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Evolving materials, attributes, and functionality in consumer electronics: Case study of laptop computers

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ABSTRACT

There is increasing interest in assessing the environmental impacts of consumer electronics using methods such as life cycle assessment (LCA) and material flow analysis (MFA). Both assessment methods depend on quantifying the materials and parts contained in these products, i.e., the bill of Attributes (BOA). While there has been significant work to develop commercial and public databases detailing material and energy flows in production processes, there have been no comparable efforts to characterize BOA. Further, such assessment is complicated by rapidly evolving production processes and product design and consumption trends. This study was undertaken to assess the degree of change in product attributes commonly used as inputs for LCA for a common consumer electronic product: laptop computers. The analysis includes (1) temporal evolution of BOA for a consistent product type over multiple generations (14.1″ laptops) and (2) variability in a fixed year within a product type (laptops of different sizes). In total, eleven laptop computers were disassembled and characterized based on function, components, and materials. In addition, the study included measurement of silicon die area for all product motherboards and thirty dynamic random access memory (DRAM) cards produced over the period 1999–2011.

Results reveal trends important for assessing and designing greener consumer electronics. The fundamental dynamic is the extent technological progress is used to improve functionality versus reduce material and energy footprint. For a variety of attributes, it was found that material footprint did not change significantly over the period 1999–2008, suggesting that improvements in functionality roughly balanced efficiency gains. In particular, total mass and material shares were roughly constant over the period studied. Battery mass, hard disk drive mass, and DRAM die area all decreased per unit of functionality (kWh, GB, MB) over time, but showed roughly constant totals per year. Initial benchmarking to other electronics (netbook, tablet, smartphone) is included here, but further work is needed to determine if the observed pattern in material intensity and functionality is continued over time. This trend, if robust, is important because (1) the BOA inputs to LCA or MFA for an established form factor are surprisingly constant over time, improving temporal robustness of assessment results, and (2) one cannot assume that dematerialization will automatically lead to material and energy reductions for consumer electronics.

There is a need for concerted effort from the LCA community to characterize and model BOAs. As collecting BOA data is labor intensive, heuristics can potentially play an important role to streamline analysis. The product attributes that were most consistent over time and across product class for the case study, like material composition, may be good candidates for streamlining data collection and product characterization. However, potential predictors of silicon die area tested here were highly variable and more sensitive to change over time. The most promising estimation methods were those that focused on measuring the area of the five largest integrated circuits (for all motherboards, just five chips contained as much as 30–70% of all die area) and estimating the rest using an average die area per chip ratio. However, given the uncertainty in all tested heuristics, their application to an LCA or MFA should be used with caution.

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1. Introduction

Rapid technological innovation has created a consumption conundrum in the consumer electronics sector: increased availability and affordability of electronic products have the potential to improve worldwide economic development and quality of life, but at the cost of increasing resource and energy demand and emission and waste generation across the life cycle of electronic devices. Technological innovation promises an enticing solution to this challenge, whereby efficiency gains achieved from improved performance may enable product dematerialization as a means of decoupling environmental impact from economic growth (Binswanger, 2001; Marechal et al., 2005; Robert et al., 2002; van der Voet et al., 2005).

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. To this end, the rapid technological innovation in consumer electronics presents an additional complication: 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).

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. Fig. 1 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

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. Methods

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. 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″, 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.

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.).

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,