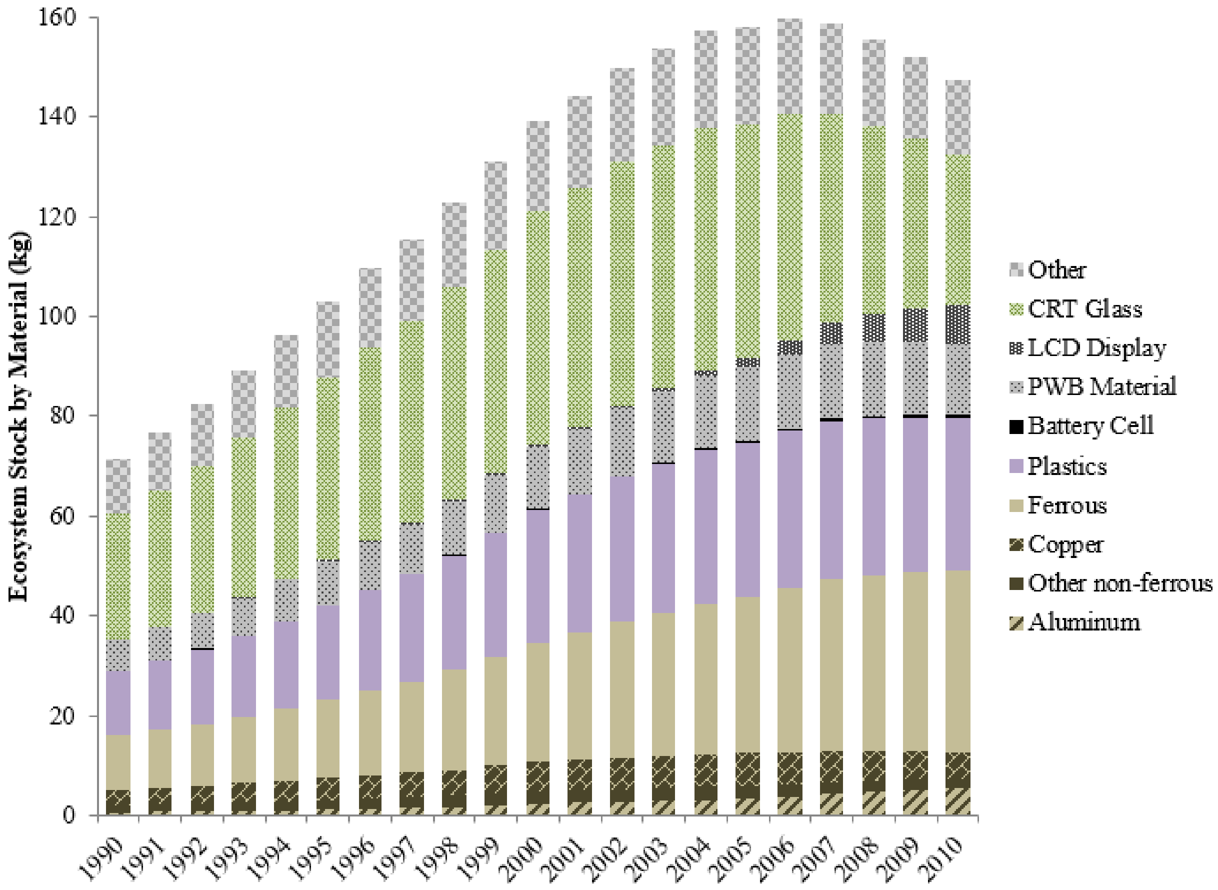

Figure B-13: Baseline ecosystem stock by material.

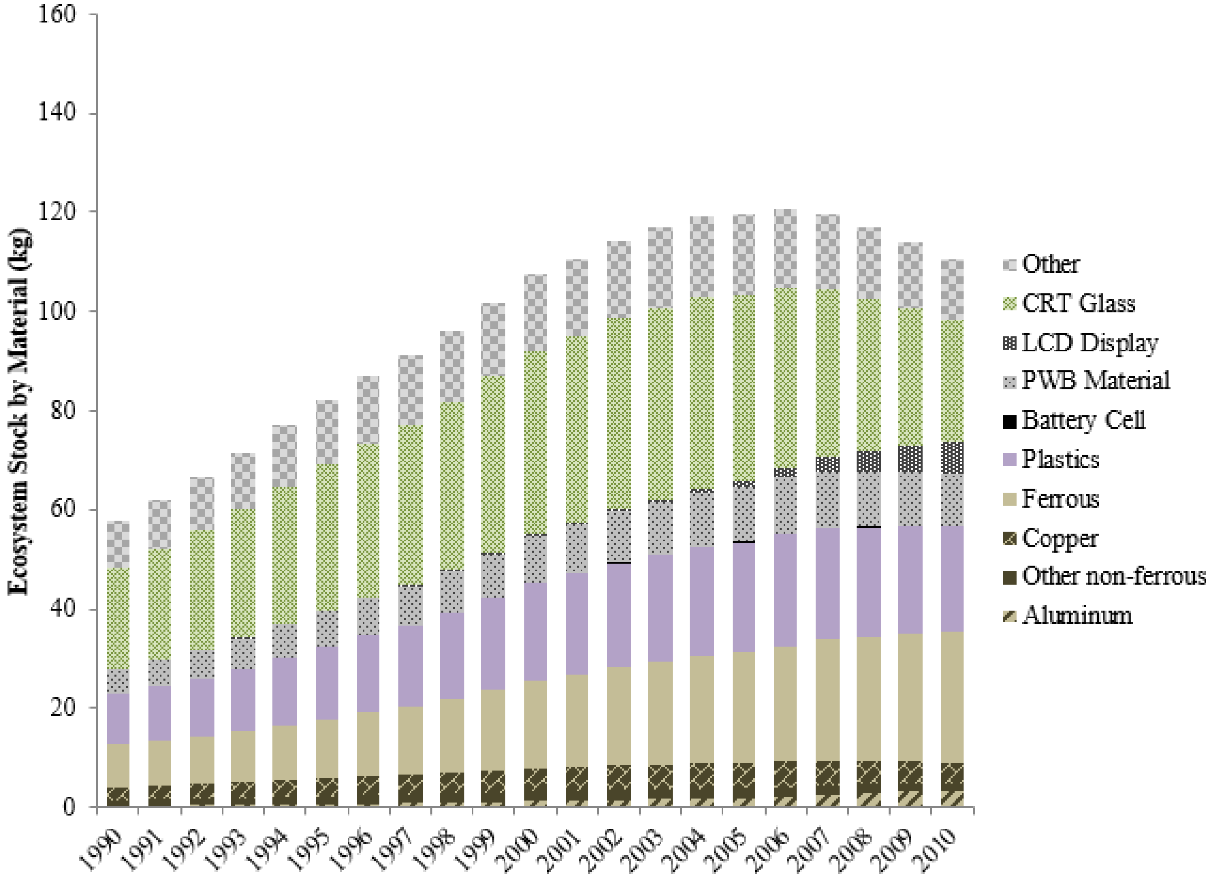

Figure B-14: Low ecosystem stock by material.

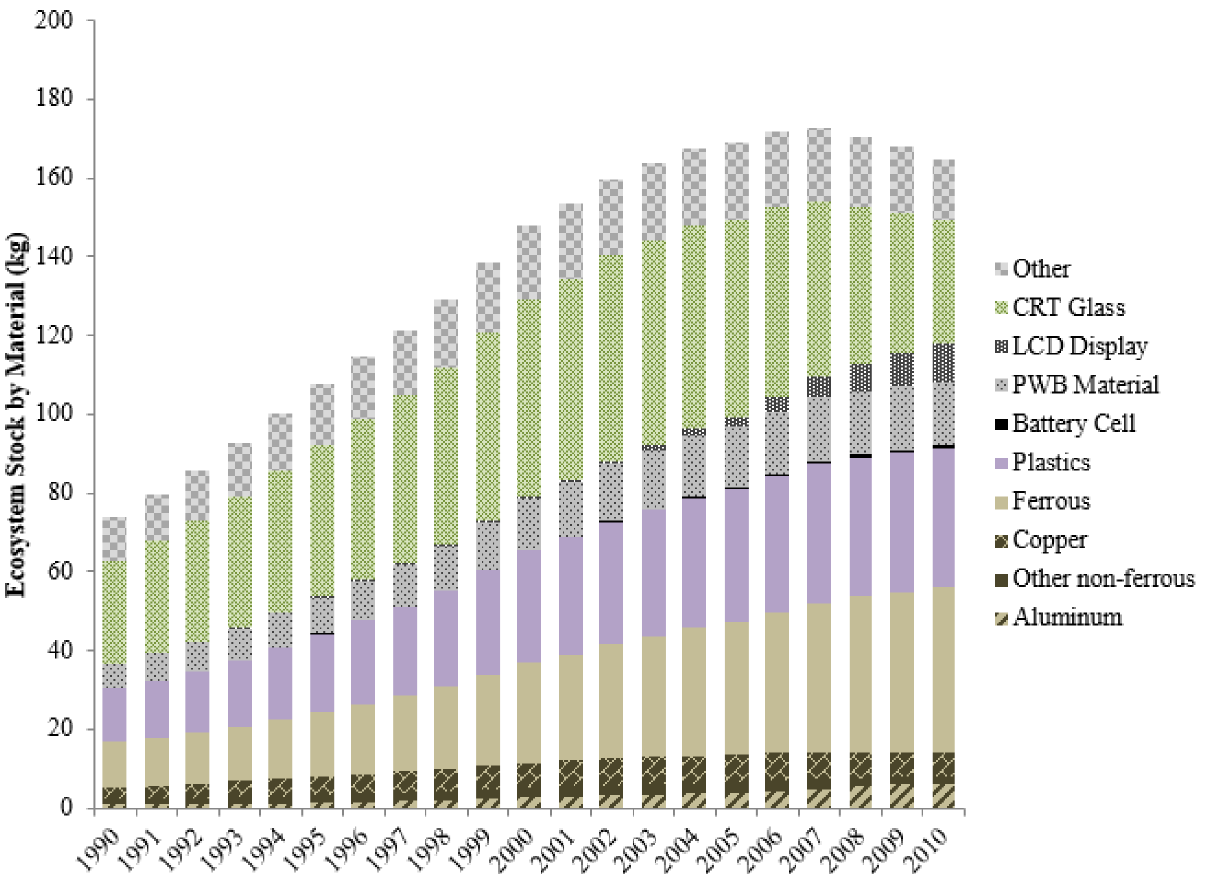

Figure B-15: High ecosystem stock by material.

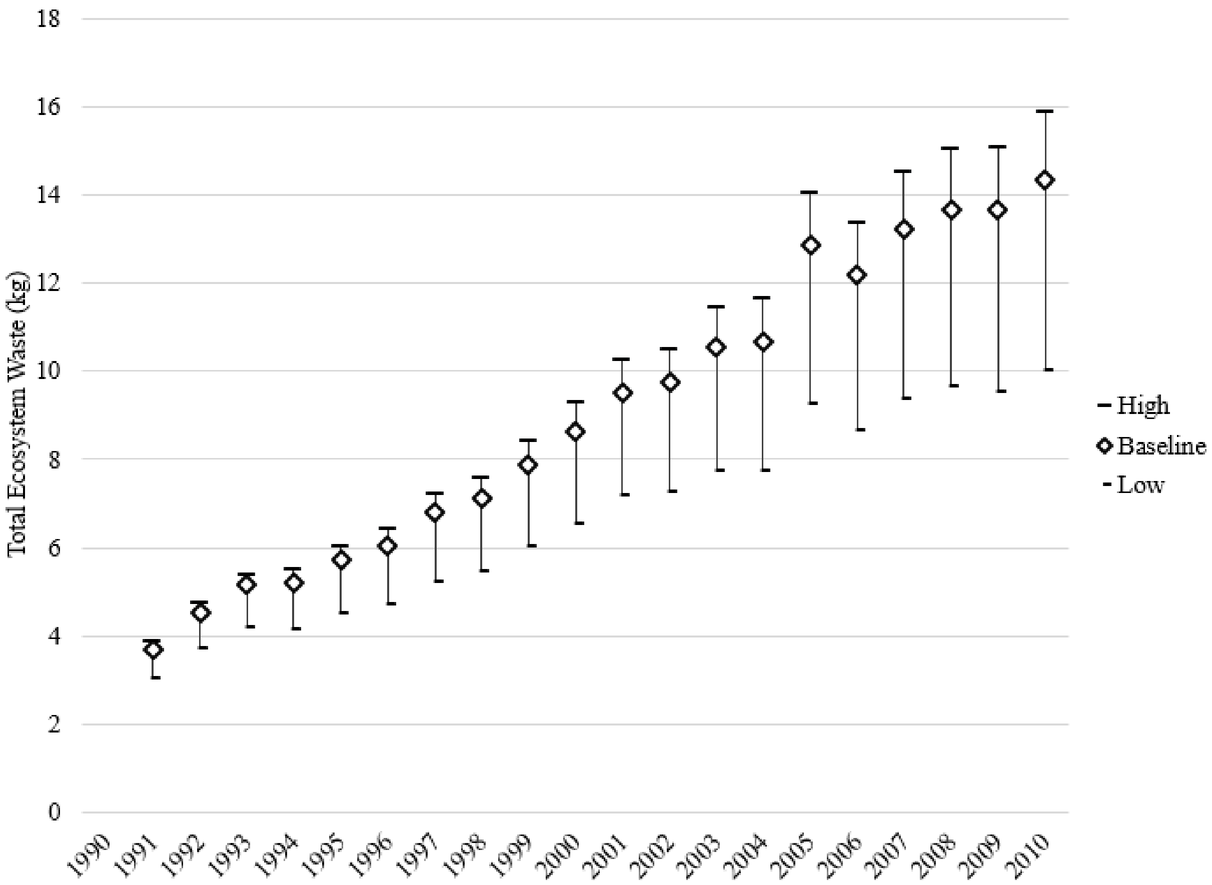

Figure B-16: Baseline, high, and low total ecosystem waste.

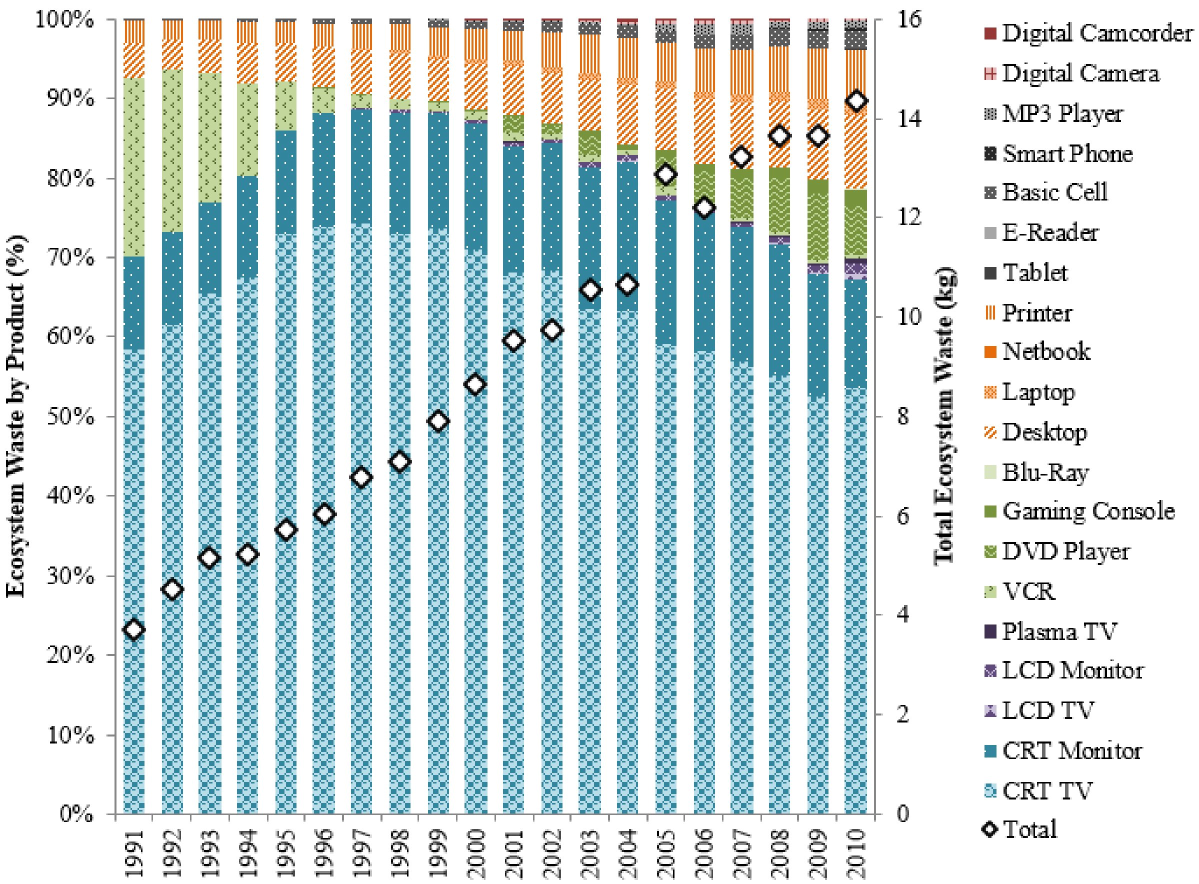

Figure B-17: Baseline ecosystem waste by product.

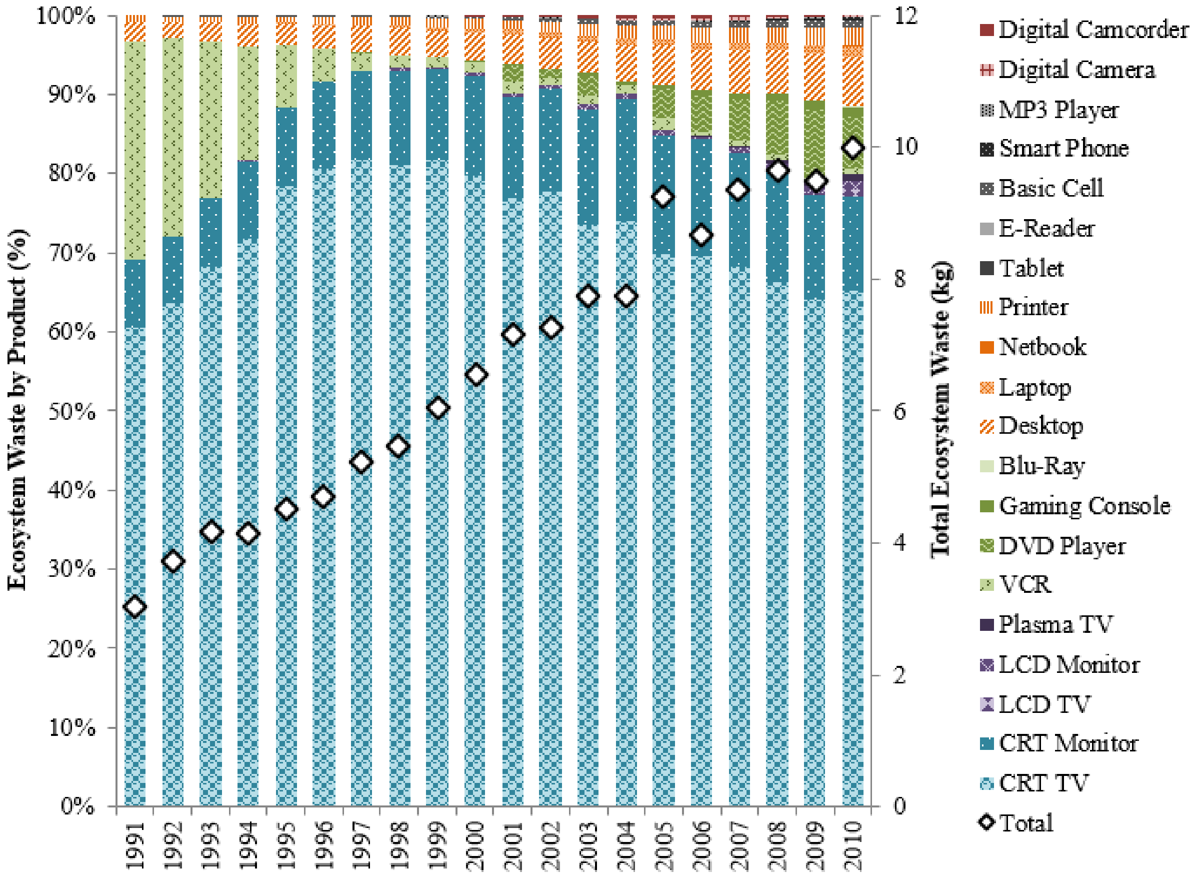

Figure B-18: Low ecosystem waste by product.

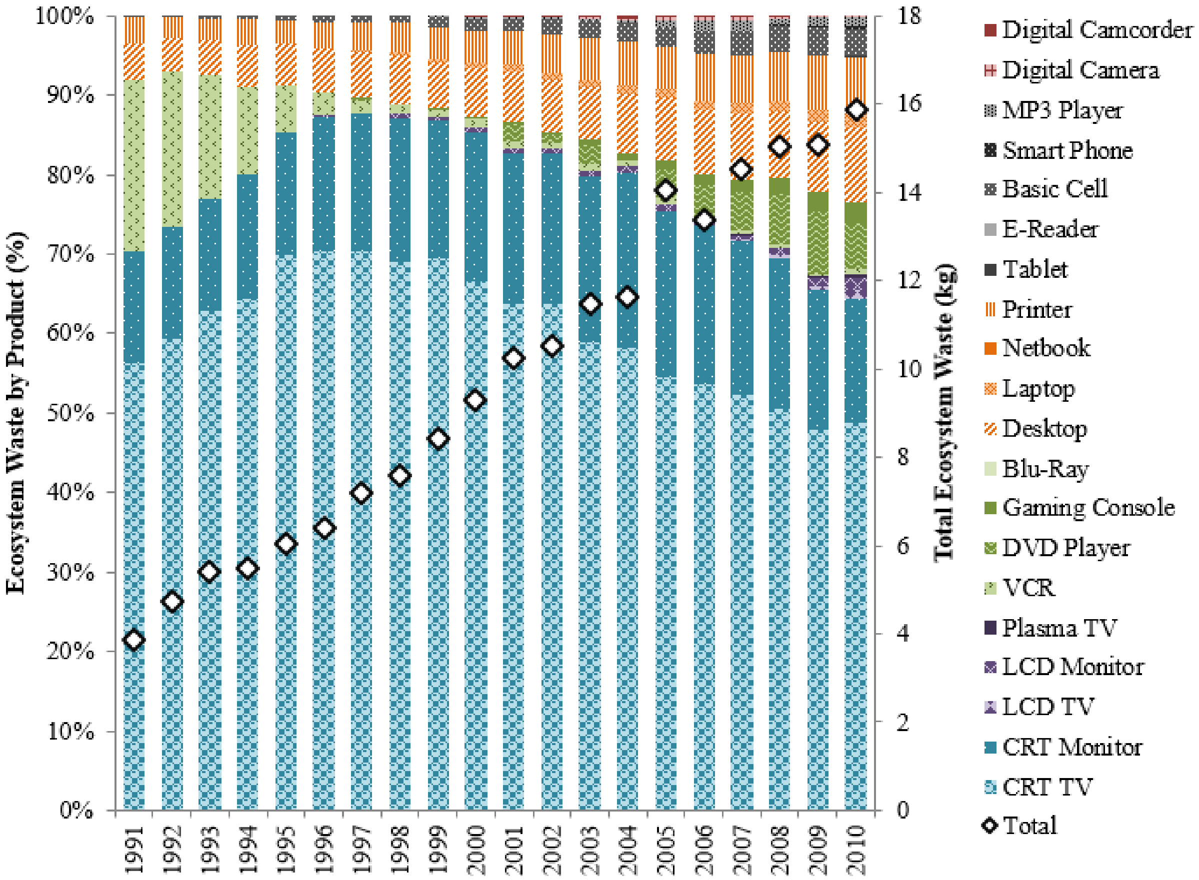

Figure B-19: High ecosystem waste by product.

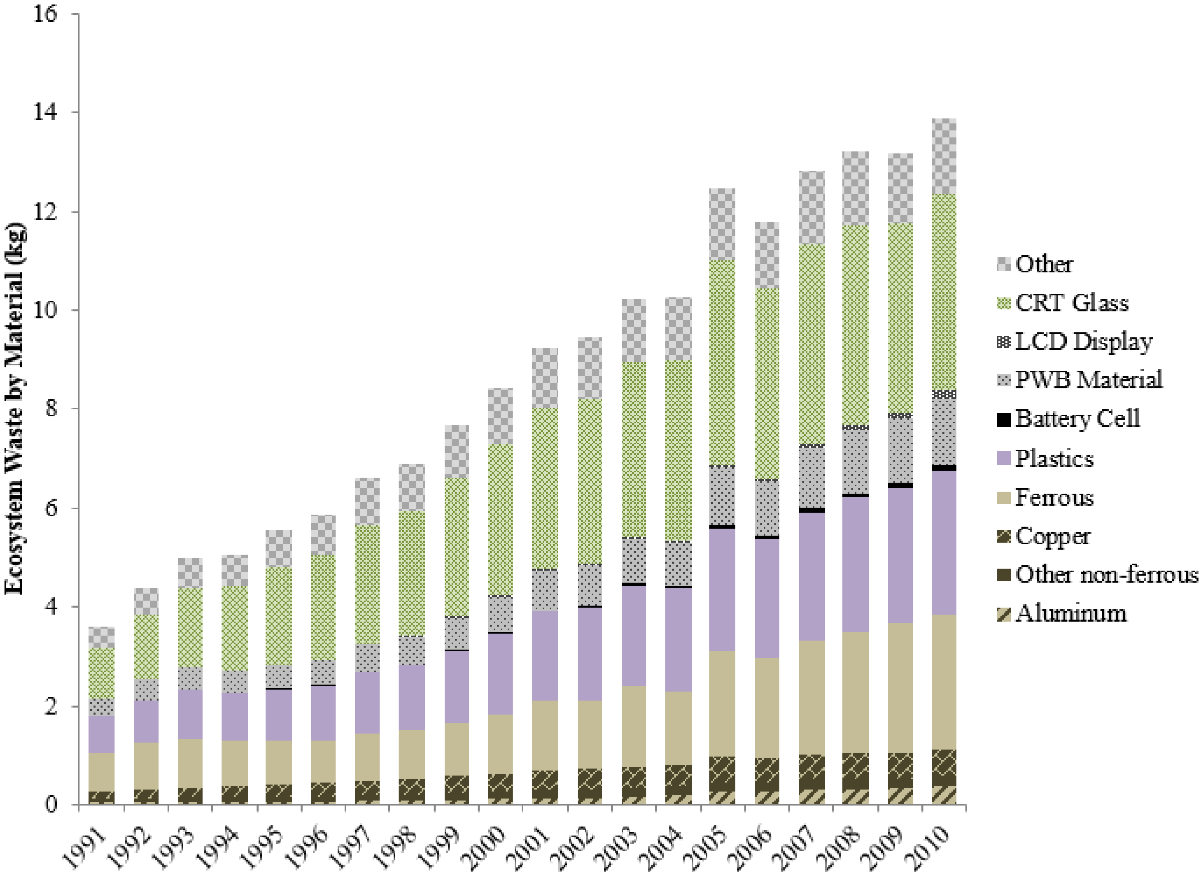

Figure B-20: Baseline ecosystem waste by material.

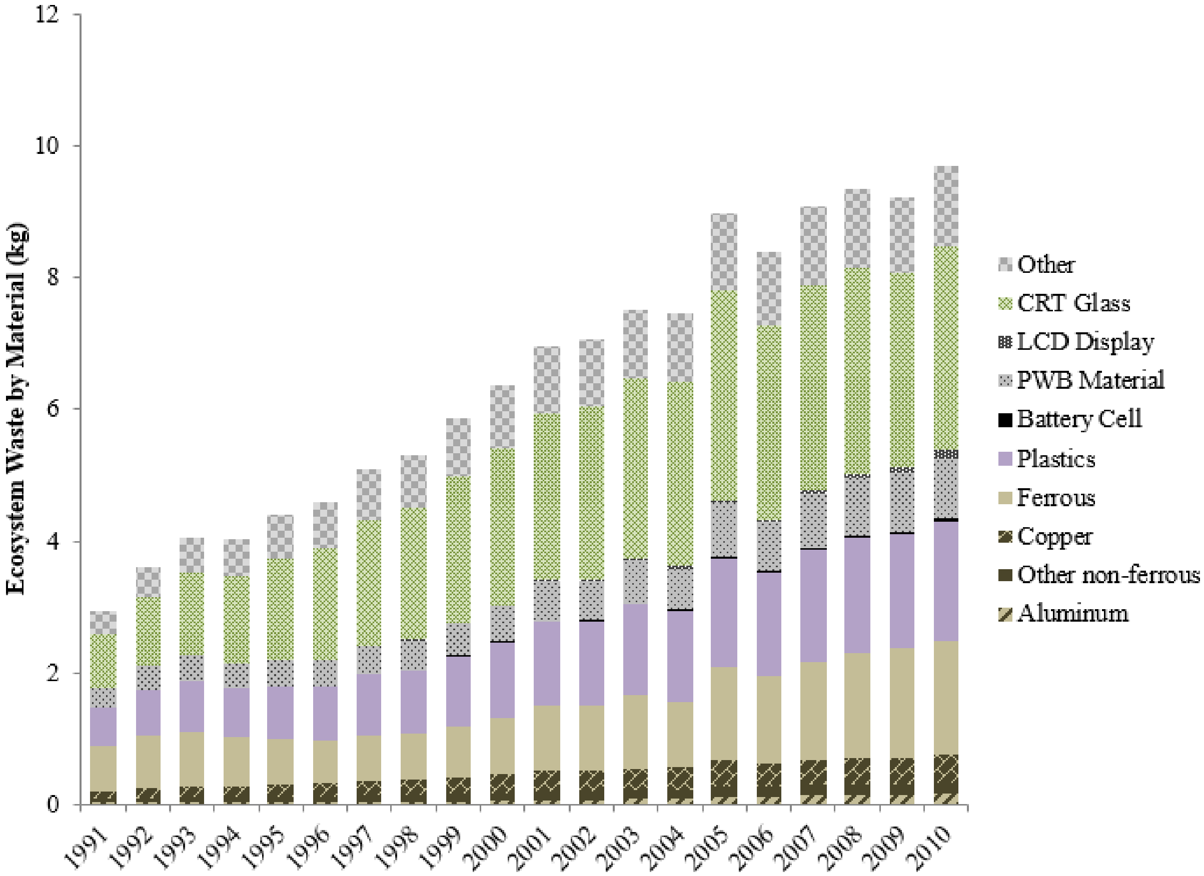

Figure B-21: Low ecosystem waste by material.

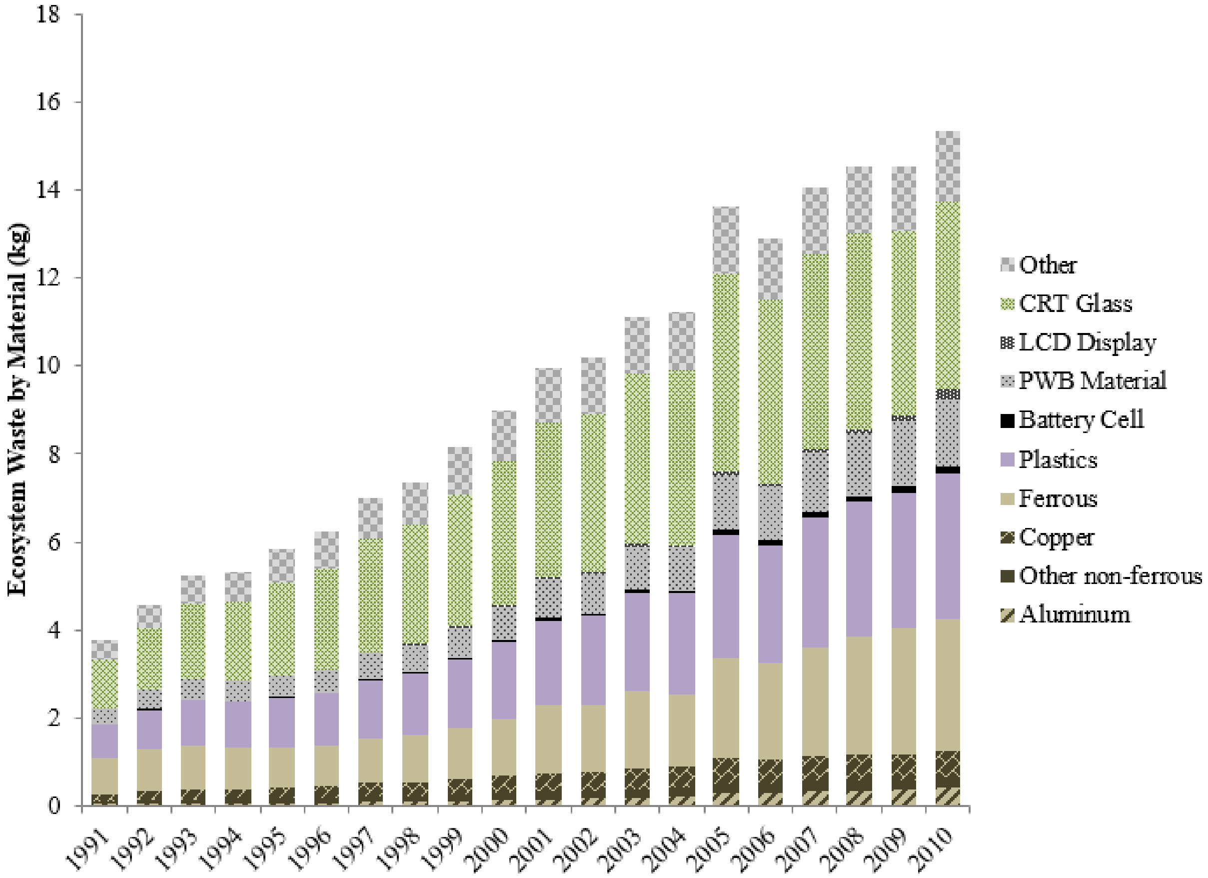

Figure B-22: High ecosystem waste by material.

Appendix C: RIT Home Technology Study & Survey Results

This appendix provides the full text and question skip coding for each question included in the survey administered in Chapter IV, summary data of results, and additional analysis not included in the main text.

Introduction and Screening

Base: All Respondents
S1. Thank you for agreeing to take this survey.

> We are interested in your opinions about and experiences with some of the electronic products you use or might use in the future. You have been selected at random to participate in this study and your responses will be treated as completely confidential.
>
> We would like to begin with a few background questions.

Base: All Respondents
Numeric Entry
S2. How old are you?

Base: All Respondents
Computed From S2
S3. AGE BRACKET [COMPUTED FROM S2]

1	0-17	**TERMINATE**
2	18-24	
3	25-29	
4	30-34	
5	35-39	
6	40-44	
7	45-49	
8	50-54	
9	55-59	
10	60-64	
11	65-69	
12	70-74	
13	75-79	
18	80 or older	

Base: All Respondents 18 and Older
S4. Are you male or female?

1. Male
2. Female

Base: All Respondents 18 and Older
S5. What state do you live in? **TERMINATE ANY RESPONDENTS NOT LIVING IN US STATE**

Qualified Respondents: 18 and over, living in US state.

Base: All Respondents 18 and Older
Q10 For each of the electronic products below, please indicate whether it is available for your use. Do not include any products provided by your employer or school. Please include all products available to you even if they are in storage or you are not actively using them.

1- Yes this product is available for my use
2- No this product is not available for my use

RANDOMIZE LIST

1- A digital camera
2- A digital camcorder (digital video recorder)
3- A Cathode Ray Tube (CRT) (box shaped) television
4- A flat screen television
5- A DVD Player
6- A Blu-Ray Player
7- A gaming console (such as a Wii, Playstation or XBOX)
8- A smartphone (such as an iPhone, Android, other web-enabled cellular device)
9- A basic mobile phone (talk and text only)
10- An MP3 Player (such as an iPod)
11- A tablet
12- A laptop computer
13- A desktop computer
14- A printer

If answer to Q10, ALL ITEMS 1 – 14 EQ 2 ➔ ASK Q240-Q248, Q300, Q412 Section 500, and Section 600

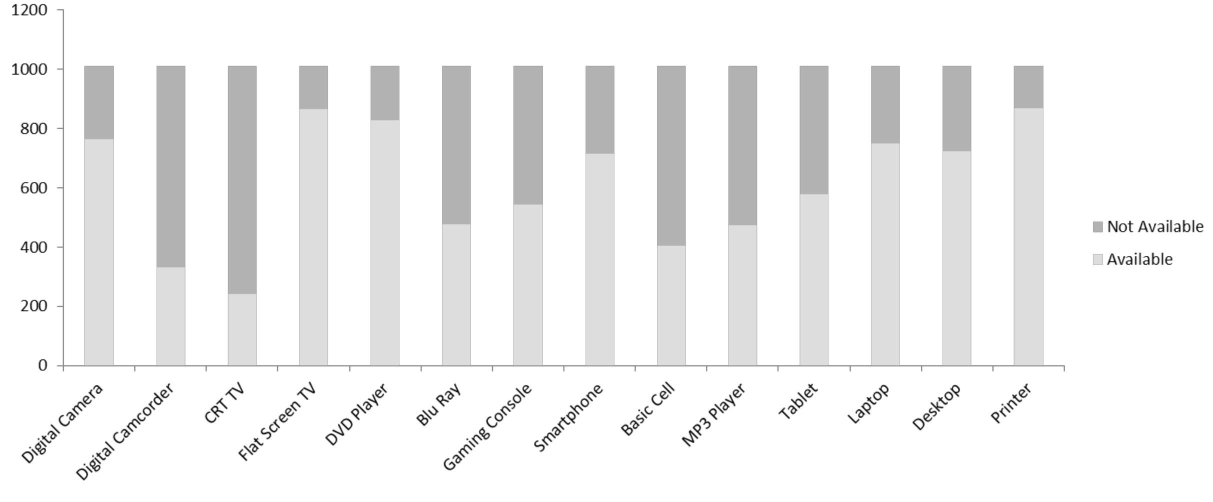

Figure C- 1: Q10 global response distribution

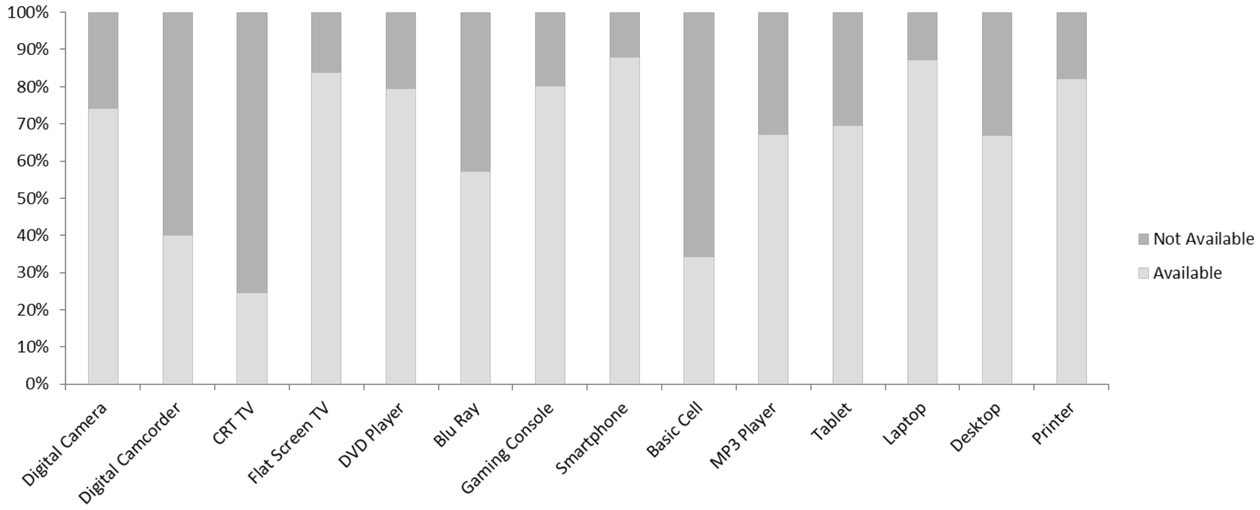

Figure C- 2: Q10 Response distribution 34 and younger

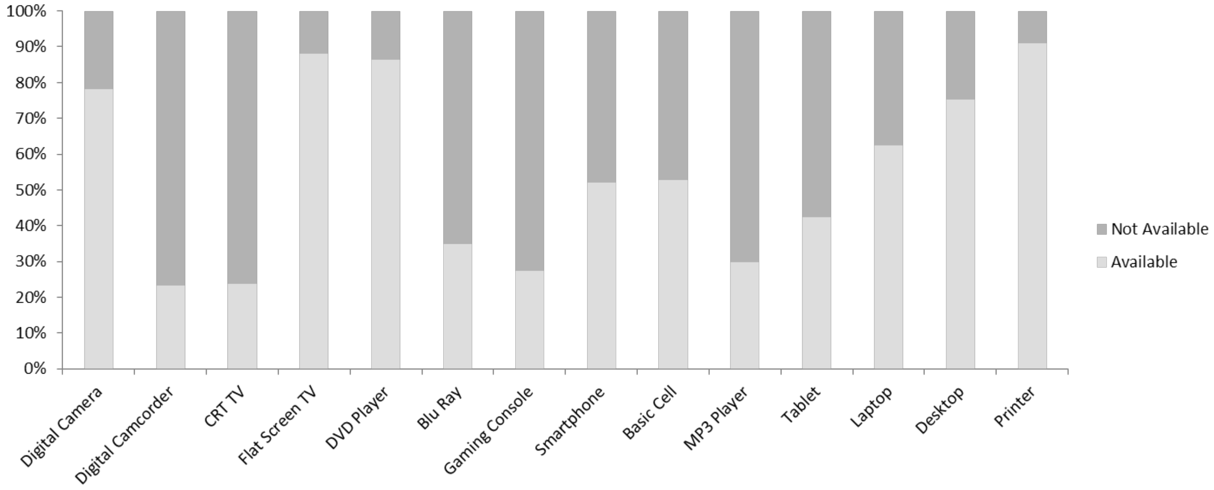

Figure C- 3: Q10 Response distribution 55 and older

Section 100: Ownership and Use of Products

Base: At least one yes (1) to Q10

Q100. You indicated that you have the following products available for your use. Please indicate when you purchased or acquired your most recently acquired version of each product.

1- Less than 6 months ago
2- Between 6 months and 1 year ago
3- Between 1 and 2 years ago
4- More than 2 years ago

RANDOMIZE LIST
KEEP AND SHOW PRODUCTS BELOW WHERE Q10 EQ 1

1- A digital camera
2- A digital camcorder (digital video recorder)
3- A Cathode Ray Tube (CRT) (box shaped) television
4- A flat screen television
5- A DVD Player
6- A Blu-Ray Player
7- A gaming console (such as a Wii, Playstation or XBOX)
8- A smartphone (such as an iPhone, Android, other web-enabled cellular device)
9- A basic mobile phone (talk and text only)
10- An MP3 Player (such as an iPod)
11- A tablet
12- A laptop computer
13- A desktop computer
14- A printer

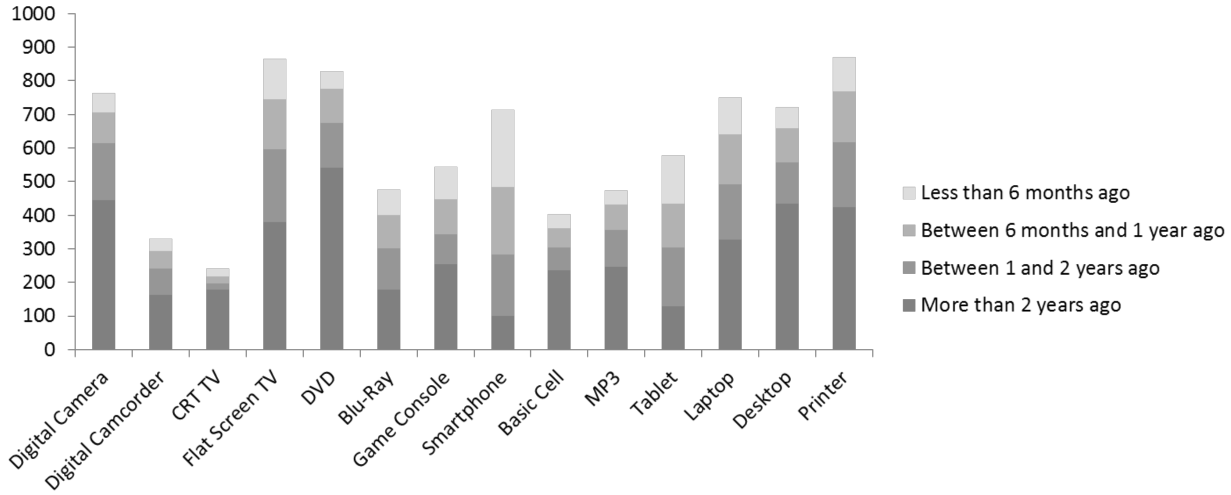

Figure C- 4: Q100 response distribution

Base: At least one yes (1) to Q10
Q110. How often do you use your most recently acquired version of each of the following products?

1- Many times per day
2- One or two times per day
3- A few times per week
4- A few times per month
5- Once or twice per year
6- Less often than once or twice per year

RANDOMIZE LIST
KEEP AND SHOW PRODUCTS BELOW WHERE Q10 EQ 1

1- A digital camera
2- A digital camcorder (digital video recorder)
3- A Cathode Ray Tube (CRT) (box shaped) television
4- A flat screen television
5- A DVD Player
6- A Blu-Ray Player
7- A gaming console (such as a Wii, Playstation or XBOX)
8- A smartphone (such as an iPhone, Android, other web-enabled cellular device)
9- A basic mobile phone (talk and text only)
10- An MP3 Player (such as an iPod)
11- A tablet
12- A laptop computer
13- A desktop computer
14- A printer

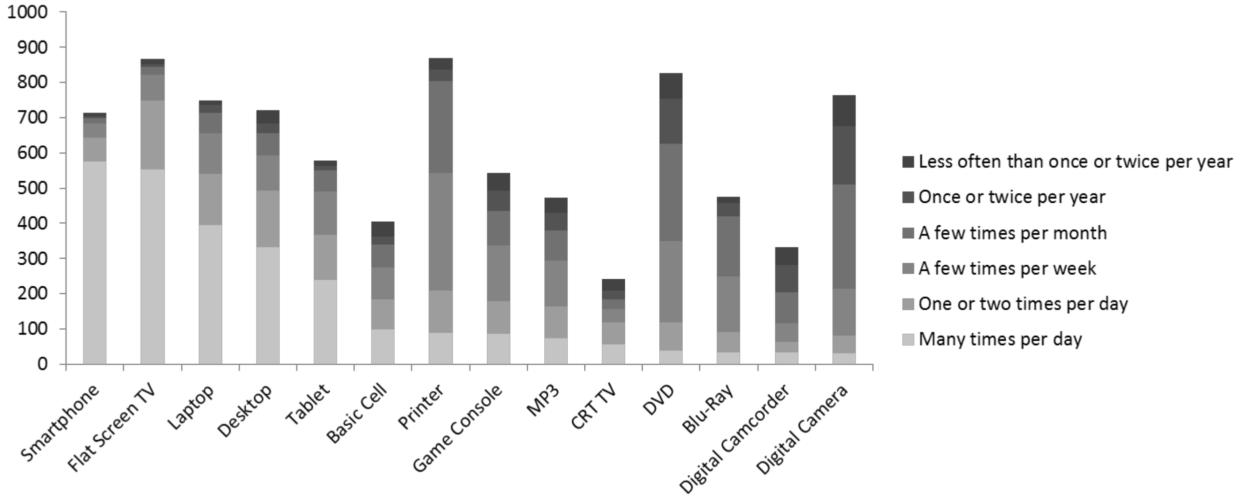

Figure C- 5: Q110 response distribution

Base: All Respondents with at least one product in Q110 that they use at least a few times a month or more often (Q110=1,2,3,4).
Q120. How has your use of your most recently acquired version of the following products changed over the past six months?

1- Increased
2- Remained about the same
3- Decreased

RANDOMIZE LIST
KEEP AND SHOW PRODUCTS WHERE Q110, ITEMS 1-14 EQ 1, 2, 3, or 4

1- A digital camera
2- A digital camcorder (digital video recorder)
3- A Cathode Ray Tube (CRT) (box shaped) television
4- A flat screen television
5- A DVD Player
6- A Blu-Ray Player
7- A gaming console (such as a Wii, Playstation or XBOX)
8- A smartphone (such as an iPhone, Android, other web-enabled cellular device)
9- A basic mobile phone (talk and text only)
10- An MP3 Player (such as an iPod)
11- A tablet
12- A laptop computer
13- A desktop computer
14- A printer

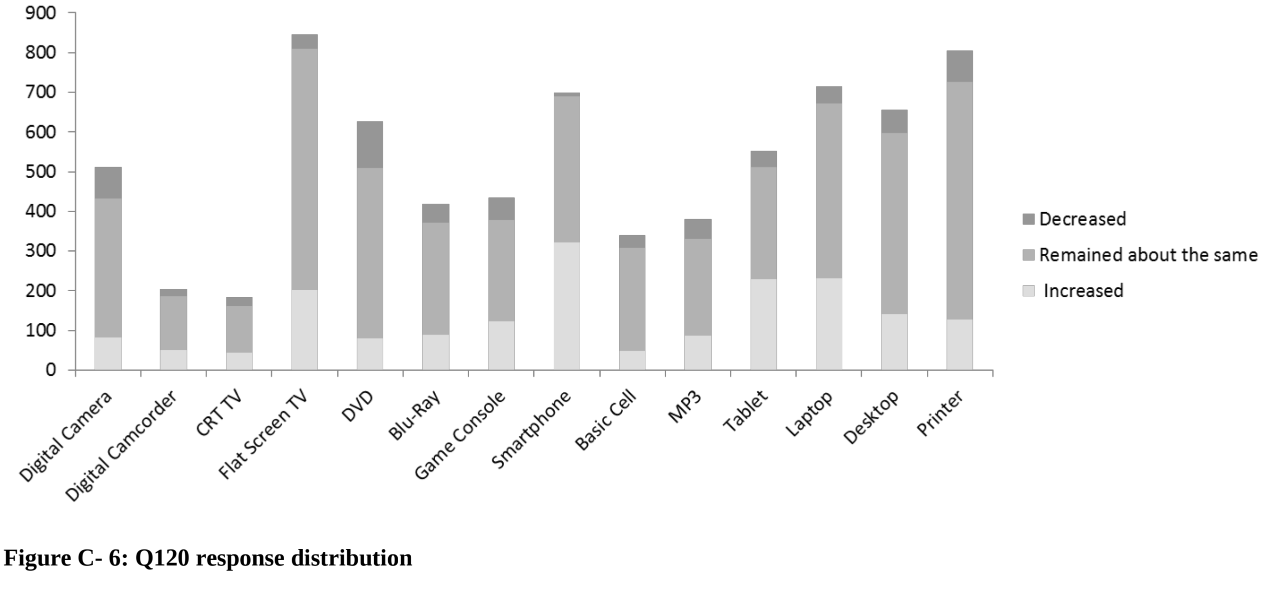

Figure C- 6: Q120 response distribution

Base: Answered 5 or 6 for DIGITAL CAMERA (Item 1) in Q110
This is a single response question.
Q130. Is the main reason you use your most recently acquired DIGITAL CAMERA once or twice per year or less often because:

RANDOMIZE LIST
ANCHOR ITEM 6 (SOME OTHER REASON)

1- You no longer take pictures
2- You are using an older digital camera instead
3- You are using your smartphone to take pictures
4- You use a film or one-time use camera when you want to take pictures
5- Your digital camera broke and you haven't had a chance to replace it yet
6- Some other reason [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

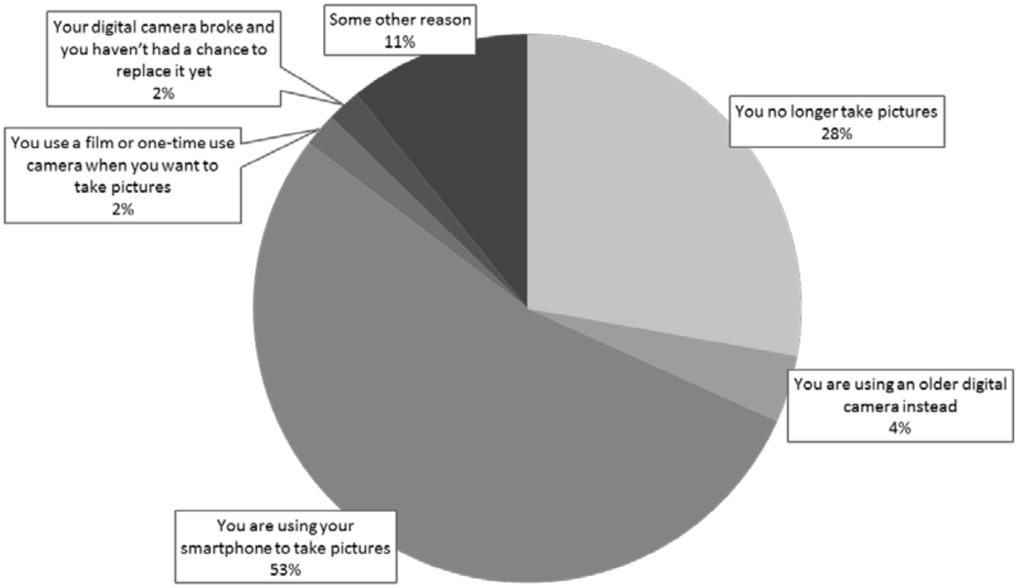

Figure C- 7: Q130 response distribution

Base: Answered 5 or 6 for FLAT SCREEN TELEVISION (Item 4) in Q110
This is a single response question
Q132. Is the main reason you use your most recently acquired FLAT SCREEN TELEVISION once or twice per year or less often because:

RANDOMIZE LIST
ANCHOR ITEM 7 (SOME OTHER REASON)

1- You no longer watch television
2- You are using an older television
3- You are using your tablet to watch television or movies
4- You are using your smartphone to watch television or movies
5- You are using your laptop computer to watch television or movies
6- Your television broke and you haven’t had a chance to replace it yet
7- Some other reason [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

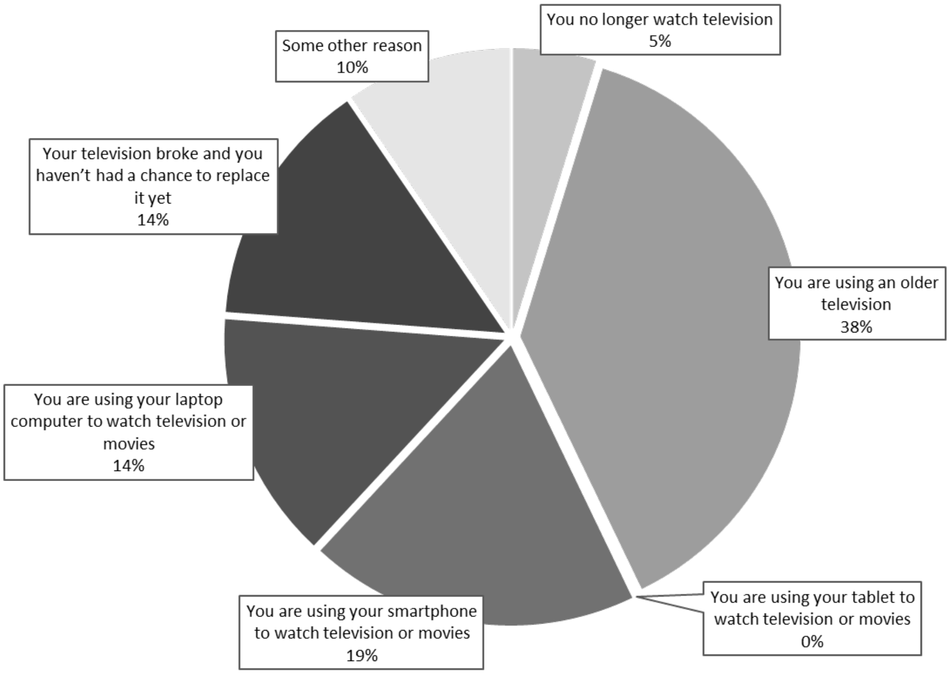

Figure C- 8: Q132 response distribution

Base: Answered 5 or 6 for SMARTPHONE (Item 8) in Q110
This is a single response question.
Q134. Is the main reason you use your most recently acquired SMARTPHONE once or twice per year or less often because:

RANDOMIZE LIST
ANCHOR ITEM 6 (SOME OTHER REASON)

1- You no longer use a smartphone
2- You are using an older smartphone instead
3- You are using a basic mobile phone or land line to make phone calls
4- You use a tablet or computer to make video calls instead
5- Your smartphone broke and your haven’t had a chance to replace it yet
6- Some other reason [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

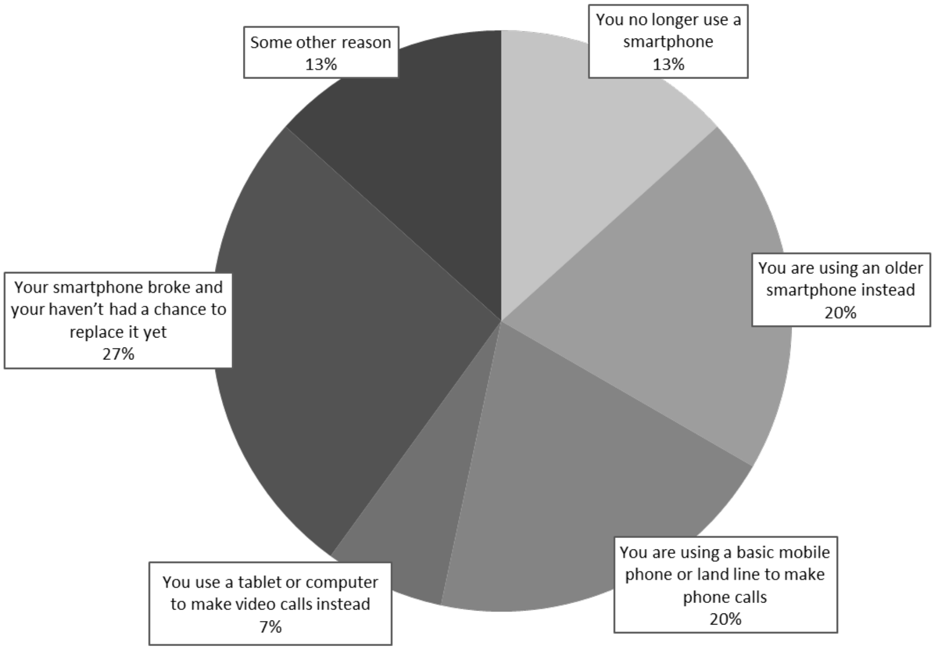

Figure C- 9: Q134 response distribution

Base: Answered 5 or 6 for TABLET (Item 11) in Q110
This is a single response question.
Q136. Is the main reason you use your most recently acquired TABLET once or twice per year or less often because:

RANDOMIZE LIST
ANCHOR ITEM 6 (SOME OTHER REASON)

1- You no longer use a tablet
2- You are using an older tablet instead
3- You are using your smartphone to accomplish all of the tablet's functions
4- You are using a computer to accomplish all of the tablet's functions
5- Your tablet broke and you haven't had a chance to replace it yet
6- Some other reason [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

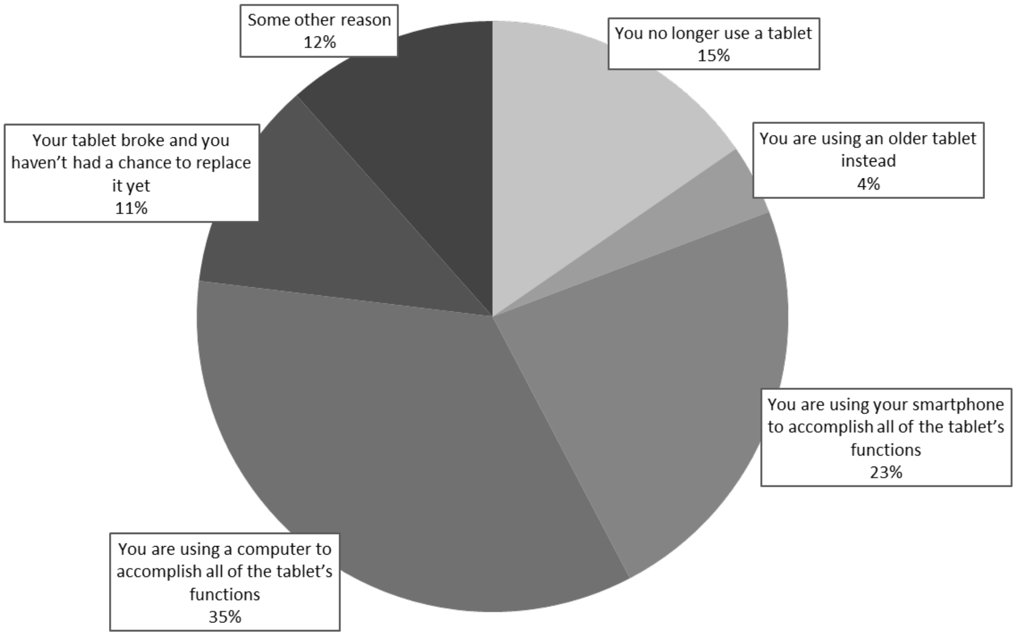

Figure C- 10: Q136 response distribution

Base: Answered 5 or 6 for LAPTOP COMPUTER (Item 12) in Q110
This is a single response question
Q138. Is the main reason you use your most recently acquired LAPTOP COMPUTER once or twice per year or less often because:

RANDOMIZE LIST
ANCHOR ITEM 6 (SOME OTHER REASON)

1- You no longer use a computer
2- You are using an older laptop computer instead
3- You are using a desktop computer instead
4- You are using your tablet to accomplish all of your computing
5- Your laptop broke and you haven't had a chance to replace it yet
6- Some other reason [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

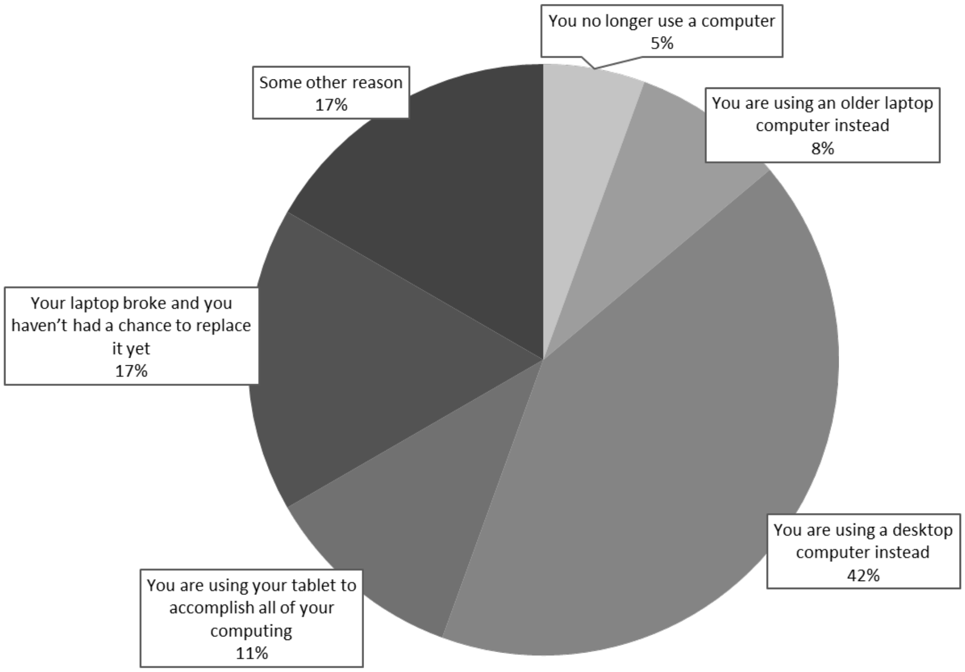

Figure C- 11: Q138 response distribution

Section 200 – Product Use and Perceived Quality

Base: All respondents who Indicate that they use their SMARTPHONE at least a few times per month (Answers 1, 2, 3, or 4) in Q110
This is a multiple response question.
Q200. Thinking about the smartphone that you acquired most recently, which of the following tasks have you performed within the last month using that smartphone?

RANDOMIZE LIST
ANCHOR ITEMS 14 and 15.

1- Made voice or video phone calls
2- Sent or received text messages
3- Sent or received emails
4- Typed or edited documents or performed other productivity tasks (spreadsheets, presentations)
5- Wrote, drew, created digital art, or other creative tasks
6- Searched or browsed the Internet
7- Visited social media sites
8- Made online purchases or other e-commerce transactions
9- Took digital photographs
10- Listened to music
11- Played games
12- Got directions
13- Watched movies or television programs
14- Other [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]
15- None of these

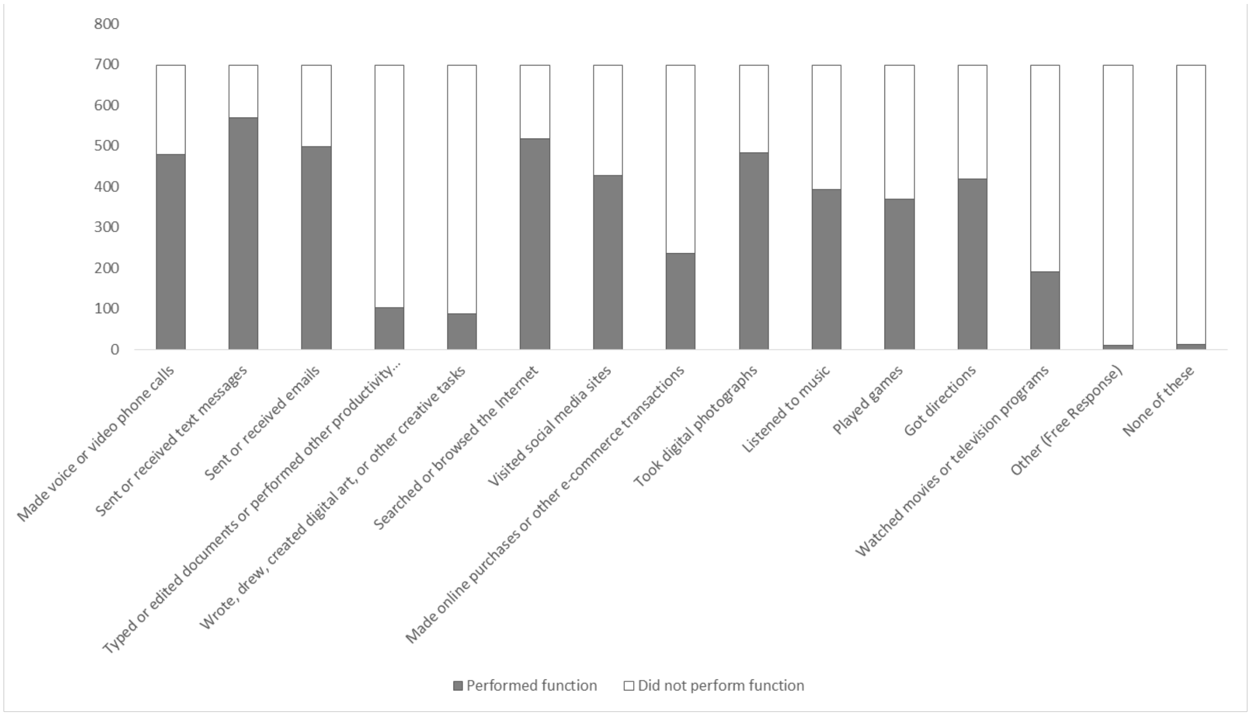

Figure C- 12: Q200 response distribution

Base: All respondents who Indicate that they use their TABLET at least a few times per month (Answers 1, 2, 3, or 4) in Q110
This is a multiple response question.
Q210. Thinking about the tablet that you acquired most recently, which of the following tasks have you performed within the last month using that tablet?

RANDOMIZE LIST
ANCHOR ITEMS 14 and 15

1- Made voice or video phone calls
2- Sent or received text messages
3- Sent or received emails
4- Typed or edited documents or performed other productivity tasks (spreadsheets, presentations)
5- Wrote, drew, created digital art, or other creative tasks
6- Searched or browsed the Internet
7- Visited social media sites
8- Made online purchases or other e-commerce transactions
9- Took digital photographs
10- Listened to music
11- Played games
12- Got directions
13- Watched movies or television programs
14- Other [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]
15- None of these

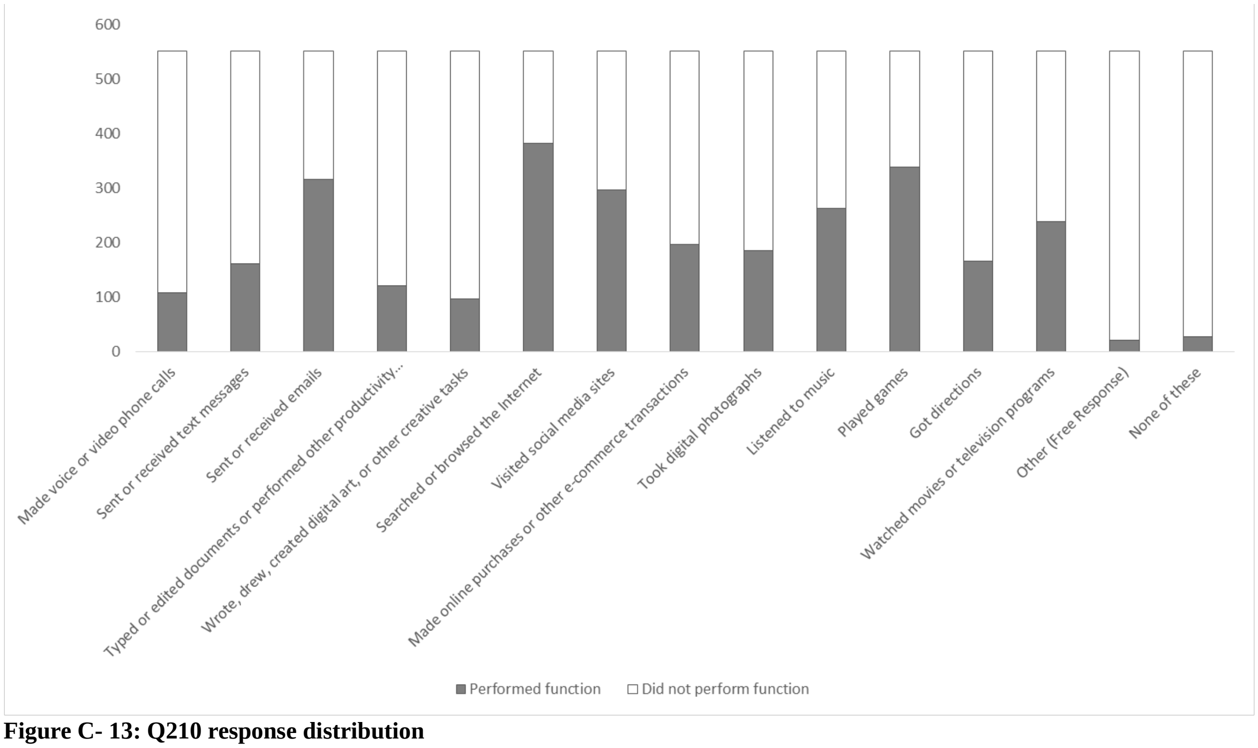

Figure C- 13: Q210 response distribution

Base: All respondents who indicate that they use their LAPTOP COMPUTER at least a few times per month (Answers 1, 2, 3, or 4) in Q110
This is a multiple response question.
Q220. Thinking about the laptop computer that you acquired most recently, which of the following tasks have you performed within the last month using that laptop?

RANDOMIZE LIST
ANCHOR ITEMS 12 and 13

1- Made voice or video phone calls
2- Sent or received emails
3- Typed documents or performed other productivity tasks (spreadsheets, presentations)
4- Wrote, drew, created digital art, or other creative tasks
5- Searched or browsed the Internet
6- Visited social media sites
7- Made online purchases or other e-commerce transactions
8- Listened to music
9- Played games
10- Got directions
11- Watched movies or television programs
12- Other [SPECIFY ALLOWING AT LEAST 100 CHARACTERS)
13- None of these

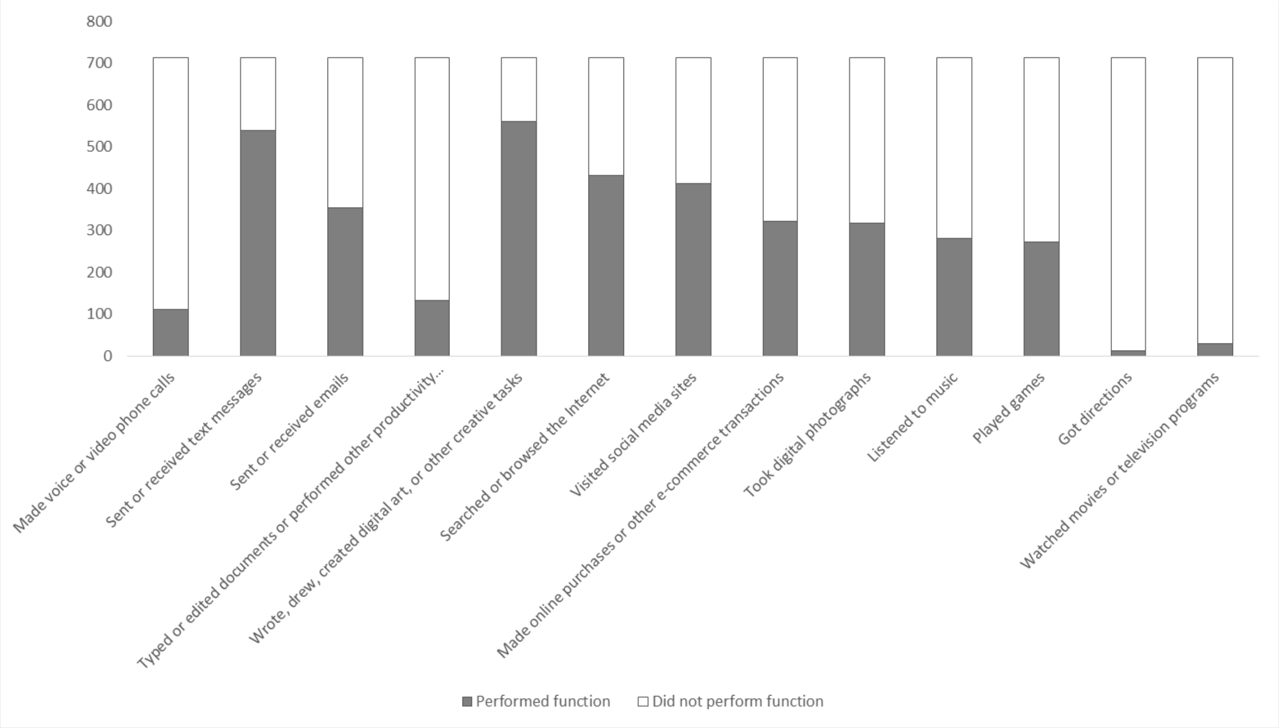

Figure C- 14: Q220 response distribution

Base: Respondents who have at least one of the products (Items 1-6 in the List Below) in Q10
This is a single response question.
Q230. Think about the times you've watched movies or television programs in the last couple of months using one of the electronic products you have at home. Which one of the following products did you use the most?

KEEP AND SHOW PRODUCTS BELOW WHERE Q10 EQ 1
RANDOMIZE LIST
ANCHOR ITEMS 7 and 8

1- Flat Screen Television
2- CRT (Box shaped) Television
3- Tablet
4- Laptop Computer
5- Desktop Computer
6- Smartphone
7- I used a different product the most [SPECIFY ALLOWING AT LEAST 100 CHARACTERS)
8- I do not watch movies or television programs at home

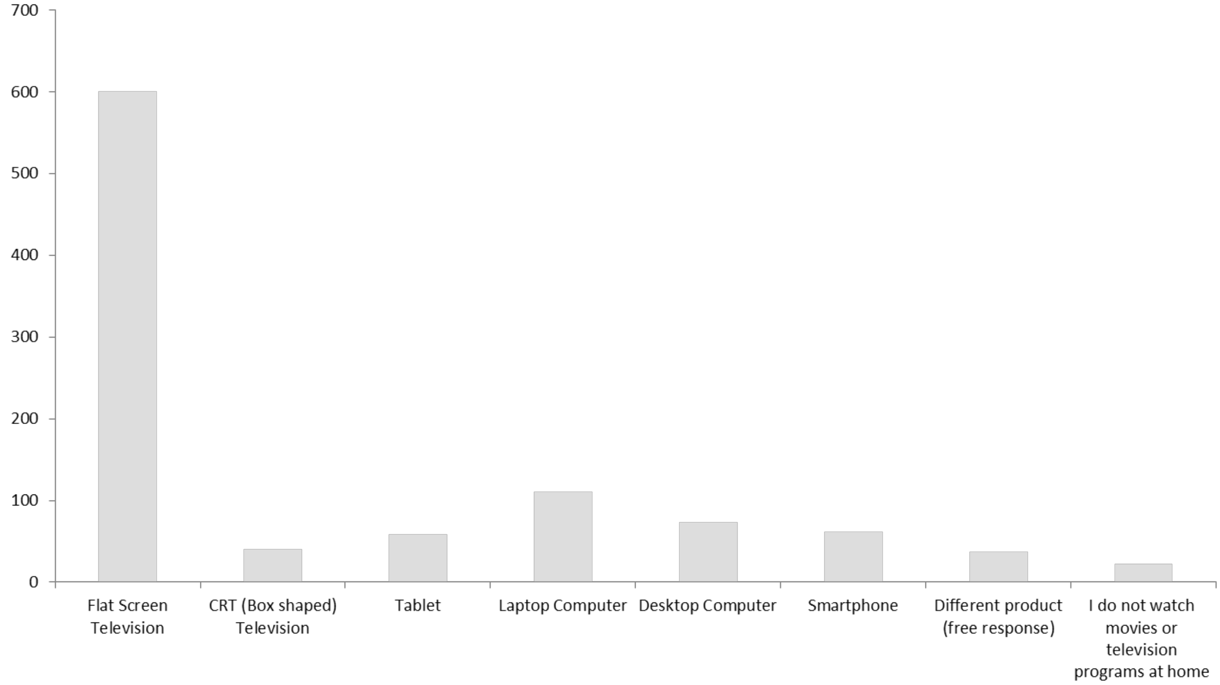

Figure C- 15: Q230 response distribution

Base: Respondents who have at least one of the products (Items 1-4 in the List Below) in Q10
This is a single response question.
Q232. Think about the times you've searched or browsed the Internet in the last couple of months using one of the electronic products you have at home. Which one of the following products did you use the most?

KEEP AND SHOW PRODUCTS BELOW WHERE Q10 EQ 1
RANDOMIZE LIST
ANCHOR ITEMS 5 and 6

1- Smartphone
2- Tablet
3- Laptop Computer
4- Desktop Computer
5- I used a different product the most [SPECIFY ALLOWING AT LEAST 100 CHARACTERS)
6- I do not search or browse the internet

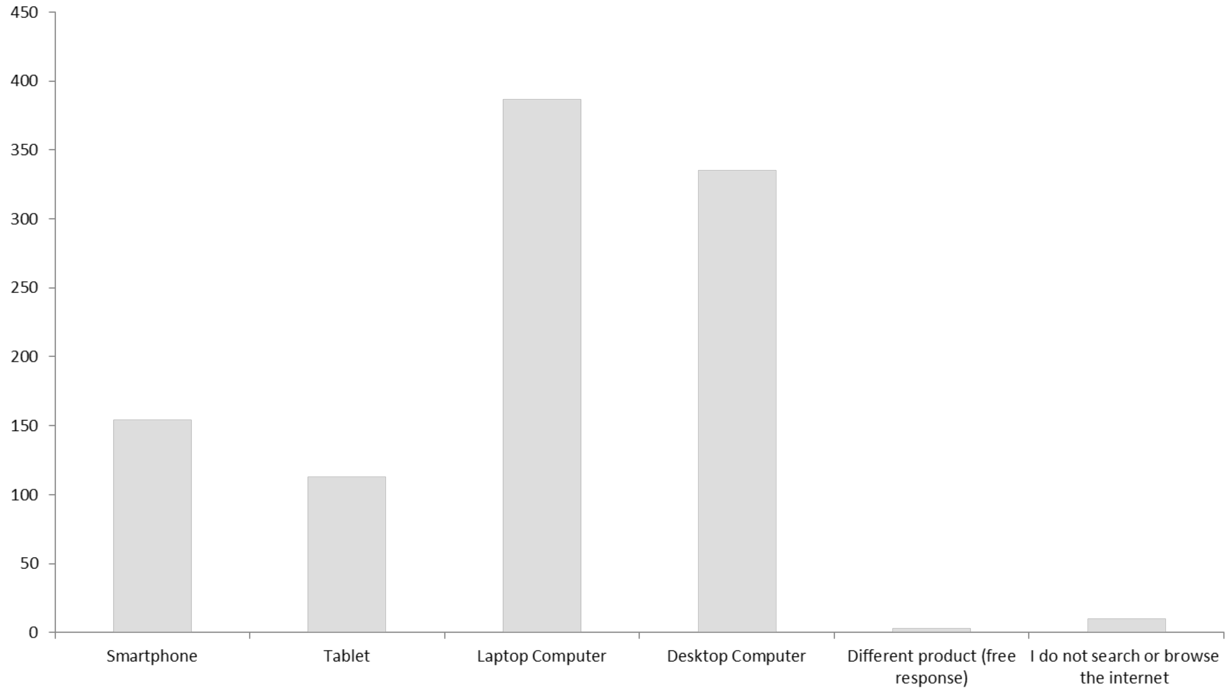

Figure C- 16: Q232 response distribution

Base: Respondents who have at least one of the products (Items 1-3 in the List Below) in Q10
This is a single response question.
Q234. Think about the times you've written a document in the last couple of months using one of the electronic products you have at home. Which one of the following products did you use most?

KEEP AND SHOW PRODUCTS BELOW WHERE Q10 EQ 1
RANDOMIZE LIST
ANCHOR ITEMS 4 and 5

1- Laptop Computer
2- Desktop Computer
3- Tablet
4- I used a different product the most [SPECIFY ALLOWING AT LEAST 100 CHARACTERS)
5- I do not write documents

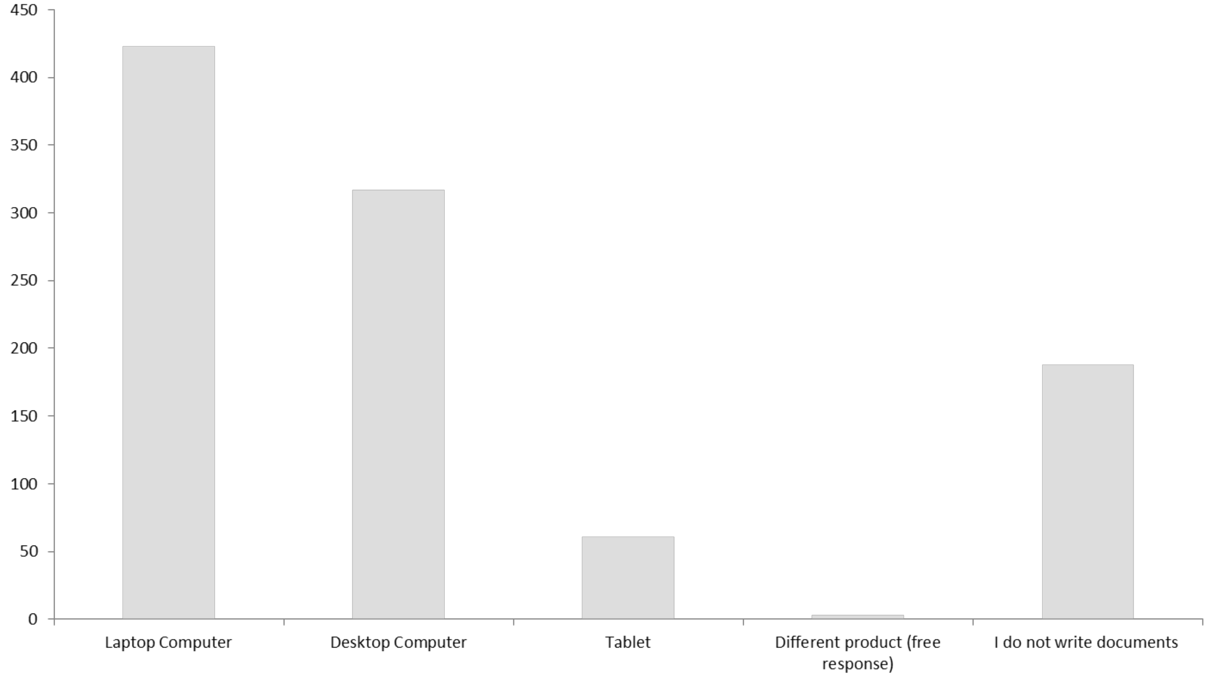

Figure C- 17: Q234 response distribution

Base: Respondents who have at least one of the products (Items 1-4) in the list below in Q10
This is a single response question.
Q236. Think about the times you've sent emails in the last couple of months using one of the electronic products you have at home. Which one of the following products did you use most?

KEEP AND SHOW PRODUCTS WHERE Q10 EQ 1
RANDOMIZE LIST
ANCHOR ITEMS 5 and 6

1- Tablet
2- Laptop Computer
3- Desktop Computer
4- Smartphone
5- I used a different product the most [SPECIFY ALLOWING AT LEAST 100 CHARACTERS)
6- I do not write and send emails

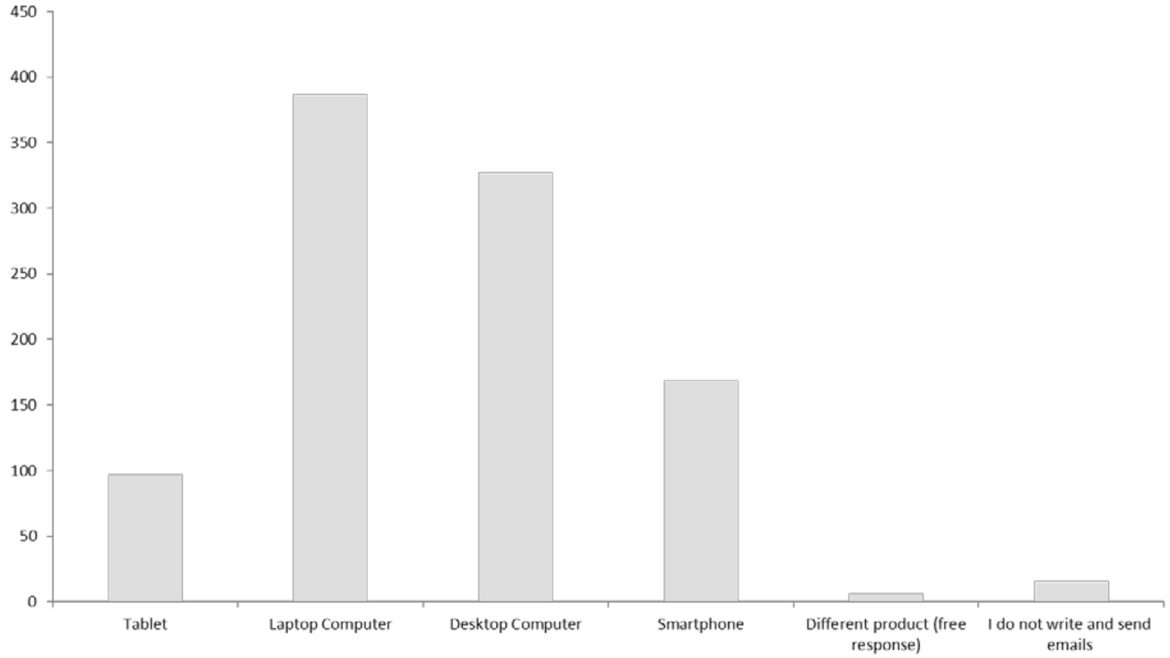

Figure C- 18: Q236 response distribution

Base: Respondents who have at least one of the products (Items 1-4) in the list below in Q10.
This is a single response question.
Q238. Think about the last few times you've taken digital photographs [EVENT FROM LIST BELOW] using one of the electronic products you have at home. Which one of the following products did you use most?

RANDOMIZE EVENT TO INSERT ABOVE FROM THE FOLLOWING. BE SURE TO RECORD WHICH EVENT WAS USED FOR EACH RESPONDENT.

PROGRAMMING: Please capture which of these inserts is used for each respondent. Create a hidden variable to capture inserts/events

with a friend you met for lunch
at a sporting event
of a family member's college graduation
of a new baby in the family

KEEP AND SHOW PRODUCTS WHERE Q10 EQ 1
RANDOMIZE LIST
ANCHOR ITEMS 5 and 6

1- Digital camera
2- Tablet
3- Smartphone
4- Mobile Phone
5- I used a different product the most [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]
6- I do not take digital photographs
7- I have not taken digital photographs at this type of event

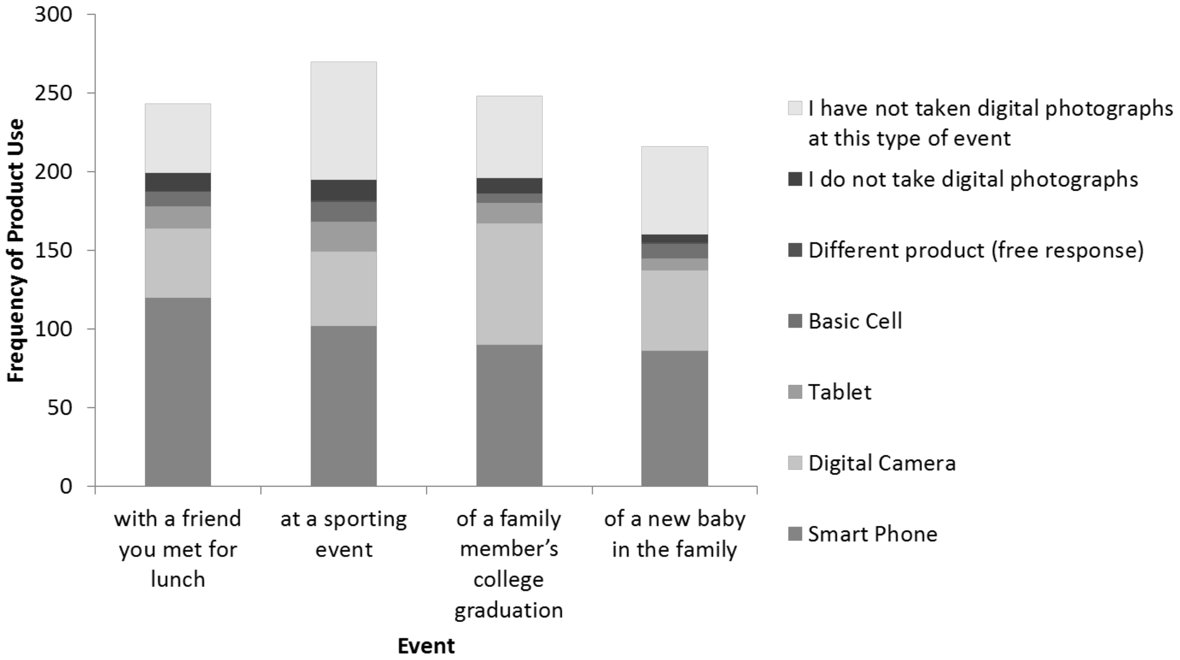

Figure C- 19: Q238 response distribution

PROGRAMMING: Please randomize the order in which Q240 to Q248 are presented to respondents.

Base: All Qualified Respondents
Q240. Suppose you wanted to watch a movie or television program at home. Based on your use of the products shown below or what you may have read or heard about them, please indicate your general impression of the experience each would provide for this activity.

1- Best possible experience
2- Satisfactory experience
3- Minimum acceptable experience
4- Unacceptable experience
5- Not Sure

RANDOMIZE LIST

1- Television (Flat Screen Television)
2- Tablet
3- Laptop Computer
4- Desktop Computer
5- Smartphone

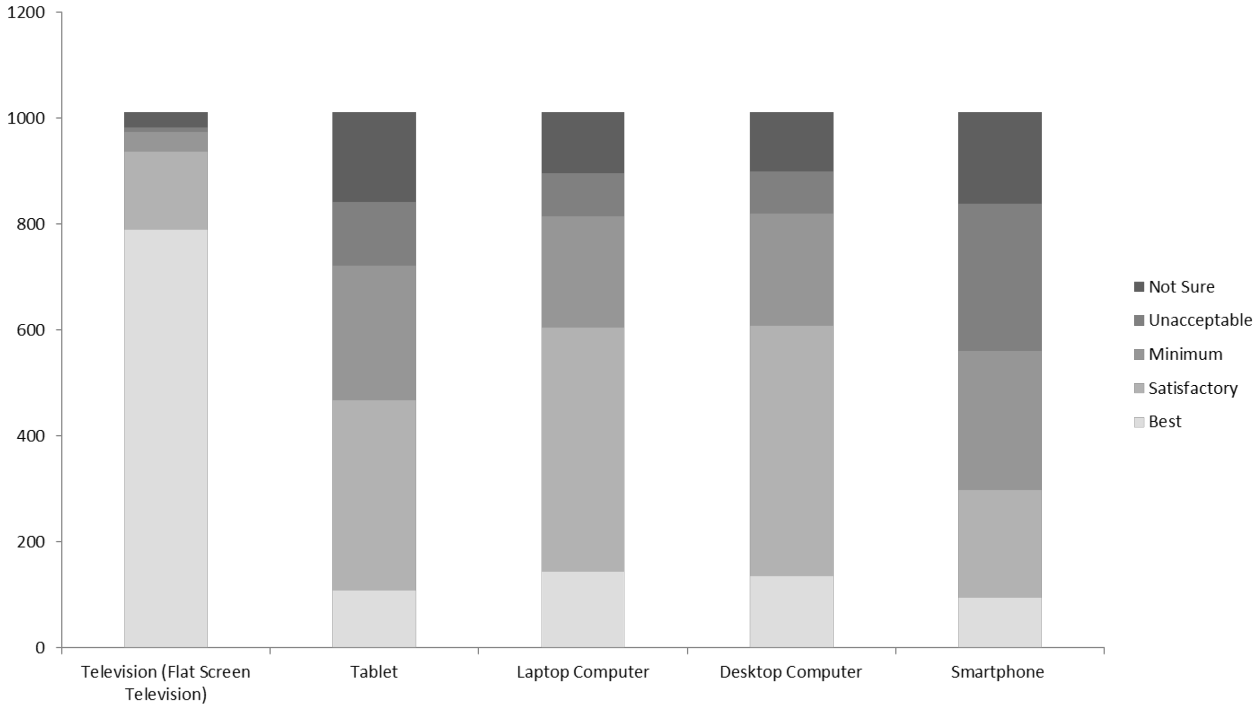

Figure C- 20: Q240 response distribution

Base: All Qualified Respondents.
Q242. Suppose you wanted to surf or browse the Internet. Based on your use of the products shown below or what you may have read or heard about them, please indicate your general impression of the experience each would provide for this activity.

1- Best possible experience
2- Satisfactory experience
3- Minimum acceptable experience
4- Unacceptable experience
5- Not Sure

RANDOMIZE LIST

1- Smartphone
2- Tablet
3- Laptop Computer
4- Desktop Computer
5- Television (Flat Screen Television)

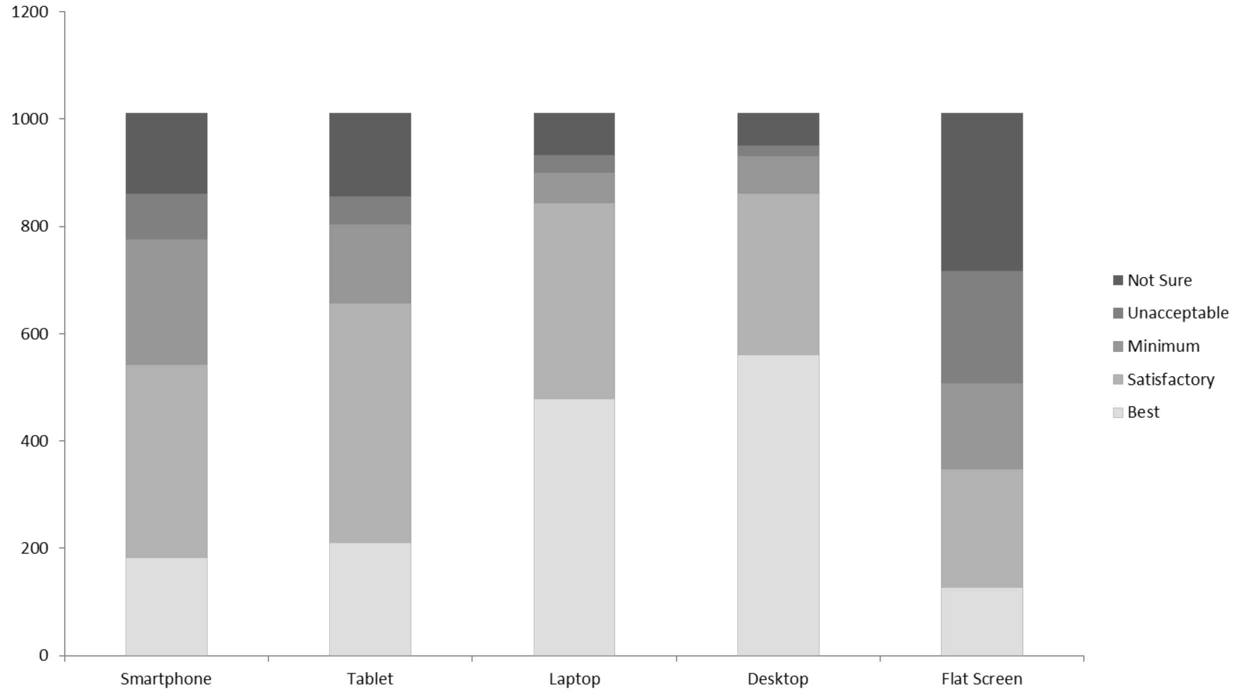

Figure C- 21: Q242 response distribution

Base: All Qualified Respondents
Q244. Suppose you wanted to write or edit a document, which you will use to share information with others. Based on your use of the products shown below or what you may have read or heard about them, please indicate your general impression of the experience each would provide for this activity.

1- Best possible experience
2- Satisfactory experience
3- Minimum acceptable experience
4- Unacceptable experience
5- Not Sure

RANDOMIZE LIST

1- Laptop Computer
2- Desktop Computer
3- Tablet

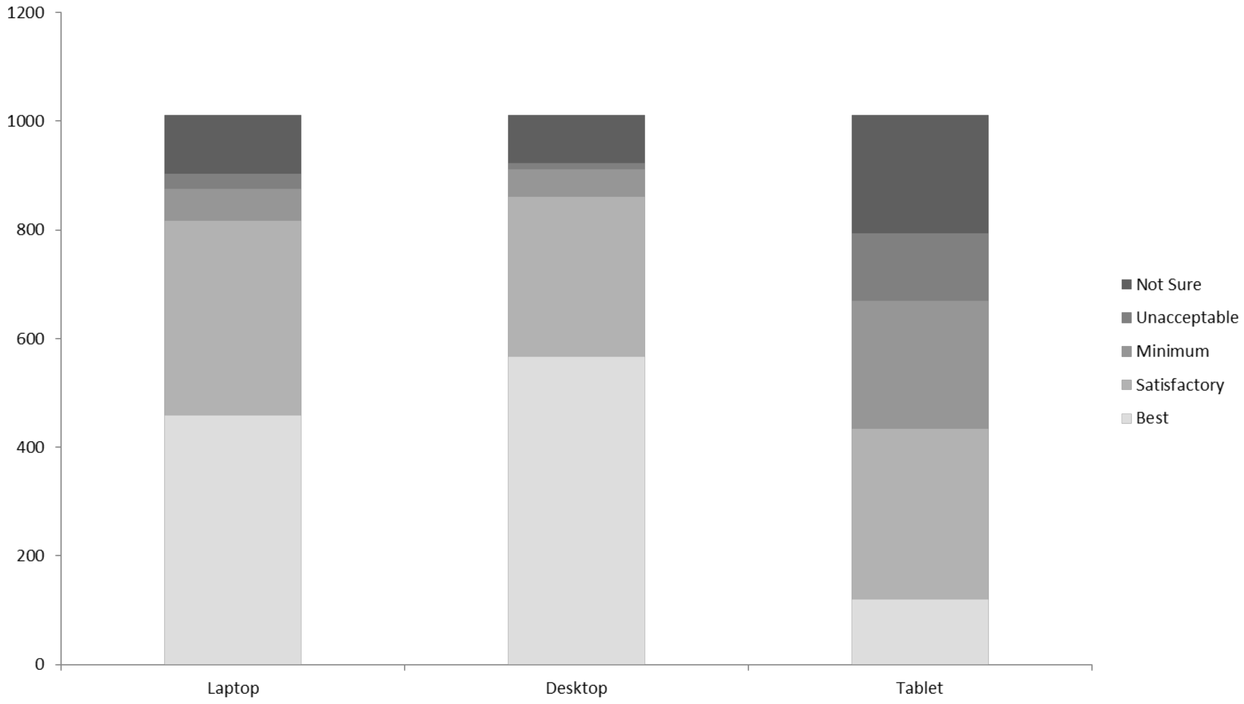

Figure C- 22: Q244 response distribution

Base: All Qualified Respondents.
Q246. Suppose you wanted to send an email. Based on your use of the products shown below or what you may have read or heard about them, please indicate your general impression of the experience each would provide for this activity.

1- Best possible experience
2- Satisfactory experience
3- Minimum acceptable experience
4- Unacceptable experience
5- Not Sure

RANDOMIZE LIST

1- Tablet
2- Laptop Computer
3- Desktop Computer
4- Smartphone

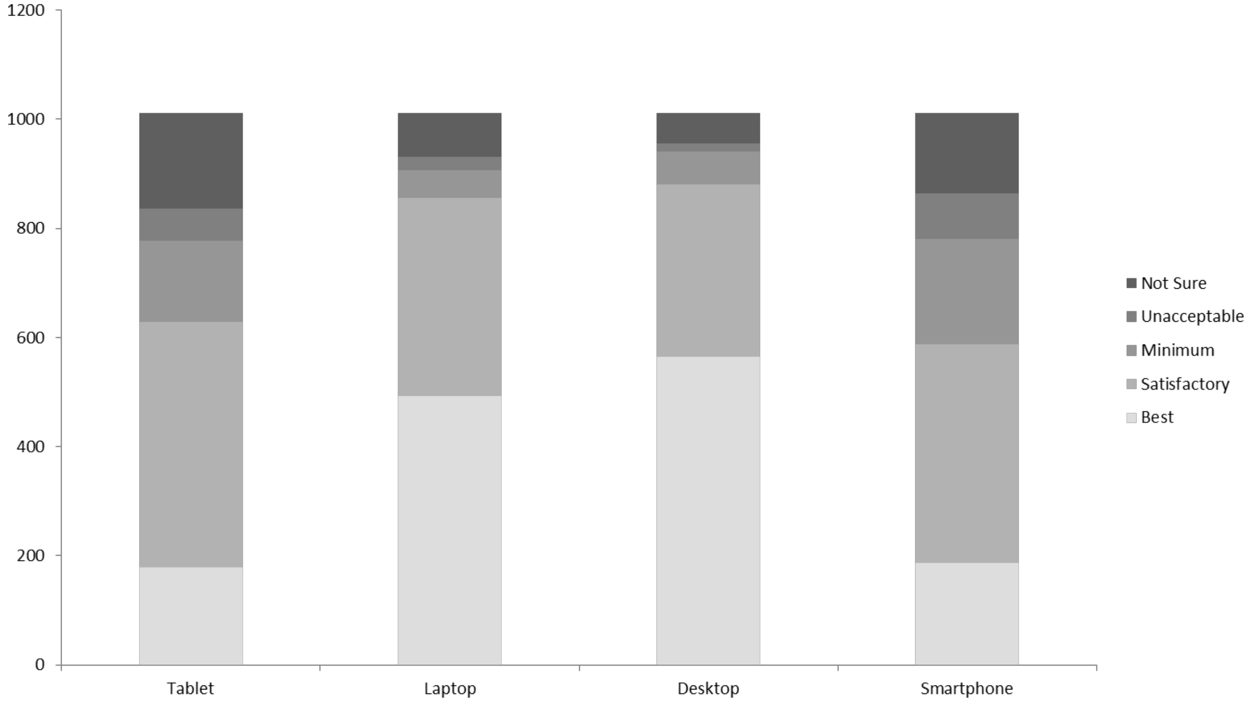

Figure C- 23: Q246 response distribution

Base: All Qualified Respondents
Q248. Suppose you wanted to take a photograph [EVENT FROM LIST AT Q238]. Based on your use of the products shown below or what you may have read or heard about them, please indicate your general impression of the experience this product would provide for this activity.

PROGRAMMING: INSERT SAME EVENT IN Q248 AS IN Q238.

1- Best possible experience
2- Satisfactory experience
3- Minimum acceptable experience
4- Unacceptable experience
5- Not Sure

RANDOMIZE LIST

1- Digital camera
2- Tablet
3- Smartphone

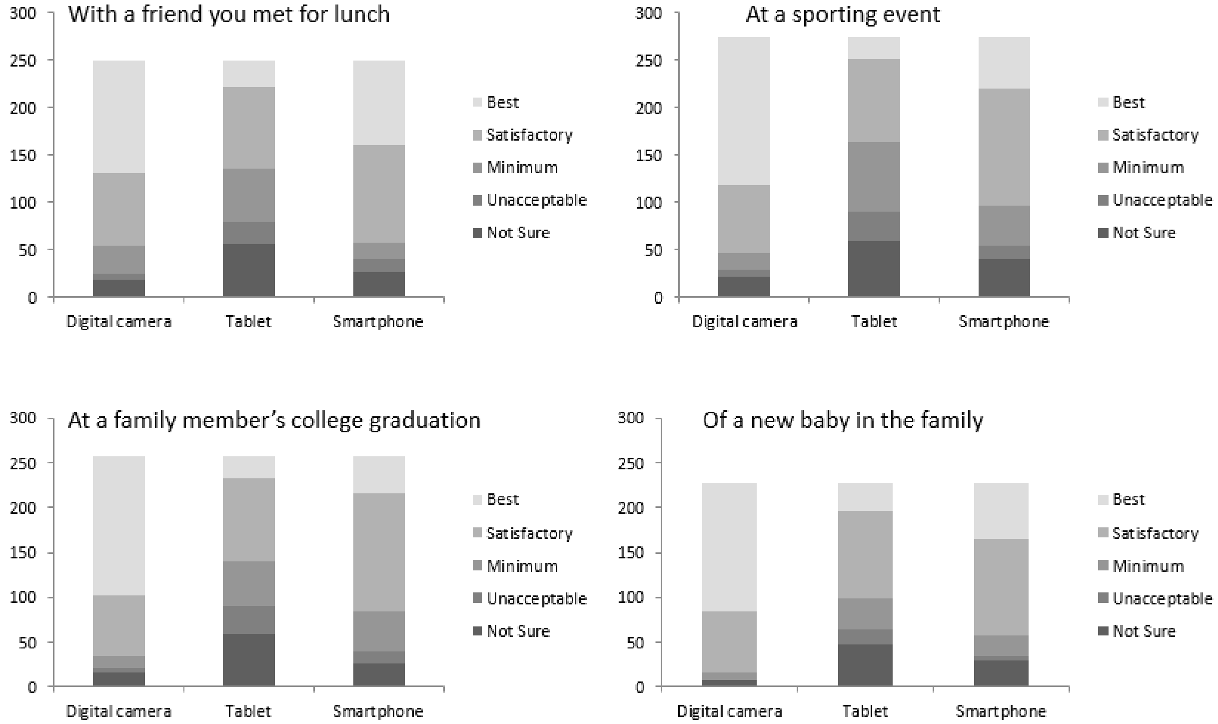

Figure C- 24: Q248 response distribution

Section 300 – Substitutable and Complementary Products

Base: All qualified respondents
PROGRAMMING: SET THIS UP AS A CONFIGURATION SCREEN. UPDATE DISPLAY OF BALANCE REMAINING AS RESPONDENTS MAKE CHOICES. ALLOW THEM NOT TO SPEND ALL DOLLARS BUT PROHIBIT THEM FROM SPENDING MORE THAN ALLOWED TOTAL. IF POSSIBLE, RECORD ORDER OF CHOICES.

Q300. Imagine that you don’t own any electronic products and you have the opportunity to purchase any new electronic products you wish. You’ve decided that you can spend up to [INSERT DOLLAR AMOUNT FROM LIST BELOW]. What would you buy assuming you could choose from the following products at the prices indicated?

RANDOMIZE DOLLAR AMOUNT TO INSERT ABOVE FROM THE FOLLOWING. BE SURE TO RECORD WHICH DOLLAR AMOUNT WAS USED FOR EACH RESPONDENT.

$1,500
$2,500

RANDOMIZE LIST

1-	A digital camera **INSERT $$ AMOUNT** **a. RANDOMIZE DOLLAR AMOUNT TO INSERT ABOVE FROM THE FOLLOWING. BE SURE TO RECORD WHICH DOLLAR AMOUNT WAS USED FOR EACH RESPONDENT.** **i. $100** **ii. $600**	
2-	A digital camcorder	$300
3-	A flat screen television	$450
4-	A DVD Player	$50
5-	A Blu-Ray Player	$100
6-	A Gaming Console (such as Wii, Playstation or XBOX)	$400
7-	A smartphone(such as an iPhone, Android, other web-enabled cellular device)	$100
8-	A basic mobile phone (talk and text only)	$50
9-	An MP3 player (such as an iPod)	$50
10-	A tablet	$350
11-	A laptop computer **INSERT $$ AMOUNT** **a. RANDOMIZE DOLLAR AMOUNT TO INSERT ABOVE FROM THE FOLLOWING. BE SURE TO RECORD WHICH DOLLAR AMOUNT WAS USED FOR EACH RESPONDENT.** **i. $250** **ii. $650**	
12-	A desktop computer	$350

Base: All Respondents with at least one product available for their use other than a CRT Television in Q10
Q310. Electronic products eventually break or wear out. For each of the product types below we'd like to know what you would do if your most recently acquired version broke or wore out today and could not be repaired.

Would you:

1- Replace it with the same make and model of the product
2- Replace it with a different make or model of the same type of product
3- Replace it with a different type of product
4- Replace it with a product I already own
5- Not replace it at all
6- Somebody else would make the decision

KEEP AND SHOW PRODUCTS WHERE Q10 EQ 1
RANDOMIZE LIST

1- A digital camera
2- A digital camcorder (digital video recorder)
3- A flat screen television
4- A DVD Player
5- A Blu-Ray Player
6- A Gaming Console (such as Wii, Playstation or XBOX)
7- A smartphone(such as an iPhone, Android, other web-enabled cellular device)
8- A basic mobile phone (talk and text only)
9- An MP3 player ((such as an iPod)
10- A tablet
11- A laptop computer
12- A desktop computer

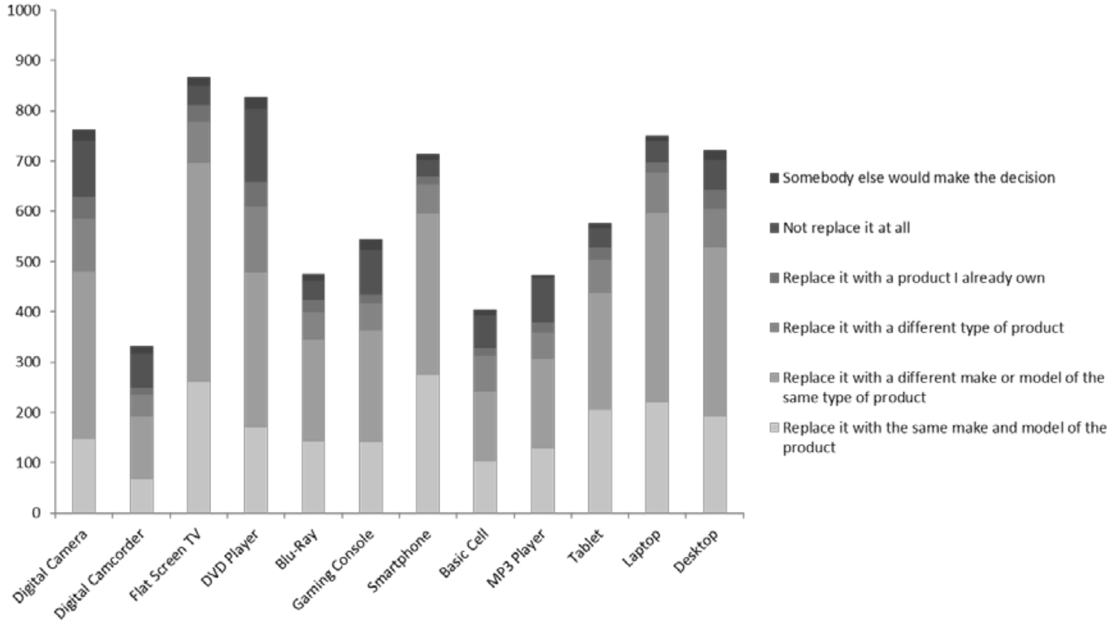

Figure C- 25: Q310 response distribution

Base: Respondents whose answer to Q310 for at least one product is either 1 (Replace it with the exact same make and model) or 2 (replace it with a different make or model of the same type of product)

Q320. You indicated that if each of the following products wore out or broke today and could not be repaired, you would replace it with another of the same type of product. How quickly would you replace them?

1- Today
2- Not today, but before the end of the week
3- Within a month
4- More than one month

KEEP AND SHOW PRODUCTS WHERE Q310 EQ 1 or 2
RANDOMIZE LIST

1- A digital camera
2- A digital camcorder (digital video recorder)
3- A flat screen television
4- A DVD Player
5- A Blu-Ray Player
6- A Gaming Console (such as Wii, Playstation or XBOX)
7- A smartphone(such as an iPhone, Android, other web-enabled cellular device)
8- A basic mobile phone (talk and text only)
9- An MP3 player (such as an iPod)
10- A tablet
11- A laptop computer
12- A desktop computer

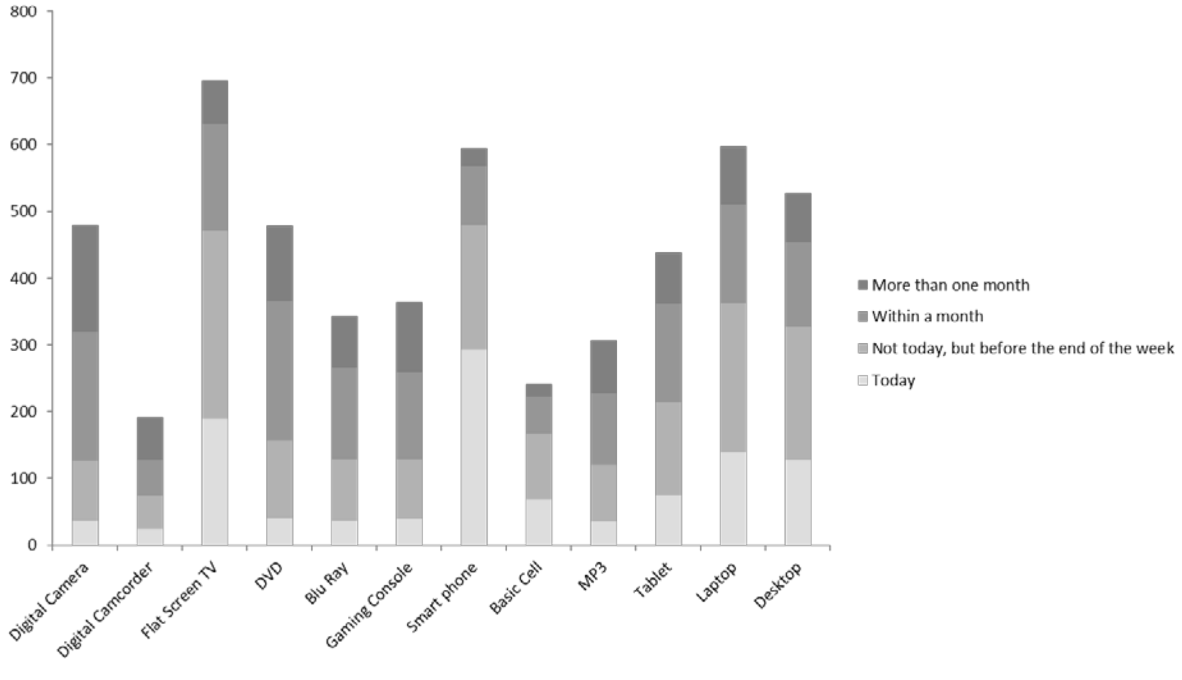

Figure C- 26: Q320 response distribution

Base: Answer Yes to having a CRT Television in Q10
This is a single response question.
Q330. You indicated that you have a CRT (box shaped) television available for you to use. We'd like to know what you would do if your most recently acquired CRT (box shaped) television broke or wore out today and could not be repaired.

Would you:

1- Replace it with a flat screen television
2- Replace it with a different type of product
3- Replace it with a product I already own
4- Not replace it at all
5- Somebody else would make the decision

Base: Respondents whose answer to Q310 for at least one product is 3 (Replace it with a different type of product)
Q340. You indicated that you would replace [INSERT PRODUCT NAME FROM NUMBERED LIST BELOW] with a different type of product. Please indicate the type of product you would replace your [INSERT PRODUCT NAME FROM NUMBERED LIST BELOW] with.
KEEP: Only display products marked yes in Q10
SINGLE RESPONSE QUESTION

PROGRAMMING: We want to ask this question for up to 5 products respondents would replace (3) in Q310. In choosing products first fill as many as possible with the first tier products below. Then fill with randomly selected products from 2nd tier.

<u>1st tier group of products</u>

1- A flat screen television
    a. A smartphone
    b. A tablet
    c. A laptop computer
    d. A desktop computer
    e. Another flat screen television that I already own
    f. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]
2- A smartphone(such as an iPhone, Android, other web-enabled cellular device)
    a. A basic mobile phone (talk and text only)
    b. A tablet
    c. Another smartphone that I already own
    d. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]
3- A tablet
    a. A smartphone
    b. A laptop computer
    c. A desktop computer
    d. Another tablet that I already own
    e. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]
4- A laptop computer
    a. A smartphone
    b. A tablet
    c. A desktop computer
    d. Another laptop computer that I already own
    e. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]
5- A digital camera
    a. A smartphone
    b. A tablet
    c. Another digital camera that I already own
    d. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

<u>2nd tier group of products</u>

1- A DVD Player
    a. A Blu-Ray Player
    b. A Gaming Console (such as a Wii, Playstation or XBOX)
    c. A smartphone (such as an iPhone, Android, other web-enabled cellular device)
    d. A tablet

    e. A laptop computer
    f. A desktop computer
    g. Another DVD Player that I already own
    h. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

2- A Blu-Ray Player
    a. A DVD Player
    b. A Gaming Console (such as a Wii, Playstation or XBOX)
    c. A smartphone (such as an iPhone, Android, other web-enabled cellular device)
    d. A tablet
    e. A laptop computer
    f. A desktop computer
    g. Another Blu-Ray Player that I already own
    h. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

3- An MP3 player (such as an iPod)
    a. A smartphone
    b. A tablet
    c. Another MP3 Player that I already own
    d. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

Base: Respondents whose answer to Q310 for at least one product is 4 (replace it with a product I already own)
Q350. You indicated that you would replace [INSERT PRODUCT NAME FROM NUMBERED LIST BELOW] with a product you already own. Please indicate what type of product you would replace your [INSERT PRODUCT NAME FROM NUMBERED LIST BELOW] with.
KEEP: Only display products marked yes in Q10
SINGLE RESPONSE QUESTION

PROGRAMMING: We want to ask this question for up to 5 products respondents would replace with a product I already own (4) in Q310. In choosing products first fill as many as possible with the first tier products below. Then fill with randomly selected products from 2nd tier.

<u>1st tier group of products</u>

1- A flat screen television
    a. My smartphone
    b. My tablet
    c. My laptop computer
    d. My desktop computer
    e. Another flat screen television that I already own
    f. A CRT (box shaped) television that I already own
    g. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]
2- A smartphone(such as an iPhone, Android, other web-enabled cellular device)
    a. My basic mobile phone (talk and text only)
    b. My tablet
    c. Another smartphone that I already own
    d. A landline telephone
    e. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]
3- A tablet
    a. My smartphone
    b. My laptop computer
    c. My desktop computer
    d. Another tablet that I already own
    e. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]
4- A laptop computer
    a. My smartphone
    b. My tablet
    c. My desktop computer
    d. Another laptop computer that I already own
    e. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]
5- A digital camera
    a. My smartphone
    b. My tablet
    c. Another digital camera that I already own
    d. A film camera that I already own
    e. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

<u>2nd tier group of products</u>

1- A DVD Player
    a. My Blu-Ray Player
    b. My Gaming Console (such as a Wii, Playstation or XBOX)
    c. My smartphone

    d. My tablet
    e. My laptop computer
    f. My desktop computer
    g. My flat screen television
    h. Another DVD Player that I already own
    i. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

2- A Blu-Ray Player
    a. My DVD Player
    b. My Gaming Console (such as a Wii, Playstation or XBOX)
    c. My smartphone
    d. My tablet
    e. My laptop computer
    f. My desktop computer
    g. My flat screen television
    h. Another Blu-Ray Player that I already own
    i. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

3- An MP3 player (such as an iPod)
    a. My smartphone
    b. My tablet
    c. Another MP3 Player that I already own
    d. A portable CD player that I already own
    e. A portable cassette player that I already own
    f. AM/FM/HD Radio
    g. Some other product [SPECIFY ALLOWING AT LEAST 100 CHARACTERS]

Base: Respondents who indicate that they have BOTH a TABLET and a LAPTOP COMPUTER available for their use (Answer 1) in Q10
This is a single response question.
Q360. Imagine that both your most recently acquired TABLET and LAPTOP COMPUTER broke at the same time and could not be repaired. Which of the following would you be most likely to do?

1- Replace only the tablet
2- Replace only the laptop computer
3- Replace neither
4- Replace neither but purchase a different electronic product intended to accomplish the same tasks [SPECIFY ALLOWING AT LEAST 100 CHARACTERS)
5- Replace both
6- Somebody else would make the decision

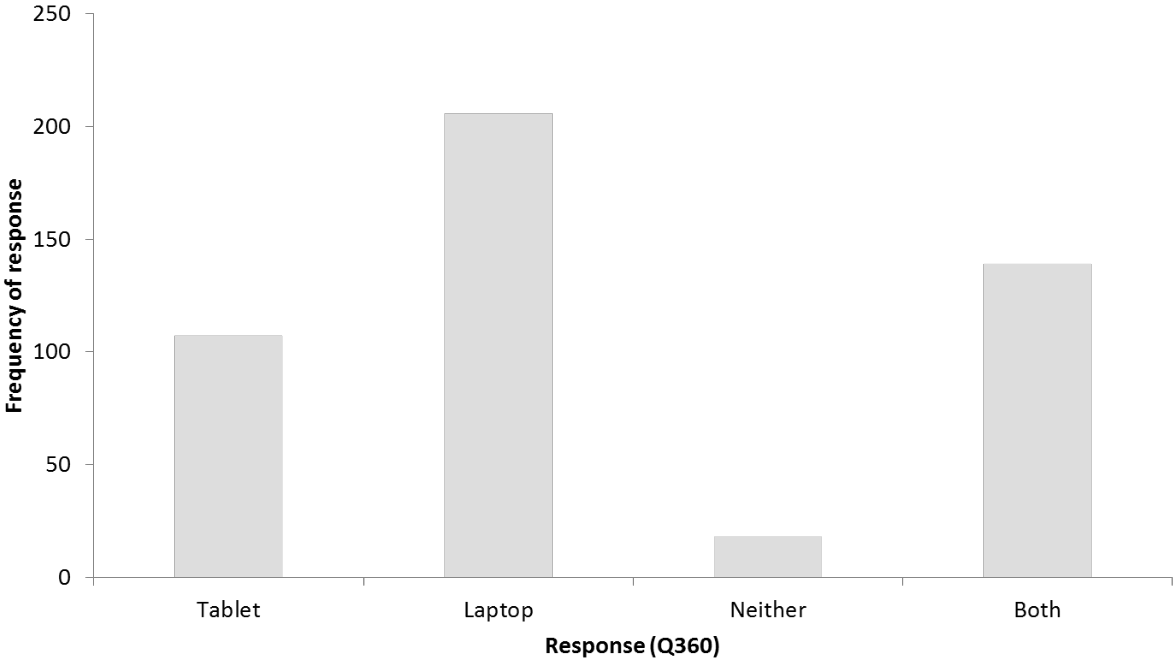

Figure C- 27: Q360 response distribution

Base: Respondents who indicate that they have BOTH a TABLET and a SMARTPHONE available for their use (Answer 1) in Q10
This is a single response question.
Q362. Suppose your most recently acquired TABLET and SMARTPHONE both broke at the same time and could not be repaired. Which of the following would you be most likely to do?

1- Replace only the tablet
2- Replace only the smartphone
3- Replace neither
4- Replace neither but purchase a different electronic product intended to accomplish the same tasks (SPECIFY ALLOWING AT LEAST 100 CHARACTERS)
5- Replace both
6- Somebody else would make the decision

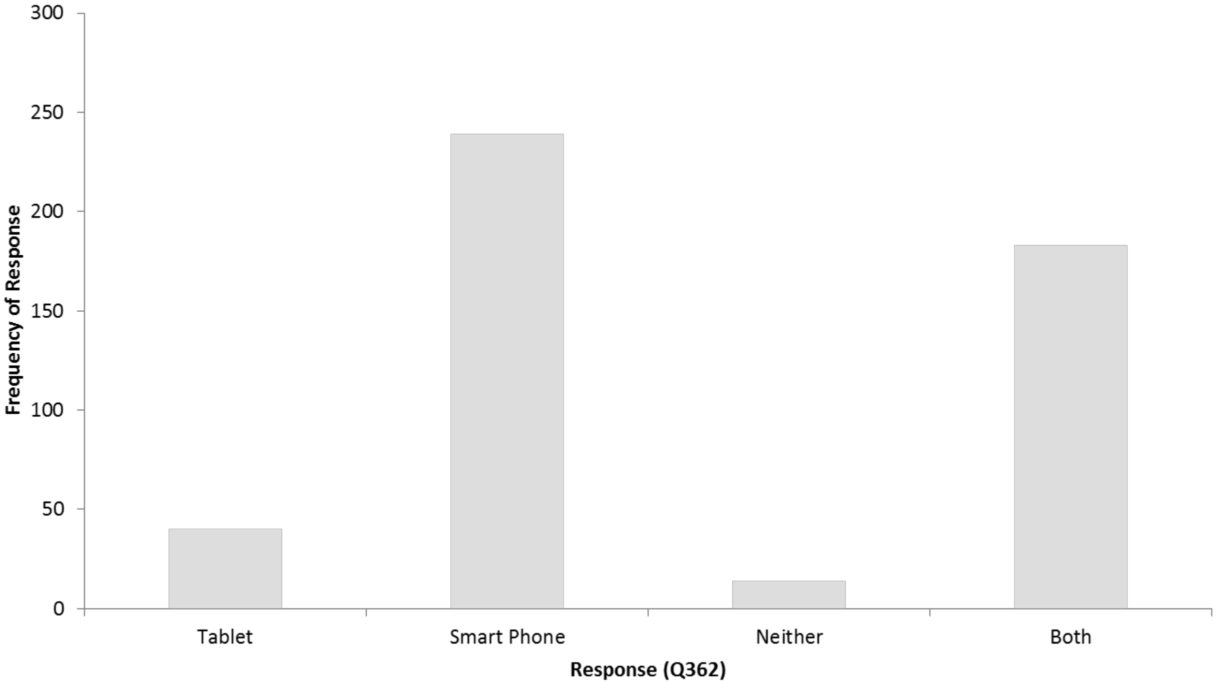

Figure C- 28: Q362 response distribution

Base: Respondents who indicate that they have BOTH a TABLET and a FLAT SCREEN TELEVISON available for their use (Answer 1) in Q10
This is a single response question.
Q364. Suppose your most recently acquired TABLET and FLAT SCREEN TELEVISION both broke at the same time and could not be repaired. Which of the following would you be most likely to do?

1- Replace only the tablet
2- Replace only the flat screen television
3- Replace neither
4- Replace neither but purchase a different electronic product intended to accomplish the same tasks (SPECIFY ALLOWING AT LEAST 100 CHARACTERS)
5- Replace Both
6- Somebody else would make the decision

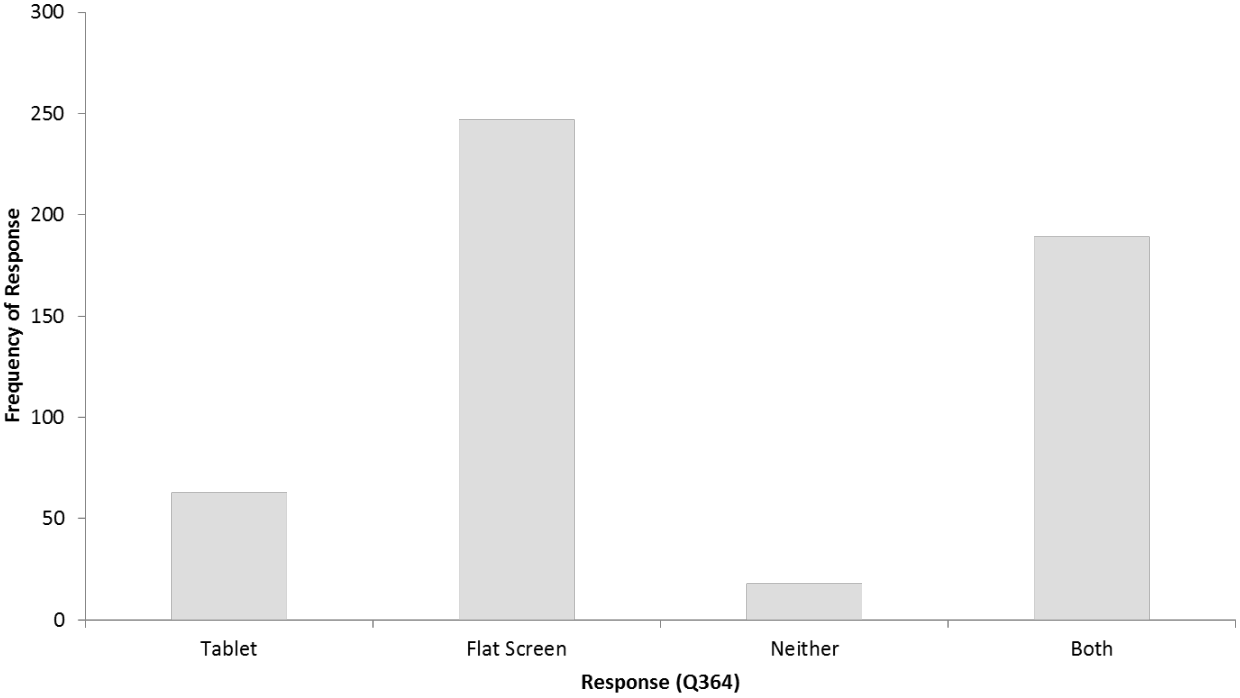

Figure C- 29: Q364 response distribution

Base: Respondent has both a smartphone and a tablet available for use in Q10
Q370. Which of the following did you purchase or acquire most recently?

1- A smartphone
2- A tablet
3- I purchased them at the same time
4- Not Sure

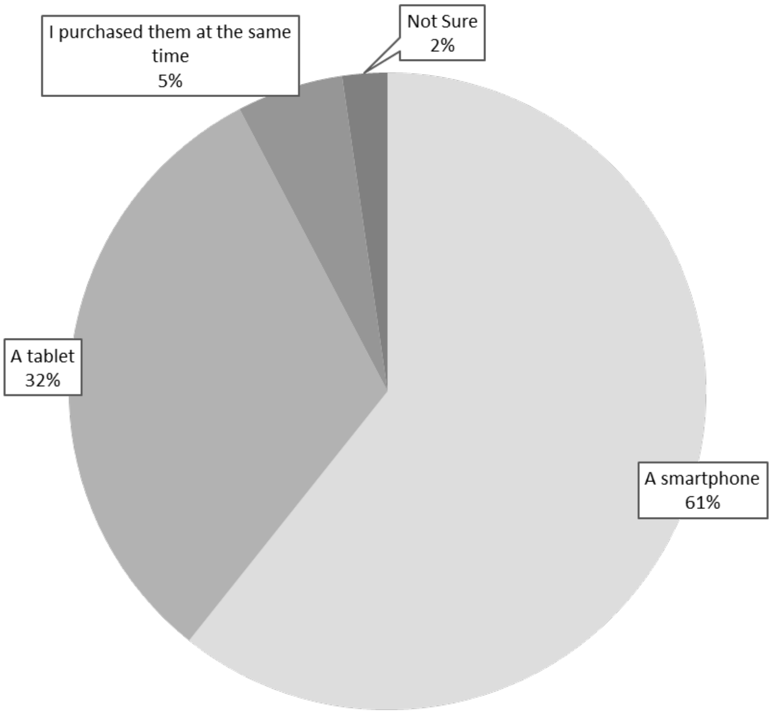

Figure C- 30: Q370 response distribution

Base: (Q370 EQ 1) OR IN Q10 RESPONDENT HAS SMARTPHONE BUT NOT A TABLET)
Q375. What impact, if any, did the availability of the following products have on your decision to purchase or acquire your most recently purchased or acquired smartphone?

1- Strongly increased
2- Slightly increased
3- No impact
4- Slightly decreased
5- Strongly decreased

SHOW PRODUCTS RESPONDENT HAS IN Q10
RANDOMIZE ORDER
IF RESPONDENT HAS NONE OF THESE PRODUCTS DO NOT ASK Q375
A Tablet
A Laptop Computer
A Flatscreen Television

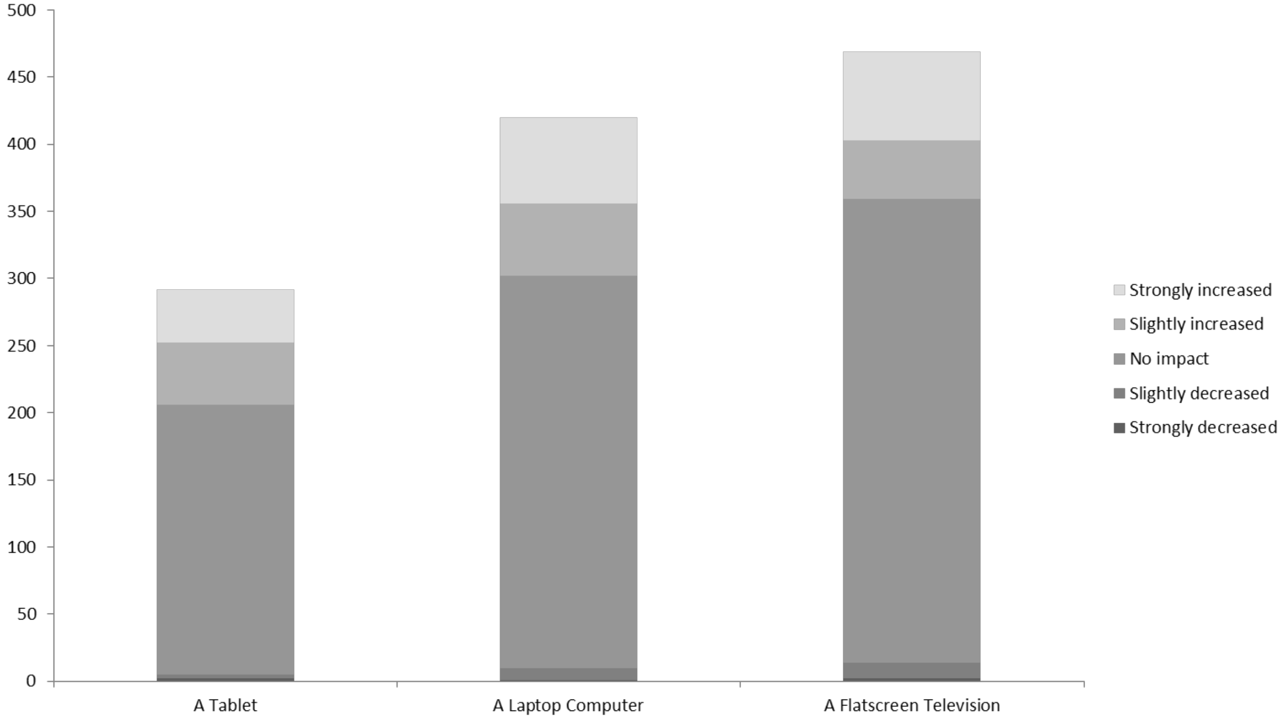

Figure C- 31: Q375 response distribution

Base: (Q370 EQ 2) OR IN Q10 RESPONDENT HAS A TABLE BUT NOT A SMARTPHONE)
Q380. What impact, if any, did the availability of the following products have on your decision to purchase or acquire your most recently purchased or acquired tablet?

1- Strongly increased
2- Slightly increased
3- No impact
4- Slightly decreased
5- Strongly decreased

SHOW PRODUCTS RESPONDENT HAS IN Q10
RANDOMIZE ORDER
IF RESPONDENT HAS NONE OF THESE PRODUCTS DO NOT ASK Q380
A Smartphone
A Laptop Computer
A Flatscreen Television

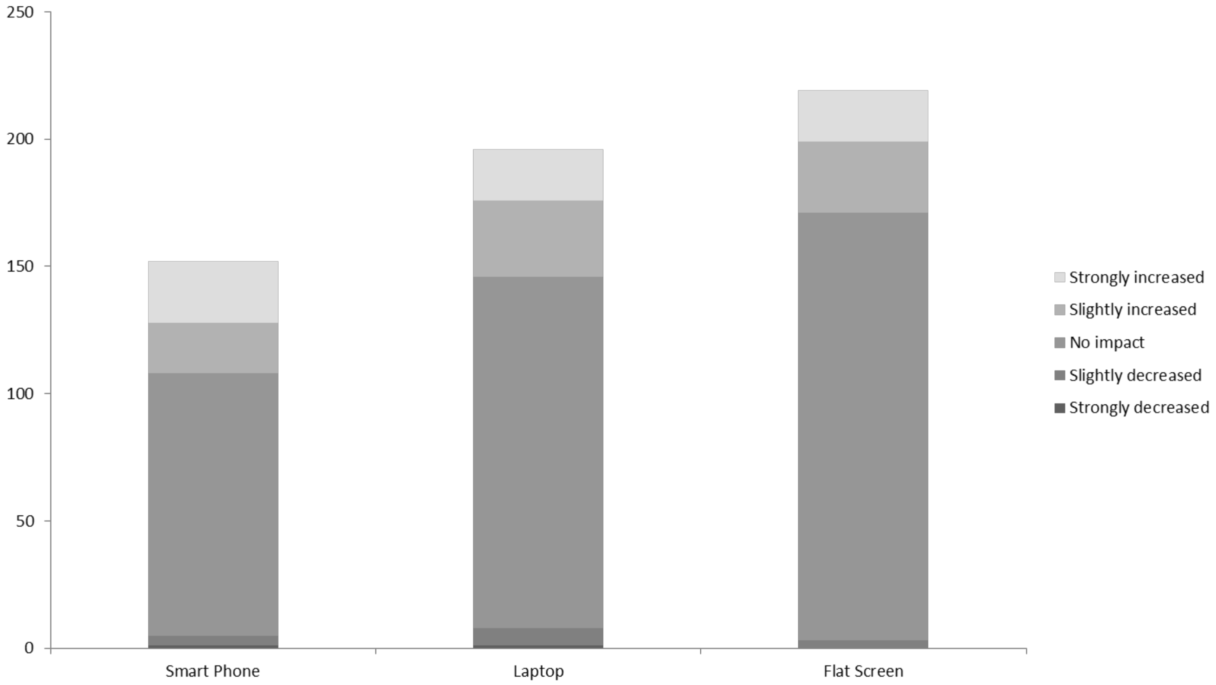

Figure C- 32: Q380 response distribution

Base: Q370 EQ 3
SINGLE RESPONSE
Q385. Which of the following most influenced your decision to purchase your most recently acquired tablet and smartphone at the same time?

1- The ability to use them together
2- Making both purchases was convenient
3- I had a coupon or there was a discount to purchase both
4- Some other reason (SPECIFY ALLOWING AT LEAST 100 CHARACTERS)

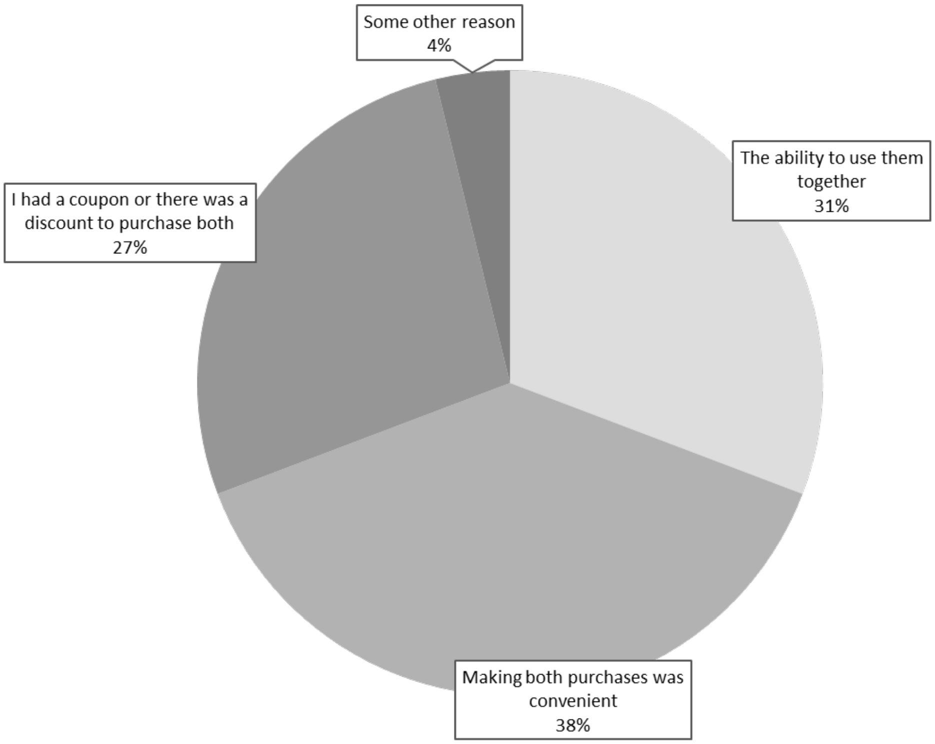

Figure C- 33: Q380 response distribution

Section 400 – Purchase Preferences

Base: Respondents With Access to a Smartphone in Q10 But No Access to a Tablet
This is a multiple response question.
Q410. If given the opportunity to own or acquire a tablet for free, which of the following reasons, if any, would prevent you from obtaining the tablet?

RANDOMIZE LIST
ANCHOR ITEMS 5 and 6

1- It would upset my routine
2- My smartphone does everything that the tablet can do
3- The associated wireless plan would cost too much
4- I don't have coverage at my location, so the tablet is useless
5- Some other reason (SPECIFY ALLOWING AT LEAST 100 CHARACTERS)
6- Nothing would keep me from getting a free tablet

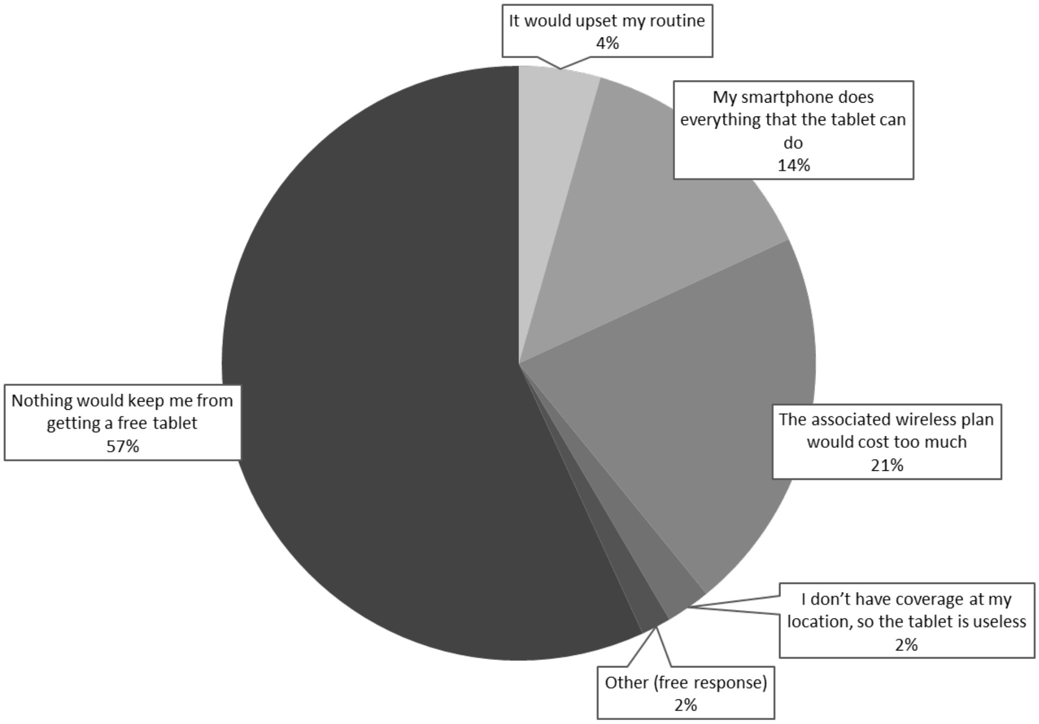

Figure C- 34: Q410 response distribution

Base: Respondents Who Answer No Access to a Smartphone in Q10
This is a multiple response question.
Q412. If given the opportunity to own or acquire a smartphone for free, which of the following reasons, if any, would prevent you from obtaining the smartphone?

RANDOMIZE LIST
ANCHOR ITEMS 5 AND 6

1- It would upset my routine
2- My other electronics cover everything that the smartphone would do
3- The associated wireless plan would cost too much
4- I don't have coverage at my location, so the smartphone is useless
5- Some other reason (SPECIFY ALLOWING AT LEAST 100 CHARACTERS)
6- Nothing would keep me from getting a free smartphone

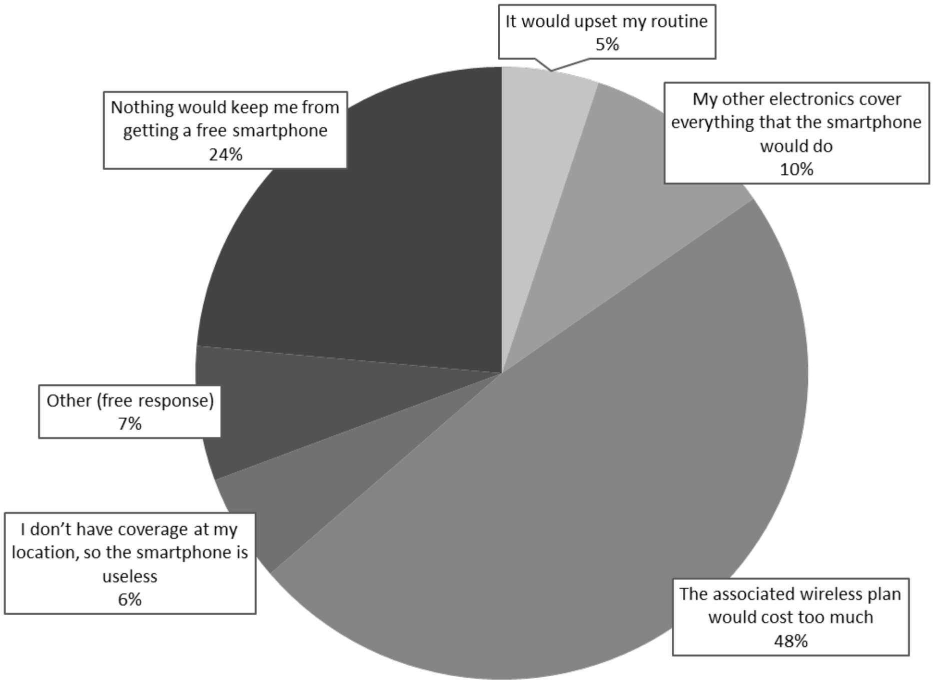

Figure C- 35: Q412 response distribution

Section 500 – Technology Adoption

PROGRAMMING: RANDOMIZE ORDER IN WHICH Q500, Q502 AND Q504 ARE SHOWN TO RESPONDENTS

Base: All qualified respondents
This is a single response question
Q500. Compared to your friends, would you say you are

1- Extremely likely to be the first to adopt new technology products
2- Very likely to be the first to adopt new technology products
3- Somewhat likely to be the first to adopt new technology products
4- Not very likely to be the first to adopt new technology products
5- Not at all likely to be the first to adopt new technology products

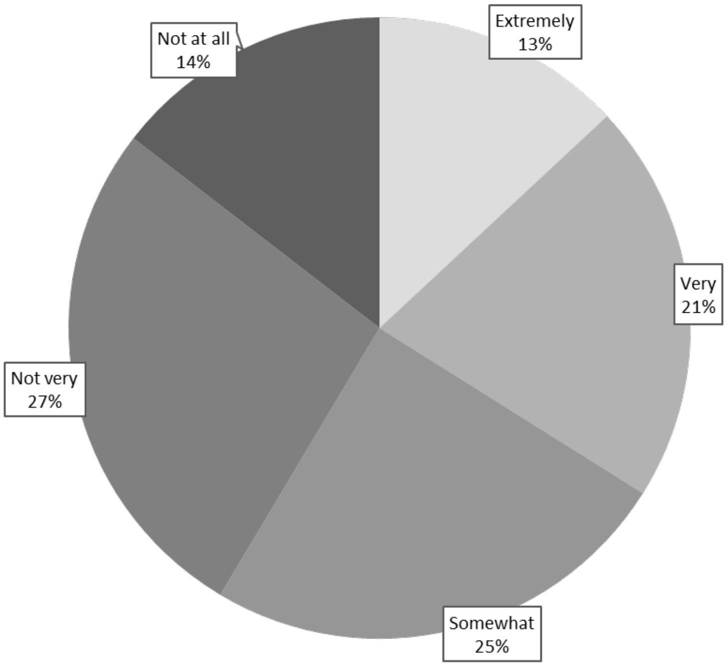

Figure C- 36: Q500 response distribution

Base: All qualified Respondents
This is a single response question
Q502. How interested would you say you are about technology products you can use at home?

1- Extremely interested
2- Very interested
3- Somewhat interested
4- Not very interested
5- Not at all interested

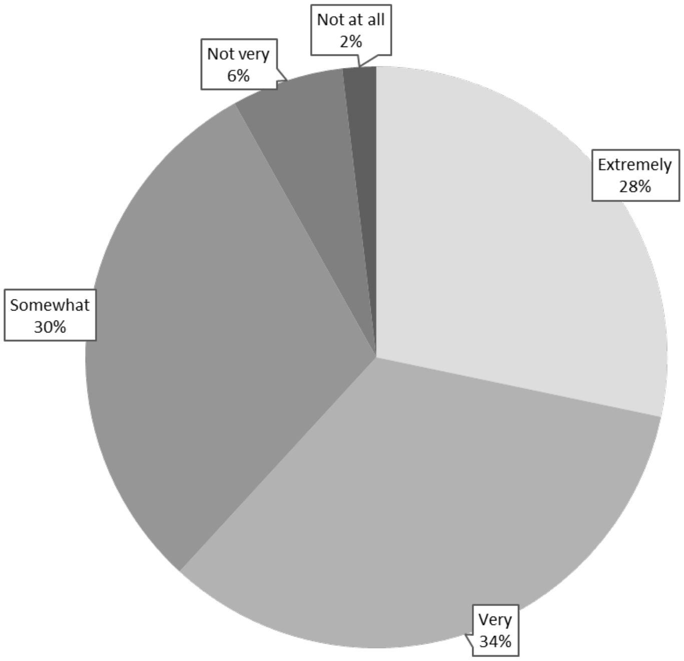

Figure C- 37: Q502 response distribution

Base: All qualified respondents
This is a single response question
Q504. How knowledgeable would you say you are about technology products you can use at home?

1- Extremely knowledgeable
2- Very knowledgeable
3- Somewhat knowledgeable
4- Not very knowledgeable
5- Not at all knowledgeable

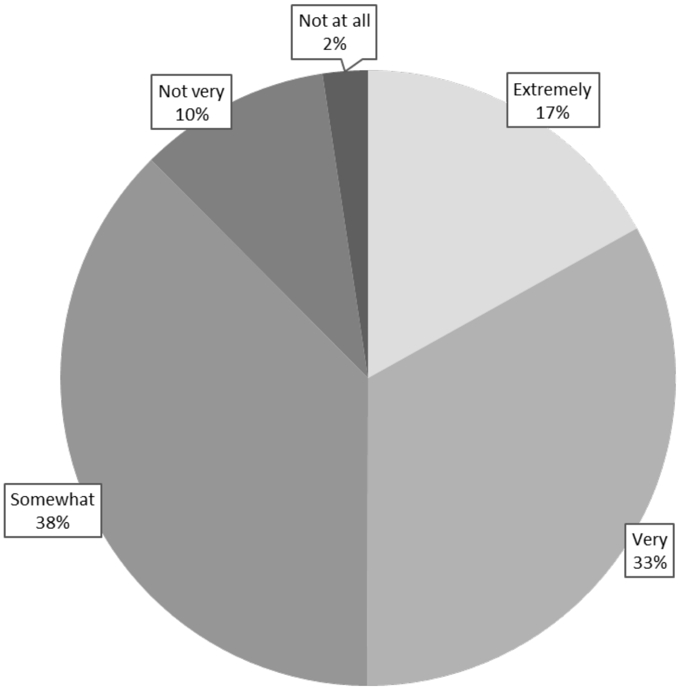

Figure C- 38: Q504 response distribution

Section 600 – Demographics

Base: All Qualified Respondents
This is a single response question
Q600. What is the highest level of education you have completed or the highest degree you have received?

1- High School graduate or less
2- Technical School
3- Some college
4- Associate's degree
5- College 4 years
6- Post graduate

Base: All Qualified Respondents
This is a single response question
Q610 Which of the following income categories best describes your total 2014 household income before taxes?

1- Less than $15,000
2- $15,000 to $24,999
3- $25,000 to $34,999
4- $35,000 to $49,999
5- $50,000 to $74,999
6- $75,000 to $99,999
7- $100,000 to $149,999
8- $150,000 or more
9- Prefer not to answer

Base: All qualified respondents
This is a single response question
Q620 Are you …

1- Married
2- Living with a partner
3- Not married and not living with a partner

Base: All Qualified Respondents
This is a single response question
Q630. How many children under the age of 18 live in your household?

1- 0
2- 1
3- 2
4- 3 or more

Base: All Qualified Respondents
This is a single response question
Q640 Are you of Spanish or Hispanic origin, such as Latin American, Mexican, Puerto Rican, or Cuban?

1- Yes, of Hispanic origin
2- No, not of Hispanic origin
3- Decline to answer

Base: All Qualified Respondents
This is a single response question
Q650 Do you consider yourself…?

1- White
2- Black
3- Asian or Pacific Islander
4- Native American or Alaskan Native
5- Mixed Race
6- Some other race
7- Hispanic
8- African American
9- First Nation/Native Canadian
10- South Asian
11- Chinese
12- Korean
13- Japanese
14- Other Southeast Asian
15- Filipino
16- Arab/West Asian
94- Decline to Answer

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