



Analyzing the environmental impacts of laptop enclosures using screening-level life cycle assessment to support sustainable consumer electronics



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ABSTRACT

The market growth of consumer electronics makes it essential for industries and policy-makers to work together to develop sustainable products. The objective of this study is to better understand how to promote environmentally sustainable consumer electronics by examining the use of various materials in laptop enclosures (excluding mounting hardware, internal components, and insulation) using screening-level life cycle assessment. The baseline material, is a fossil plastic blend of polycarbonate-acrylonitrile butadiene styrene. Alternative materials include polylactic acid, bamboo, aluminum, and various combinations of these materials known to be currently used or being considered for use in laptops. The flame retardants considered in this study are bisphenol A bis(diphenyl phosphate), triphenyl phosphate, 9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide, and borax-boric acid-phosphorous acid. The Tool for the Reduction and Assessment of Chemical and other environmental Impacts v2.1 was used for the assessment of impacts related to climate change, human and ecological health, and resource use. The assessment demonstrates that plastics, relative to the other materials, are currently some of the better performing materials in terms of having the lowest potential environmental impact for a greater number of impact categories based on product life cycle models developed in this study. For fossil plastics, the material performance increases with increasing post-consumer recycled content. To best characterize and improve the environmental sustainability of bio-based materials like polylactic acid, it will be necessary to better model end-of-life options for this application. The impacts of using pressed bamboo materials in laptop enclosures can be lessened by improving key sub-processes, such as strip gluing. The final issue highlighted by this study is the need to develop more sustainable alternatives for flame retardants and fillers because they can represent a significant portion of the cradle-to-grave life cycle impacts, even though they often constitute a small portion of the weight of the final product.

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1. Introduction

Over the past forty years, an evolving and expanding array of computers, mobile devices, and other consumer electronic devices (CEDs) has revolutionized daily life in the areas of communication, entertainment, and personal productivity. It is estimated that since 1980, more than 900 million desktop computers and laptops and more than 700 million cathode ray tube (CRT) and flat screen monitors have been sold in the United States (US EPA, 2011). The total market for personal computing devices is expected to

continue to grow 11% globally between 2013 and 2015, with nearly all of the growth occurring for tablets, mobile phones, and other ultramobiles (Gartner, 2014).

There are numerous environmental impacts associated with consumer electronics, from the climate change impacts arising from the large embodied energy related to manufacturing and use (Teehan and Kandlikar, 2013), to the risk of human and ecological health effects that may result from the release of toxic materials (heavy metals, flame retardants, etc.) during end-of-life management (Wäger et al., 2011). Given the growth in sales of these devices, manufacturers, policy makers, and purchasers are seeking ways to reduce the life cycle environmental impacts of electronics by promoting greener design, use of safer materials, and increasing

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reuse and recycling. Institutional purchasers in the public and private sectors are trying to direct their procurement dollars toward “environmentally preferable” electronics products – those “products or services that have a lesser or reduced effect on human health and the environment when compared with competing products or services that serve the same purpose”. This comparison applies to raw materials, manufacturing, packaging, distribution, use, reuse, operation, maintenance, and disposal (Dodd and Wolf, 2013).

The demand for environmentally-preferable (US EPA, 2014a) electronics can be seen in the development of environmental standards and eco-labels for personal computers and other electronics around the world. A review of a database maintained by the Global Eco-labelling Network (Global Ecolabelling Network, 2014) finds more than 16 private or government sponsored standards and eco-labels pertaining to common CEDs such as computers, printers, copiers, televisions and cell phones. In addition, there are more standards that pertain to specific aspects of CEDs such as energy use (for instance, the Energy Star program in the United States and 34 other countries). Purchasers are using these standards, and eco-label programs based on these standards extensively. U.S. Federal government purchasers are required to ensure that 95% of all electronic products they purchase are EPEAT registered (Federal Acquisition Regulation (FAR), 2014), unless there is no EPEAT standard for such products. EPEAT is a certification system that grew out of the Electronic Product Environmental Assessment Tool (EPEAT) and is maintained by the U.S. Green Electronics Council. EPEAT registered products must be conformant with the Institute of Electrical and Electronics Engineers (IEEE) 1680 family of standards for the environmental assessment of electronic products. The EPEAT organization reports that hundreds of businesses, schools, hotels, hospitals and governments around the world are using the system and the underlying standards in procuring covered products, and more than 40 manufacturers have registered products meeting the standards (EPEAT, 2014).

In seeking to identify environmentally preferable products, nearly all of these standards and eco-labels include criteria to encourage manufacturers to choose safer and more sustainable materials. The goals of these criteria are to promote materials that meet performance requirements but that have a smaller environmental footprint. These criteria are driven, in part, by concerns about the management of electronics at the end of their life.

As noted above, with tens of millions of CEDs becoming obsolete each year, there is a growing concern about how to manage the volume of electronic waste (White et al., 2003). In the U.S. alone, electronic waste comprised 1.4% of the municipal solid waste stream in 2012 (US EPA, 2014c). Some of the constituents of these products, such as heavy metals and additives could pose risks to human health or the environment if mismanaged at their end-of-life. In addition, electronic products are made from valuable resources, such as precious metals, copper, and engineered plastics, all of which require considerable energy to process and manufacture. Only 29.2% of used electronics in the U.S. are collected for recycling (US EPA, 2014c).

Many of the electronic product environmental performance standards and eco-labels provide requirements or incentives for including post-consumer recycled content in products. This is driven by LCA data showing that post-consumer recycled content plastic has significant environmental benefits over the use of virgin materials, especially due to reductions in resource extraction, refining and manufacturing (Boyd, 2011). They seek to expand the market for resin recovered from electronics.

The focus on plastics is not surprising - while components vary among different products, plastics comprise between 25 and 30% by weight of electronic products (Stenvall et al., 2013). Despite their

pervasiveness in the electronics waste stream, their potential value, and their potential contributions (if recycled) to reducing the environmental impacts of electronic waste, plastics are among the least recycled materials in the electronics waste stream (Markets and Markets, 2011). This is mainly because CED plastics are difficult to recycle efficiently and thus may not offer enough of an economic incentive for recycling (Gutowski et al., 2001; White et al., 2003; Xiuli et al., 2006). In addition, many plastics in CEDs contain additives such as flame retardants, fillers, and stabilizers that can affect their ability to be reused. Some of these additives are restricted in new products by national or international regulations, further reducing the value of recycled resins.

Some stakeholders have stated concern that environmental performance standards such as IEEE 1680, Tjänstemännens Centralorganisation (TCO) Certification, and others have singled out plastics for environmental credit, which may result in ignoring potential benefits and tradeoffs associated with other materials that could be used in laptop enclosures. Manufacturers are increasingly looking to other materials such as steel, aluminum, alloys, as well as bio-based and other forms of plastics. These market shifts have raised the following questions:

- *What are the potential replacements for virgin plastics in electronic products, such as post-consumer recycled plastics, metals, or bio-based materials made from rapidly-renewable materials like bamboo?*
- *What are the environmental consequences on a life cycle basis of casings made from alternate materials?*

These questions are being actively discussed in the development of a number of environmental performance standards, including the revision of the IEEE 1680.1-2009 Standard for the Environmental Assessment of Personal Computer Products, the Underwriters Laboratories (UL) 110 Standard for Sustainability of Mobile Phones, and the National Science Foundation (NSF) 426 Environmental Leadership Standard for Servers, among others. Life Cycle Assessment (LCA) can be used to answer these questions and has become widespread because of its multi-impact, holistic nature that allows users to identify improvements in product life cycles that minimize trade-offs and avoids burden shifting.

However, most LCAs of computers and displays examine the whole product and lack detail regarding specific material options. Such studies have examined computers, mobile phones, televisions/displays, and network systems, as well as individual components of electronic devices such as printed circuit boards (Yao et al., 2010). Selected studies that include casing materials for the example of laptops are summarized in Table 1. In all but one reference, the LCAs were fairly limited in scope regarding impact assessment and focused primarily on global warming potential as an indicator for climate change, with emphasis on carbon emissions. The majority of carbon emissions for laptops can be attributed to their manufacture, which is most likely the impetus for companies turning to bio-based materials during product design as a means to reduce the carbon footprint of products. In addition to carbon emissions, Apple Inc. (Apple Inc., 2011) considers material usage as part of its product evaluations, as did Teehan and Kandlikar (Teehan and Kandlikar, 2013). To support sustainable materials management, Apple Inc. has opted to make aluminum-based enclosures to promote recycling during end of life. Perhaps the most useful study for this work is the review provided by Boyd (Boyd, 2011) because it examined the gaps that needed to be addressed when comparing fossil and bio-based plastics as enclosures for consumer electronics. Specifically, Boyd identified the need to incorporate additives such as fillers and flame retardants

Table 1

A description of published LCAs related to laptops enclosures (Kimura and Horikoshi, 2005; Apple Inc., 2011; Boyd, 2011; Deng et al., 2011; Grzesik-Wojtysiak and Kuklinski, 2013; Teehan and Kandlikar, 2013).

Study	Goal	Assessment type	Assessed Impact(s)
Apple Inc. (2011)	Apply life cycle inventory analysis to 17" aluminum laptop from 2011 to evaluate the greenhouse gas emissions and material consumption	Cradle-to-Cradle	Greenhouse gas emissions and material usage
Boyd (2011)	A review of LCA literature for conventional and bio-based plastics for electronic housings to identify future study needs	Cradle-to-Grave	Global warming potential
Deng et al. (2011)	Apply hybrid LCA to a 15" commercial laptop from 2002 to evaluate its energy and carbon intensity	Cradle-to-Gate	Life cycle energy and carbon emissions
Grzesik-Wojtysiak and Kuklinski (2013)	Apply LCA to a 15" commercial laptop from 2000 to evaluate its life cycle impacts	Cradle-to-Grave	Carcinogenics, Respiratory organics, Respiratory inorganics, Climate change, radiation, ozone layer, Ecotoxicity, Acidification/eutrophication, Land use, Minerals, Fossil fuels Carbon emissions
Kimura and Horikoshi (2005)	Apply LCA to a laptop enclosure made from a PLA-fossil resin blend to determine the life cycle carbon emissions	Cradle-to-Grave	Carbon emissions
Teehan and Kandlikar (2013)	Apply hybrid LCA to a 16" commercial laptop from 2009 to evaluate its embodied emissions	Cradle-to-Gate	Global warming potential and material usage

into life cycle models and to develop more realistic end-of-life options.

The objective of this study is to perform a screening-level life cycle assessment of a laptop enclosure to provide knowledge to support the development of more sustainable consumer electronic products. It seeks to better understand the potential environmental tradeoffs across the life cycles of alternative laptop housings used (and disposed of) by the general public in the US. The goal of this LCA is to compare typical housing made from fossil plastics with alternative materials, including aluminum and materials made from renewable feedstocks such as bamboo or polylactic acid. This work seeks to build on previous studies by addressing gaps identified by Boyd. Although specific models of laptops are selected for certain materials to better understand manufacturing processes and specifications, the purpose of this study is not to target particular brands. The use of screening-level (secondary) data for inventory modeling precludes the interpretation of the results of this study as a comparative assertion regarding the products studied.

2. Methods

The application of screening-level LCA to a laptop enclosure was carried out in accordance with the requirements and practices contained in the ISO 14040:2006 and 14044:2006 standards (ISO, 2006). The discussion of methods is based on the required phases of a life cycle assessment.

2.1. Goal and scope definition

The goal of this study is to evaluate the cradle-to-grave environmental impacts of a common consumer electronic device (laptop enclosure) manufactured from fossil plastics, biomaterials, metals, or a combination thereof to identify what aspects of these materials must be improved to promote environmental sustainability within the consumer electronics market. This information will be valuable to both product developers and policy makers addressing emerging concerns surrounding electronics manufacturing and e-waste. The specific materials selected include Aluminum (metal), Bamboo-Aluminum (biomaterial-metal), Bamboo-polycarbonate (PC)-acrylonitrile butadiene styrene (ABS) (biomaterial-fossil fuel), Bamboo-polylactic acid (PLA)

(biomaterial-bioplastic), PC-ABS (fossil plastic, baseline), and PLA (bioplastic). Flame retardants for the biomaterials and fossil plastics vary based on the material treated and include bisphenol A bis(-diphenyl phosphate) (BDP), triphenyl phosphate (TPP), 9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide (DOPO), and borax-boric acid-phosphoric acid (BBAP).

Based on market research at the time the project was started in 2012, the functional unit of this study is a single laptop enclosure with a 43.9-cm (17.3-inch) display providing protection for the internal components of a laptop over a useful life of 3 years. The average dimensions of the enclosure based on specifications for laptops that were available in 2013 are 41.65 cm × 27.75 cm × 3.3 cm (Fig. 1). The enclosure mass was assumed to be 870.2 g, the value reported by Boyd for an unspecified plastic laptop (Boyd, 2011). The enclosure was assumed to be a unibody construction and formed using injection molding, die-casting, or milling. The modeled enclosures are assumed to adhere to current material standards regarding durability and flammability. The study is bounded strictly around the enclosure itself and excludes the internal laptop components and their use. This means only the materials used directly as part of the laptop enclosure are included and even excludes such things as mounting

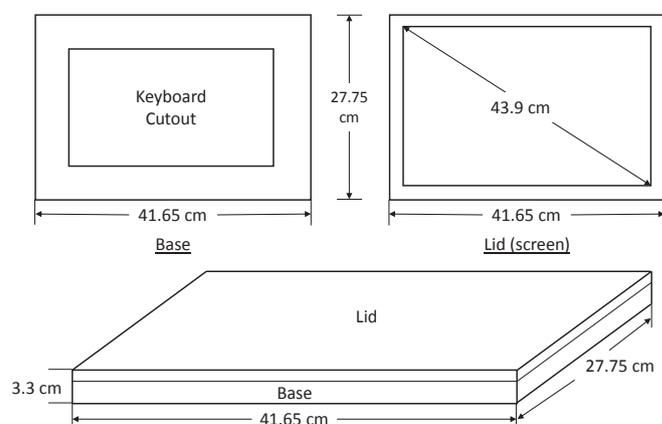


Fig. 1. A schematic of the laptop enclosure showing key dimensions and placement of the keyboard and screen.

hardware and insulating materials. All identified processing steps throughout the life cycle were modeled and include upstream material feedstock production (from both primary and recycled sources when applicable), enclosure forming, transportation, and end-of-life treatment. All aspects of the life cycle are assumed to occur hypothetically within the continental United States. Although this is not a realistic representation of the current supply chain, this decision was made to simplify the simultaneous analysis of materials given the wide variability within the supply chain, and to avoid the complexity of measuring transportation impacts, especially given the uncertainty in the supply chain for emerging materials.

2.2. Life cycle inventory (LCI)

Inventories for the screening-level study were built using secondary data, including the ecoinvent database (Swiss Centre for Life Cycle Inventories, 2010), the U.S. LCI database (National Renewable Energy Laboratory, 2012), patents, academic literature, technical reports, and manufacturers' technical publications. All ecoinvent unit processes and selected infrastructure were adapted for US conditions primarily by modifying the underlying energy and transportation flows. Whenever possible, equivalent material production processes representing U.S. or North American conditions were substituted for non-US processes. A summary of inventories is presented here with more detailed information available upon request.

2.2.1. Aluminum

The life cycle of an aluminum laptop enclosure is shown in Fig. 2. The design of the laptop enclosure is loosely based on the Apple MacBook (Apple Inc., 2011) product line and is not intended to be a direct representation of these products. Data for the production of average aluminum (primary from mined ore blended with secondary from recycled material) were obtained by adapting existing ecoinvent processes for US conditions. A module for aluminum die casting was developed based on the work of Brevick et al. (Brevick et al., 2004) and Dalquist and Gutowski (Dalquist and Gutowski, 2004). Major material inputs, energy requirements, and basic VOC emissions were accounted for during modeling. For CNC milling, aluminum sheets (41.65 cm L × 27.75 cm W with a thickness of 0.16 cm, 0.95 cm, or 2.54 cm) were assumed to be milled in a CNC machine using a calculated total energy of 4.3 kWh. The energy value was estimated using the Heidenhain technical bulletin

(Heidenhain, 2010) and material removal rates of 275.3 and 96.8 cm³ min⁻¹ for milling and grinding (Polgar et al., 1996), respectively. Laptop assembly included only the energy required to mount the laptop components in the enclosure (US EPA, 2001). No inventory was assumed to be associated with the laptop enclosure during the use phase of the laptop. Although a number of scenarios can be considered for EOL, the scrap after disassembly was treated as being either completely recycled or completely landfilled because these scenarios are believed to represent the best and worst case scenarios, respectively. Landfilling was modeled using Swiss data in ecoinvent describing the sanitary landfill of process specific burdens in ecoinvent because the documentation for this process stated it was similar to US practices. This is an appropriate assumption for the screening level nature of this, but would need to be replaced with US-specific data if end-of-life is determined to be a major source of impact. Recycling was modeled using the cut-off method, whereby the system boundary is drawn at the secondary aluminum refinery and the impacts related to the aluminum at end-of-life account for the dismantling of the laptop and transportation to the secondary refinery. The benefit of recycling is accounted for during manufacturing by using a blend of 68% primary and 32% secondary aluminum as the input to the aluminum working process (DC or CNC). Transportation was assumed to occur by either a diesel-powered combination truck using generic distances of 1000 km (manufacturing inputs), 100 km (transport to and from a train for recycling), 50 km (transport to electronics recycling facility or landfill) or by train using a generic distance of 1000 km (transport to secondary refinery region). The distances were selected as order-of-magnitude representations of local (50–100 km) and regional/national (1000 km) services. A summary of the inventory for the aluminum laptop enclosure, as entered in SimaPro, is shown in Supplementary Information Tables S1 and S2.

2.2.2. Polycarbonate-acrylonitrile butadiene styrene

The life cycle of a PC-ABS laptop enclosure is shown in Fig. 3. Inventory data for PC and ABS were adapted from ecoinvent. The ratio of PC to ABS in the laptop enclosure was assumed to be 3–1 (Boyd, 2011). The average composition of flame retardant in the laptop enclosure was calculated as 11.2% using data from Levchik et al. (Levchik et al., 2001) and Levchik and Weil (Levchik and Weil, 2005). The amount of PTFE blended as a filler was assumed to be 5%. Although the flame retardant in the cited studies was an equal blend of BDP, TPP and RDP, the flame retardant was assumed to be a single component to better understand the impact of each option. Based on data availability, BDP and TPP were considered. Inventory for the production of BDP was based on US patent 6,319,432 B1 (Harrod and Klobucar, 2001) describing a two-step preparation of BDP for use as a flame retardant in plastic blends, including PC-ABS. During the first step, bisphenol A is reacted with phosphoryl chloride using magnesium chloride as a catalyst. The intermediate of this reaction is then reacted with phenol in the presence of magnesium chloride catalyst to yield BDP. Data for bisphenol A, phosphoryl chloride, and phenol were adapted from ecoinvent. Inventory for the production of magnesium chloride was constructed by subtracting the energy required for electrolysis of magnesium chloride to yield magnesium from inventory data for magnesium production. The hydrochloric acid that is evolved throughout the process was assumed to be recovered and treated as an avoided product. For process heating requirements, a minimum estimate was made based on the heat capacities and latent heats of vaporization of the materials and the reported process temperatures. Other estimated processing energies included mixing and vacuum pressure regulation. The product is purified by solvent extraction in toluene and methylcyclohexane and washed in 10% sodium hydroxide. Data for the production of these materials was

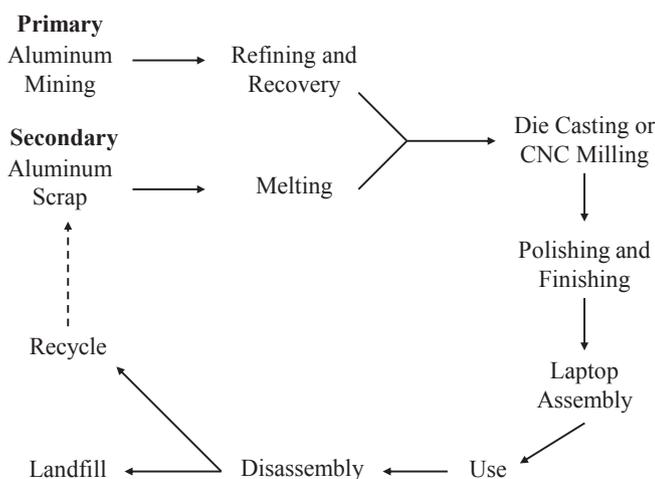


Fig. 2. The cradle-to-grave life cycle of an aluminum laptop enclosure using die casting and the option to recycle or landfill scrap.

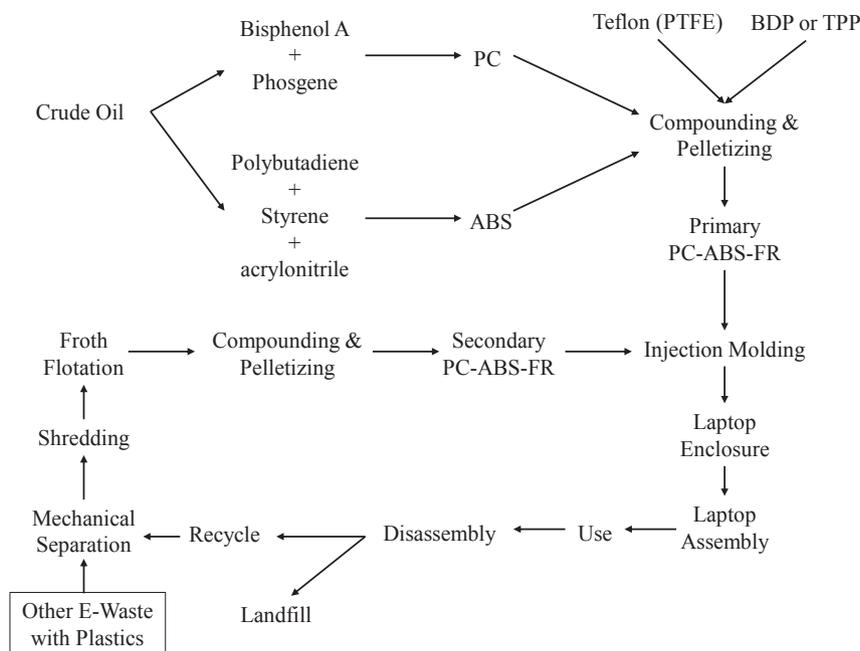


Fig. 3. The cradle-to-grave life cycle of a PC-ABS laptop enclosure using either BDP or TPP flame retardant and the option to recycle or landfill waste plastics.

adapted from existingecoinvent processes. TPP is produced from the reaction of phenol with phosphoryl chloride using zinc chloride as a catalyst. The inventory for TPP was obtained from EPA report 560/6-76-008 (Kopp, 1976) and included a complete description of average material and energy use and waste treatment based on five industrial processes. Again, hydrochloric acid evolved during the process was assumed to be recovered and treated as an avoided product. Tetrafluoroethylene data was used as a proxy for PTFE and adapted from existingecoinvent data.

The extrusion and pelletizing of the flame retardant PC-ABS was modeled using the work of Thiriez (Thiriez, 2004) with an assumed mass loss of 2.4%. The emissions during extrusion were obtained from Rhodes et al. (Rhodes et al., 2002). The data for injection molding was adapted from European data inecoinvent. As with the aluminum laptop enclosure, final laptop assembly included only the energy required to mount the laptop components in the enclosure. No inventory was assumed to be associated with the laptop enclosure during the use phase of the laptop. Although some emission of the flame retardant during use may occur, adequate data is currently not available to estimate characterization factors for BDP and TPP. After disassembly, landfilling was modeled using the sameecoinvent data described previously. Although plastics can be subjected to incineration and energy recovery during disposal, a worst-case landfill option was selected as the baseline because no consistent data could be identified describing the typical incineration quantities for these materials in the US. For the recycling option, the preparation of secondary flame retardant PC-ABS was modeled based on the Argonne shredder residue recycling process (Gallon and Binder, 2006) for automotive and electronic waste. The waste is first treated in a mechanical separation plant where the plastics are separated and shredded. The shredder residue is then fed to a froth flotation process used to separate the various plastics based on density. The life cycle data reported by Gallon and Binder was applicable to the entire process. A mass-based allocation was used to determine the material and energy requirements for the recovery of PC-ABS within this process. The recovered PC-ABS was assumed to be reblended in an extruder with make-up plastic and flame retardant and pelletized to produce a

post-consumer recycled (PCR) resin. The cut-off method described above for aluminum was applied to the PC-ABS recycling scenario. To better understand the impacts of recycling plastics for consumer electronics, a set of scenarios were included for impact assessment using a secondary PC-ABS composition in the laptop enclosure ranging from 20% to 100% (pure secondary) PCR. As modeled here, a 100% PCR content would represent a completely closed product loop. Transportation was assumed to occur by either a diesel-powered combination truck using generic distances of 1000 km (manufacturing inputs), 100 km (transport to and from a train for recycling), 50 km (transport to electronics recycling facility or landfill) or by train using a generic distance of 1000 km (transport to secondary refinery region). The inventories for BDP, TPP, and representative PC-ABS laptops are summarized in Supplementary Information Tables S3–S6.

2.2.3. Polylactic acid

The basic life cycle of a PLA laptop enclosure with DOPO flame retardant is shown in Fig. 4. The PLA laptop modeled for this study is based on US patent application 2013/0012631 A1 (Serizawa et al., 2013). The data for the production of PLA was available inecoinvent and is based on the U.S. process used by Nature Works, LLC. Aluminum hydroxide data was adapted fromecoinvent data. The same adapted tetrafluoroethylene data created for the PC-ABS blend was used here. The production of DOPO was modeled using US patent application 2010/0298470 A1 (Kaplan et al., 2010). DOPO is prepared by reacting phosphorous trichloride with o-phenylphenol in the presence of an anionic exchange resin and zinc chloride catalysts. Data for the production of phosphorous chloride and zinc chloride were adapted fromecoinvent data. Data for the production of phenol was adapted fromecoinvent data and used as a proxy for o-phenylphenol. Energy estimates were made using the same methods employed for BDP. Hydrochloric acid is evolved during the reaction and was assumed to be recovered and treated as an avoided product. Although compounding and pelletizing of the resin was assumed to be the same as the process for PC-ABS, no emissions data was available for inclusion in the inventory. The same injection molding and laptop assembly data used for PC-ABS

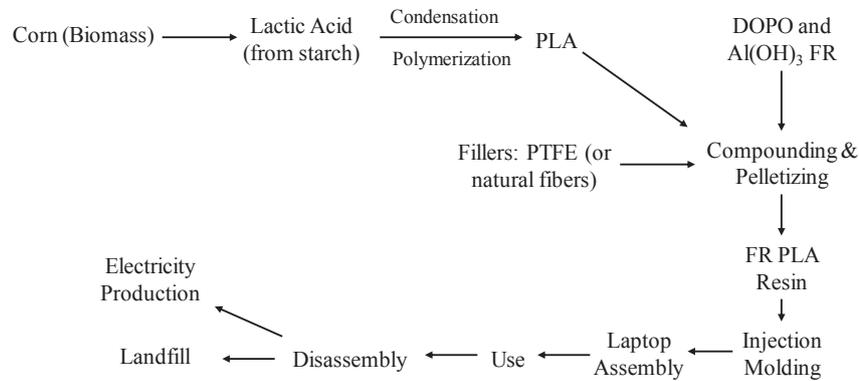


Fig. 4. The cradle-to-grave life cycle of a PLA-DOPO laptop enclosure with the end-of-life options of landfilling or electricity generation.

was applied to PLA-DOPO. Again, no inventory data were assumed to be associated with use. Disassembly for landfill used the same sanitary landfill data described previously. Electricity production was modeled using data from Nature Works, LLC describing the heating value and emissions (carbon dioxide, water, residue) for the incineration of PLA (Nature Works, 2013). The electricity generation per mass of PLA, estimated using data for bamboo as a reference (see below), was assumed to be $0.834 \text{ kWh kg PLA}^{-1}$ or $0.457 \text{ kWh kg PLA-DOPO}^{-1}$. This is accompanied by a total release of $1.57 \text{ kg CO}_2 \text{ kg PLA-DOPO}^{-1}$, $0.06 \text{ kg P}_2\text{O}_{10} \text{ kg PLA-DOPO}^{-1}$, $0.29 \text{ kg water kg PLA-DOPO}^{-1}$, and $0.14 \text{ kg residue kg PLA-DOPO}^{-1}$ (to landfill). The emissions for the combustion of DOPO were estimated by assuming all carbon was converted to carbon dioxide, all phosphorous was converted to phosphorous pentoxide, and all hydrogen was converted to water. Aluminum hydroxide, the other major component in the laptop enclosure, was assumed to be converted to aluminum oxide and landfilled. The average production mix of electricity in the US was treated as an avoided product. Transportation distances were assumed to be generic distances of 1000 km (manufacturing inputs), 100 km (transport to landfill), 50 km (transport to electronics recycling facility), and 5 km (on-site electricity generation) traveled by diesel-powered trucks. A summary of the life cycle inventory is presented for DOPO and the PLA-DOPO laptop enclosure in Supplementary Information Tables S7 and S8.

2.2.4. Bamboo

The basic life cycle of a bamboo-based laptop enclosure is shown in Fig. 5 and is based on the laptop made commercially available by ASUSTeK. Although only the bamboo-aluminum laptop has been offered commercially, bamboo-based laptops using both metals and plastics are included because ASUSTeK has multiple patent applications describing both options (Tsai, 2008; Yang, 2008; Tsai, 2009).

The bamboo for the enclosure was assumed to be *Phyllostachys pubescens*, or moso bamboo, grown on a commercial plantation in the southeastern United States. The plantation was configured according to guidelines proposed by Kigomo (Kigomo, 2007) using a 7 m by 7 m spacing per plant for 1 ha of land. The process for seedling production was adapted from an existing ecoinvent process and included the energy and fertilizer inputs at a greenhouse. After thinning, each plant was assumed to yield 20 culms. Nutrient and water requirements were adapted from research by Kleinhenz (Kleinhenz and Midmore, 2000; Kleinhenz et al., 2003), and included 250:50:141 kg N:P:K inorganic nutrients per hectare per year and 2000 mm water. Although organic nutrients were recommended to maintain soil quality, this material was assumed to be supplied by the decay of biomass generated within the

plantation. The long term average rainfall in the southeastern United States, as reported by the Southeast Regional Climate Center in 2012 (SERCC, 2012), was 1274 mm water. Therefore, the yearly irrigation rate was assumed to be 726 mm water. The amount of N_2O emissions (direct + indirect) were calculated using the IPCC 2006 guidelines (IPCC, 2006). Phosphorous run-off calculations were based on the work of Vadas et al. (Vadas et al., 2009), where rainwater run-off calculations were estimated using methods presented by the Watershed Management Group (WMG, 2013). The harvest fraction was assumed to be 20% of the standing culms annually. Carbon sequestration was only counted for the rejuvenation of the harvested fraction using factors of $1.83 \text{ kg CO}_2 \text{ kg dry bamboo}^{-1}$ above ground and 32% of bamboo mass being above ground (van der Lugt et al., 2012). Bamboo was assumed to be harvested manually using machetes and air dried for curing. The required diesel consumption to transport the felled culms to a central drying area on the plantation and the water released during drying were modeled for harvesting (Yu et al., 2011).

Energy use during the preparation of the glued bamboo laminate was modeled using the process described by IPIRTI Bangalore (IPIRTI, 2013). The cut culms were assumed to be 16 m long with a 12 cm diameter (Lee and Addis, 2001). The energy required to store the culms at the production facility was assumed to be the value of 15.6 MJ t^{-1} reported by Yu et al. (Yu et al., 2011). The culms were assumed to be cut into strips with dimensions of $42 \text{ cm L} \times 2 \text{ cm W} \times 0.2 \text{ cm T}$. The energy needed for stripping and knotting was 0.803 kWh per laminate (IPIRTI, 2013). Based on the strip dimensions, 65 strips would be needed to produce one bamboo laminate with assumed dimensions of $41.65 \text{ cm L} \times 25.75 \text{ cm W} \times 1 \text{ cm T}$. These dimensions were chosen based on the dimensions of the bamboo shell needed for the laptop enclosure. The strips were assumed to be treated with a Borax-Boric Acid-Phosphoric Acid (BBAPA) solution (preservative and flame retardant) based on methods described in US patent 6,319,431 B1 (Basson and Conradie, 2001). The total energy requirement for treating, drying, and planning the strips was 3 kWh per laminate (IPIRTI, 2013). The strips were glued and pressed into a laminate using resorcinol phenol formaldehyde as the adhesive and finished using trimming and planning. The energy use during these steps was 0.154 kWh per laminate (IPIRTI, 2013). A bamboo laminate produced using this method had a total mass of 0.2051 kg . Other inventory during preparation of the laminate included bamboo scrap, liquid wastes from the treatment bath and formaldehyde emissions during gluing and pressing. Treatment of the liquid waste was adapted from a Swiss process for wastewater with slight organic and inorganic contaminants in ecoinvent.

The bamboo shell for the laptop enclosure was prepared using a CNC milling machine (Tsai, 2008). The laminate shell dimensions

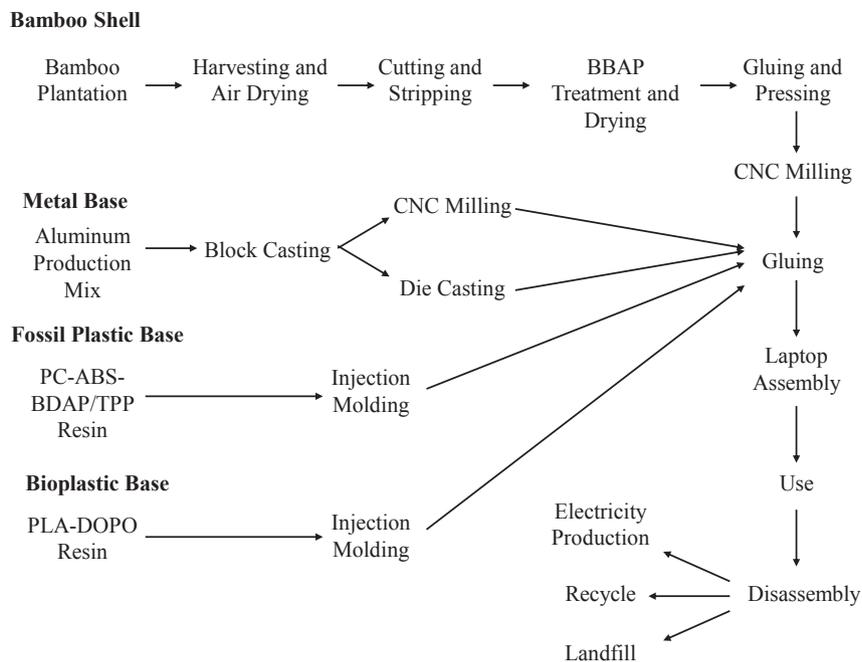


Fig. 5. The life cycle of a bamboo-based laptop enclosure using aluminum, PC-ABS, or PLA as a base material and considering landfilling, recycling, or energy production during end-of-life.

were approximated from specifications in the Asustek patent application and were assumed to be simple rectangular cut-outs to simplify milling volume calculations. A total of 3 laminates were required per laptop enclosure. A total energy requirement of 3.7 kWh was estimated using a Heidenhain technical bulletin (Heidenhain, 2010) on energy efficiency during machine tooling with the material removal rate for medium density fiberboard (Sutcu and Karagoz, 2012), $90 \text{ cm}^3 \text{ min}^{-1}$, as a proxy for bamboo.

The base for the laptop enclosure was assumed to be prepared using either aluminum, PC-ABS-BDP, or PLA-DOPO. Both die casting and CNC milling as previously described were considered for the preparation of an aluminum base. The plastic bases were prepared using injection molding as described previously with the masses of the mold injected parts decreased to account for the mass of bamboo in the laptop enclosure. To better explore material options, three fossil plastic compositions were considered: primary, 40% recycled content, and 100% recycled content. No data could be obtained to make similar considerations for PLA. Instead, energy generation using PLA was considered as an alternative EOL method. The adhesive used to bond the shell to the base was assumed to be a high density polyethylene modified with maleic anhydride (Sui et al., 2000). As with the other options, laptop assembly included the electricity use while installing the internal components and no inventory is associated with the use phase. Bamboo scrap generated during the manufacture of the laptop enclosure and its EOL disposal was either used for electricity generation or disposed of in a sanitary landfill. For electricity generation, the bamboo was assumed to generate $0.833 \text{ kWh kg bamboo}^{-1}$ (Eco-Energy Solutions) and release $1.83 \text{ kg CO}_2 \text{ kg bamboo}^{-1}$ (van der Lugt et al., 2012). The generated electricity was used to offset the required electricity at the facility where the bamboo scrap/waste was generated. The recycle of aluminum or plastics was the same as described previously. All landfill treatment was based on the adaptation of the Swiss process presented inecoinvent. A summary of the inventory data for representative bamboo-based laptop enclosures is shown in Supplementary Information Tables S9–S12. The same assumptions for transportation applied to the other

materials were used for bamboo too, with the exception of the dry bamboo that was assumed to be 100 km from the laminate processing facility.

2.3. Life cycle impact assessment

The inventories for the laptop enclosure options were entered into SimPro 7.3.3 (PRé Consultants, 2013). Impact assessment was performed using the U.S. Environmental Protection Agency's Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) 2.1, version 1.0 (Bare, 2012). This is the latest version of TRACI and incorporates USEtox for calculation of ecological and human health (carcinogens, non carcinogens) impacts. TRACI is a US-based impact assessment method that includes the following mid-point impact categories: Ozone Depletion (OD, kg CFC-11 eq), Global Warming (GW, kg CO_2 eq), Smog (S, kg O_3 eq), Acidification (Acid, kg SO_2 eq), Eutrophication (Eut, kg N eq), Carcinogenics (Car, CTUh), Non carcinogenics (N-Car, CTUh), Respiratory Effects (RE, kg $\text{PM}_{2.5}$ eq), Ecotoxicity (Eco, CTUe), and Fossil Fuel Depletion (FFD, MJ surplus). Updated US normalization factors for TRACI were obtained from Ryberg et al. (Ryberg et al., 2013). As noted by Ryberg et al. interpretation of USEtox results for metal emissions should include consideration that the metal characterization factors are interim (Ryberg et al., 2013). For the simultaneous analysis of material options, the 95% confidence intervals were calculated using the Monte Carlo uncertainty package included in SimaPro and 1000 simulation runs.

3. Results and discussion

Results are first presented for each material type. Given the large number of scenarios considered, the findings from these analyses were used to identify the best option(s) for inclusion in comparison simultaneous material analysis.

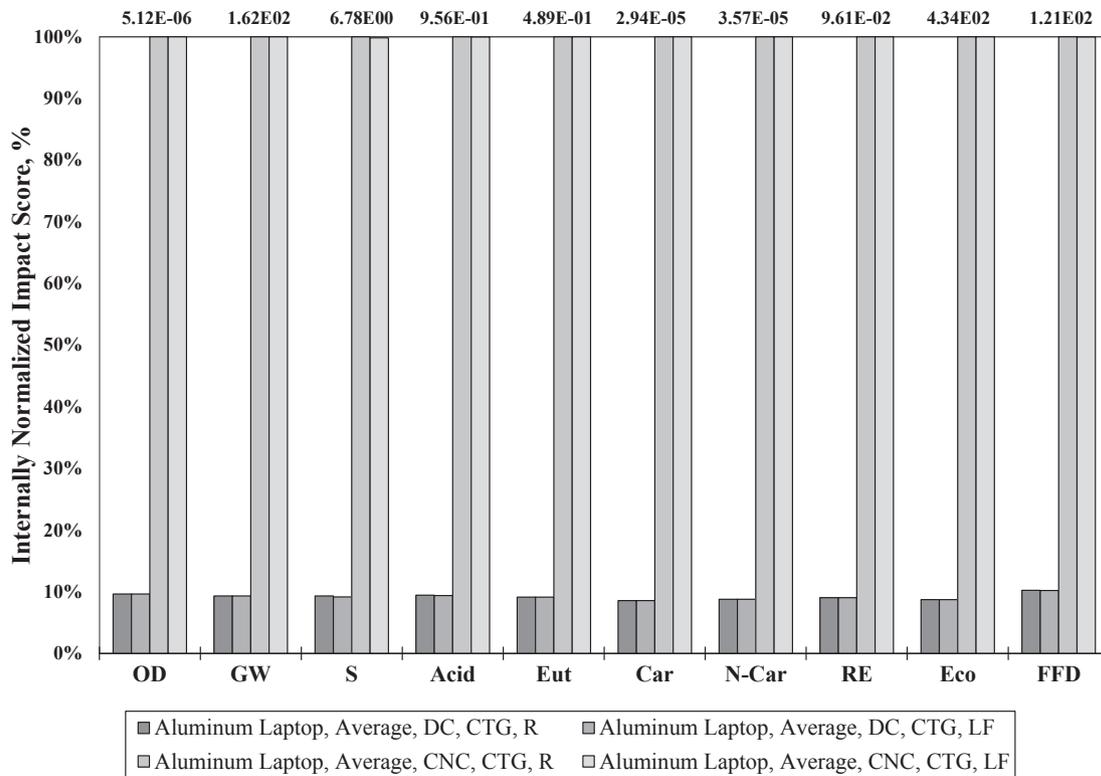


Fig. 6. Internally normalized impact scores for aluminum laptop enclosures prepared using either die casting (DC) or CNC milling. Note: CTG = cradle-to-grave, R = recycle, LF = landfill.

3.1. Aluminum

The impact assessment scores for the aluminum laptop enclosure options are shown in Fig. 6. The scores have been internally normalized to the largest individual score within each category, with the score corresponding to 100% shown at the top of the graph. It is readily apparent the method of manufacturing has a significant effect on the results, with die casting reducing all impacts by approximately 90%. These differences can be attributed to the much larger quantity of electricity required for CNC machining. The differences associated with the EOL options are negligible. Given recycled metals are known to have reduced impacts when compared to primary metals for impacts like energy use, water use, and waste generation (NSW, 2010) and aluminum must be recycled to support this option, the scenario for a die cast aluminum laptop enclosure with EOL recycling was selected for the final material analysis. Comparison of the data with the results reported by Apple (Apple Inc., 2011) for their products is not possible because the Apple data is not reported at the component level.

3.2. Polycarbonate-acrylonitrile butadiene styrene

A total of twenty four life cycle scenarios were run for PC-ABS accounting for flame retardant selection (BDP or TPP), recycled material content (0%, 20%, 40%, 60%, 80%, 100%), and end of life processing (recycle or landfill). The results were first sorted and compared for each flame retardant option (not shown). When using BDP, increasing the recycled content leads to a reduction of impacts in nine of the ten impact categories, with the only exception being eutrophication. For TPP, the use of recycled content reduced impacts in seven of the ten impact categories, with the exception of eutrophication, carcinogenics, and a negligible change in ecotoxicity. Eutrophication potential increases for both flame retardant

options as recycling content is increased because of the energy required to produce the numerous chemicals needed to recover and reprocess the plastics using density separation. For TPP, the increase in carcinogenics is related to the make-up flame retardant required for blending the secondary pellets and the zinc chloride catalyst used to make it. When comparing scenarios for landfilling and recycling, the recycling option produces slightly larger impacts based on the order-of-magnitude increase in transportation distances. This finding illustrates the need for accurate transportation modeling when evaluating EOL options. Recycling is only possible if the material is recovered at end-of-life. Therefore, the comparison of PC-ABS-BDP with PC-ABS-TPP was carried out using the results for recycling when recycled content is present and landfilling for enclosures made only from primary material. To further reduce the number of impact scores to analyze, the scenarios for 20% and 60% recycled content were omitted because the general trend in impact scores based on recycling content was still visible with only the four remaining points. The resulting comparison is shown in Fig. 7.

The impacts for PC-ABS-BDP are larger for nine of the ten impact categories. The primary cause for this can be attributed to the flame retardant manufacturing because this is the only difference between the two materials. More specifically, the liquid extraction and purification of the BDP requires more energy, resulting in bigger impacts. The results for ozone depletion are one exception to this trend because more hydrochloric acid is generated as an avoided product for BDP than TPP. This credit yields a negative contribution for BDP to the life cycle ozone depletion impact, whereas TPP has a positive contribution. As previously discussed, recycling generally reduces the impact scores, except for eutrophication because of the additional requirements during recovery and processing of the plastics. Interestingly, the PC-ABS-BDP and PC-ABS-TPP enclosures display opposite trends for the carcinogenics impact because of the different catalyst required to make

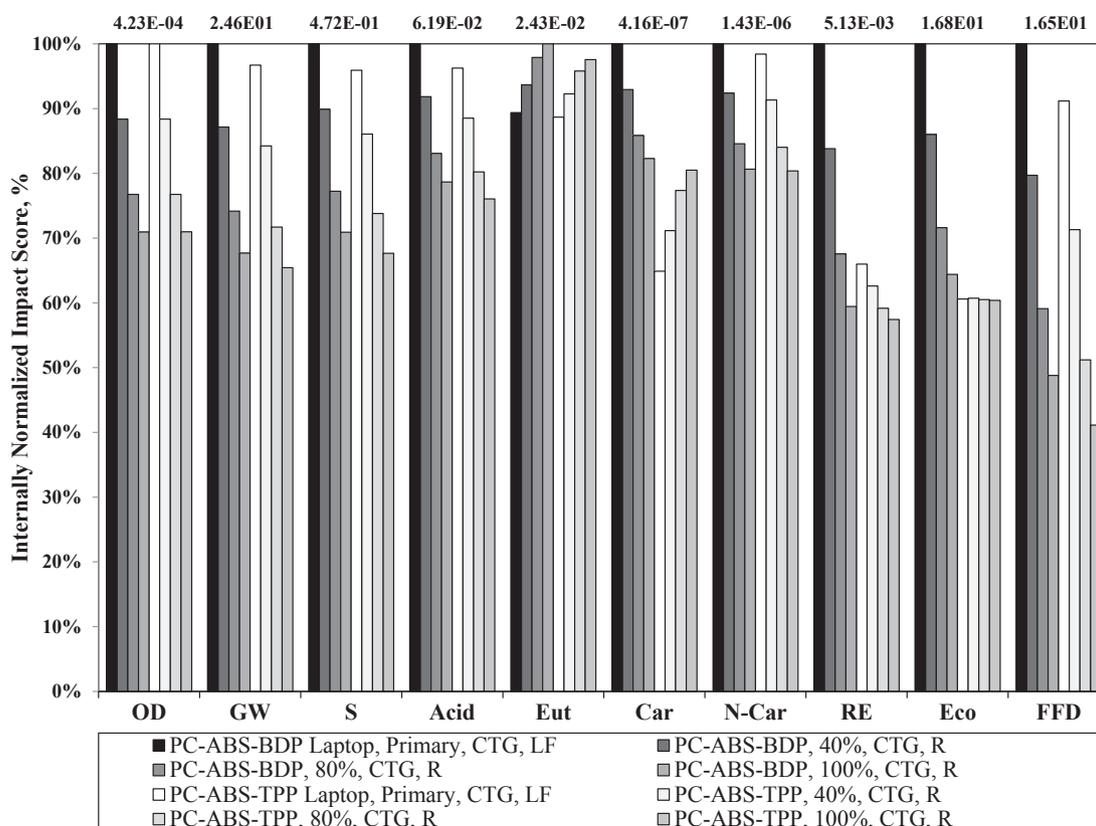


Fig. 7. Internally normalized impact scores for PC-ABS laptop enclosures showing the influence of flame retardant selection and recycled content levels. Notes: CTG = cradle-to-grave, R = recycle, LF = landfill; Percentages represent the content of secondary resin by mass.

BDP and TPP. Given the two options for a flame retardant, PC-ABS-TTP actually yields impacts that are 2% lower on average than PC-ABS-BDP in six impact categories, with larger impact reductions of 17%, 16%, 20%, and 8% for carcinogenics, respiratory effects, ecotoxicity, and fossil fuel depletion, respectively. For the current study, it should be noted the potential toxicity of the various flame retardants is not reflected in the human and ecological health categories because of a lack of data to support derivation of accurate characterization factors in USEtox. As a last means of analysis, the average global warming potential during manufacturing obtained in this study was compared with the value reported by Boyd (Boyd, 2011) and showed the inclusion of the flame retardant and filler substantially increased the global warming potential from 5.7 kg CO₂ eq per laptop to 23.4 kg CO₂ eq per laptop. Based on the analysis, the PC-ABS-TTP material was selected for the simultaneous material analysis. Although not shown in Fig. 6, the results for both 20% and 60% PCR were actually selected for the subsequent analysis in order to explore the environmental impacts of moderately (20%) or significantly (60%) increasing the volume of PCR in these products beyond current practices. For example, manufacturers declare on the EPEAT registry using between 0 and 10% PCR. If mechanically viable, increasing the PCR should be an attractive option for companies because recycled materials can often be cheaper than primary feedstocks.

3.3. Polylactic acid

The impact assessment results for PLA-DOPO are shown in Fig. 8. The impacts for landfilling are only 3% greater on average for eight of the ten impact scores. Generation of electricity for end-of-life increases both global warming and eutrophication potential

because of the combustion emissions. These results may change when the data is available to include the specific degradation behavior of PLA in the landfill model. Composting during end-of-life has generally been preferred over landfilling for materials such as bioplastics based on the perceived environmental benefits (OECD, 2013). However, PLA typically requires industrial composting with temperature control to support rapid decomposition (Leejarkpai et al., 2011) and insufficient data for this type of blended PLA was not available to include this option in the current study. Furthermore, a recent study has suggested composting of PLA food packaging is not the environmentally preferred end-of-life option based on impact assessment (Rossi et al., 2015). Based on the results, the generation of electricity on-site at the waste electronics processing facility was selected as the option for the simultaneous material analysis. A comparison of the global warming potential for manufacturing the PLA-DOPO enclosure with the value presented by Boyd (Boyd, 2011) demonstrates an increase from 1.7 to 6.8 kg CO₂ eq per laptop because of the inclusion of the flame retardant and fillers.

3.4. Bamboo

Similar to PC-ABS, the number of options and scenarios associated with the bamboo laptop enclosure made it difficult to compare in a single evaluation. Instead, the options were compared first by grouping based on the support material. The most promising option of each material set was then compared to determine which option should represent bamboo for the simultaneous material analysis.

For the comparison of bamboo aluminum (not shown), only the die cast production method was considered based on the earlier

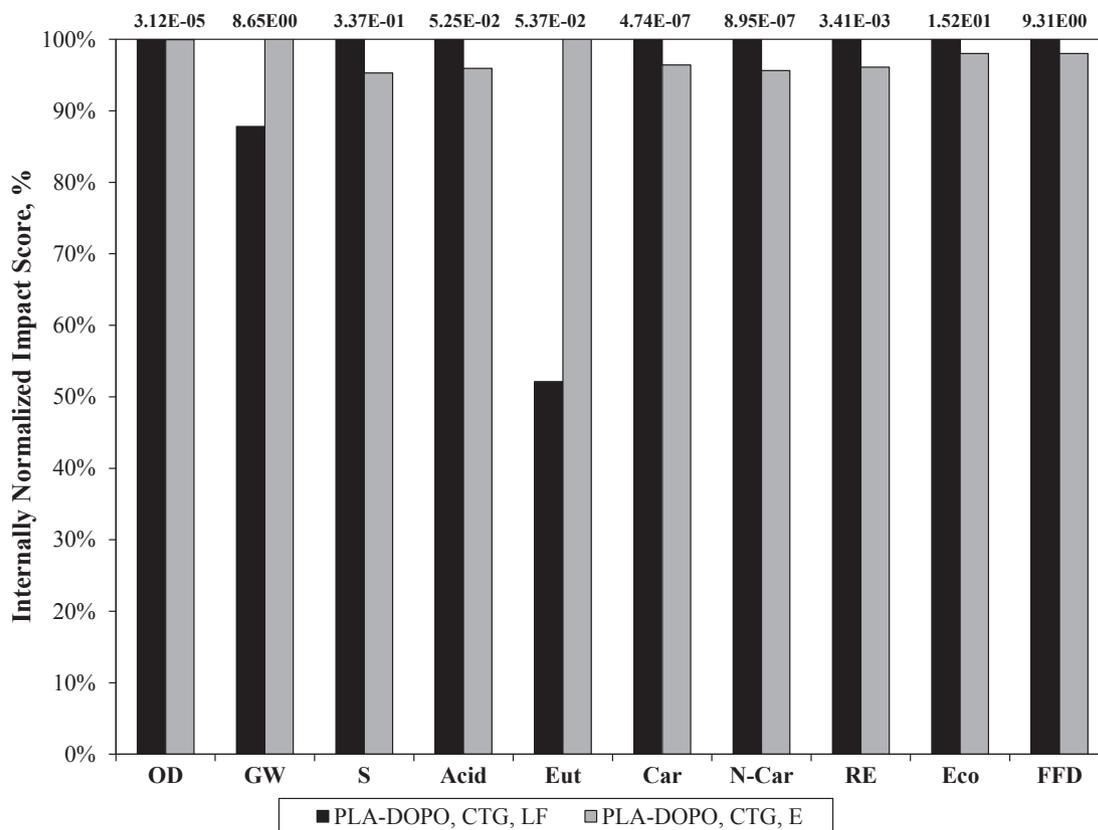


Fig. 8. Internally normalized impact scores for PLA-DOPO laptop enclosures with differing EOL options. Notes: CTG = cradle-to-grave, E = energy generation, LF = Landfill.

findings when comparing aluminum production methods. The three EOL options included electricity from bamboo and aluminum recycling, landfilling bamboo and aluminum recycling, and landfilling both materials. The differences in the three options are negligible (<0.1%) because of the small mass of bamboo contained in the laptop enclosure and the variations in transport distances. For further comparison, the energy and recycle option was considered after conversations with people in the bamboo industry who expressed interest in using bamboo scrap to offset on-site electricity needs whenever possible.

The bamboo PC-ABS options were first grouped by flame retardant and compared. The three EOL options included electricity from bamboo and plastic recycling, landfilling bamboo and plastic recycling, and landfilling both materials. The best performing option for each flame retardant were then compared (not shown). The analysis identified the same trends as when comparing pure PC-ABS options because of the small mass of bamboo in the laptop enclosure. However, the reduction in impacts achieved through recycling is offset by the increased energy impacts associated with processing the bamboo using CNC machining. The Bamboo PC-ABS-TPP laptop with 40% PCR (representative intermediate value), bamboo disposal for energy generation, and plastic recycling was selected for further comparison.

Bamboo PLA-DOPO scenarios included electricity generation from the entire enclosure, electricity from bamboo and landfilling PLA, and landfilling the entire enclosure. The difference between impact scores for the three options is less than a tenth of a percent for eight of the ten impact categories, with the emissions from electricity generation increasing global warming potential by 4% and eutrophication by 15%. Applying the same contextual reasoning

as with the other base materials, the PLA-DOPO laptop enclosure with energy generation was selected for further comparison.

The final comparison of the bamboo enclosure options is shown in Fig. 9. The use of an aluminum base yields the largest impacts in seven of the ten impact categories based on contributions from upstream processes associated with aluminum mining and fossil-based feedstocks for energy generation. Of the two plastics considered, the differences in impact scores for smog formation, acidification, and respiratory effects are negligible because most of the impacts are related to the bamboo. The use of the bioplastic in place of the fossil plastic leads to significant reductions of 92% and 29% for ozone depletion and global warming potential, respectively, because of the reduced need for petrochemical processing. Similarly, small reductions of 2% and 10% are observed for non carcinogenics and fossil fuel depletion, respectively. The eutrophication impact for bamboo PLA-DOPO is actually 19% greater than bamboo PC-ABS-TPP because of the impacts associated with energy generation during end-of-life. The ecotoxicity and carcinogenics impacts for bamboo PLA-DOPO are slightly greater than bamboo PC-ABS-TPP by an average of 6% because of processes associated with manufacturing the flame retardant and fillers. Interestingly, although the bamboo constitutes 5% by mass of the final product, the production of the glue required to make the laminate boards accounted for 94% of the average smog impact, 79% of the average acidification impact, 24% of the average eutrophication impact, 76% of the average non carcinogens impact, 37% of the average respiratory effects impact, 26% of the average ecotoxicity impact, and 14% of the average fossil fuel impact for all three options. For global warming, 18% of the average impact is the result of electricity generation from bamboo scrap. Although bamboo has a reputation

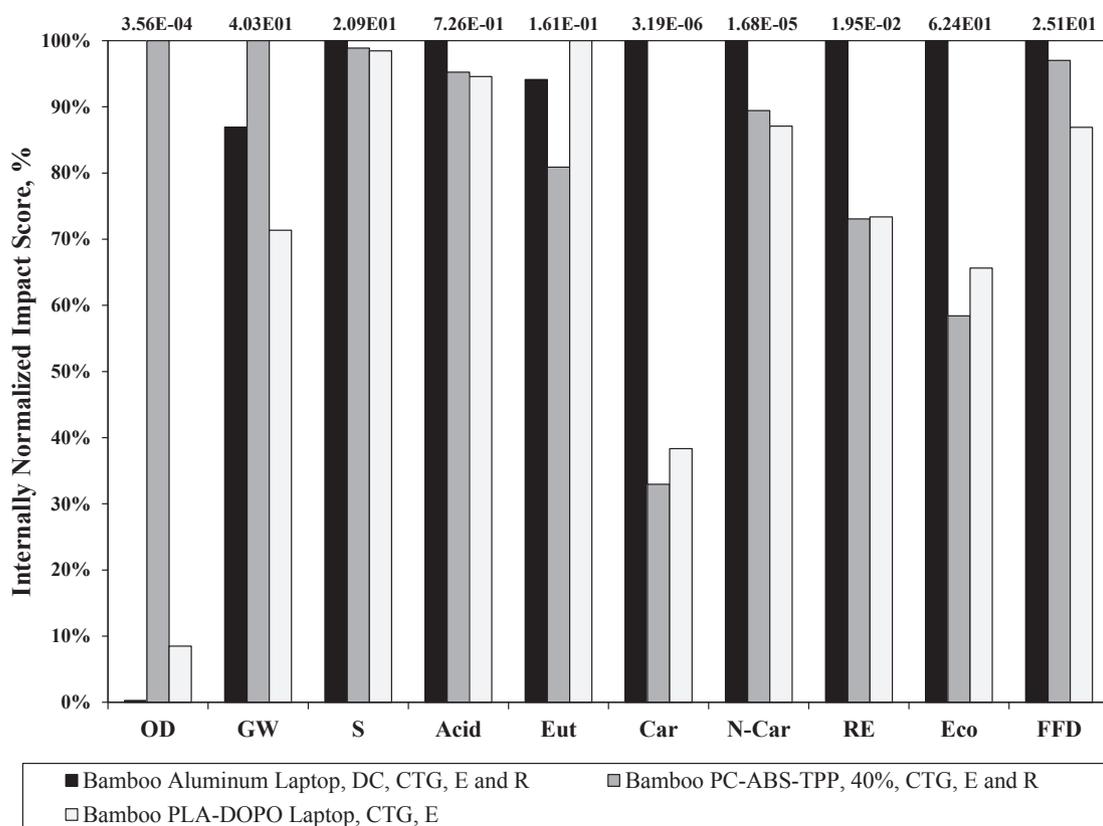


Fig. 9. Internally normalized impact scores for Bamboo laptop enclosures using either aluminum, PC-ABS-TPP or PLA-DOPO as a base support. Notes: CTG = cradle-to-grave, E = energy generation, R = recycle.

for being a sustainable material as a fast-growing renewable feedstock, these results suggest more attention must be given to bamboo product manufacturing and EOL management. Based on the impact results, the bamboo PLA-DOPO enclosure with energy generation was selected for the simultaneous material analysis.

3.5. Simultaneous material analysis

3.5.1. Laptop enclosures

The externally normalized impact results for the selected enclosure options are shown in Fig. 10 with the 95% confidence intervals based on Monte Carlo uncertainty analysis. The benefit of external normalization is the magnitude of the value provides an understanding of the importance of a given impact category. For this study, the major categories are smog, acidification, eutrophication, and human health (carcinogenics and non carcinogenics). In all but the carcinogenics and ozone depletion categories, the mean impact scores of using bamboo are the largest and are driven by the adhesives needed to make bamboo laminates and the CNC machining used for product fabrication. Ultimately, these impacts would negate the perceived benefits of using a renewable bio-feedstock and highlight the need to apply life cycle thinking to product design. The energy requirements for the production of aluminum produce the largest carcinogenic impact and the second largest mean impact scores in six of the remaining categories. These results correspond to the average recycled metal content of 32% used in ecoinvent and should improve if this value is increased. A quick analysis (not shown) indicated impacts for the aluminum enclosure could be reduced up to 80% for a PCR content of 100%. The PC-ABS-TPP enclosures yield lower mean impact scores relative to the aluminum and bamboo options for smog formation, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory

effects and ecotoxicity. For fossil fuel depletion, PC-ABS-TPP becomes a more suitable alternative than the modeled aluminum option once the PCR content increases to 60%. The ozone depletion potential related to the production of the flame retardants for the PC-ABS blend makes it the least desirable for this impact category. The PLA-DOPO plastic option has the least impact of all of the alternatives when considering global warming, smog, acidification, non-carcinogenic human health, and fossil fuel depletion. The preparation of the flame retardant for PLA-DOPO makes it more impactful than the aluminum alternative for ozone depletion. The larger eutrophication impacts for PLA-DOPO relative to PC-ABS-TPP are related to growing the corn and electricity generation during end-of-life. The increased carcinogenic health impacts for PLA-DOPO are related to the energy needs throughout the supply chain. The negative aspects of using fossil plastics relative to bioplastics are clearly visible in the remaining impact categories. The ozone depletion impact appears to be proportional to the amount of PTFE filler used because both the impact score and amount of PTFE used in PC-ABS versus PLA-DOPO differ by an order of magnitude. Similarly, the larger quantity of PTFE and the use of PC produce a 122% (60% PCR) to 158% (20% PCR) increase in the global warming potential. The production of PC causes an 18%–37% increase in smog formation, a 4%–15% increase in acidification, and an 11%–48% increase in fossil fuel depletion. The combination of PC production and upstream chlorine production necessary for making both PTFE and the TPP are the major contributors to a 49%–59% increase in the non-carcinogen impact.

The above results are dependent on the reliability of trends, as measured by the confidence interval. For ozone depletion, global warming, smog formation, non-carcinogenics, and fossil fuel depletion, either the range of uncertainty or the overlap of uncertainties is small enough that the trends described above are discernable. For

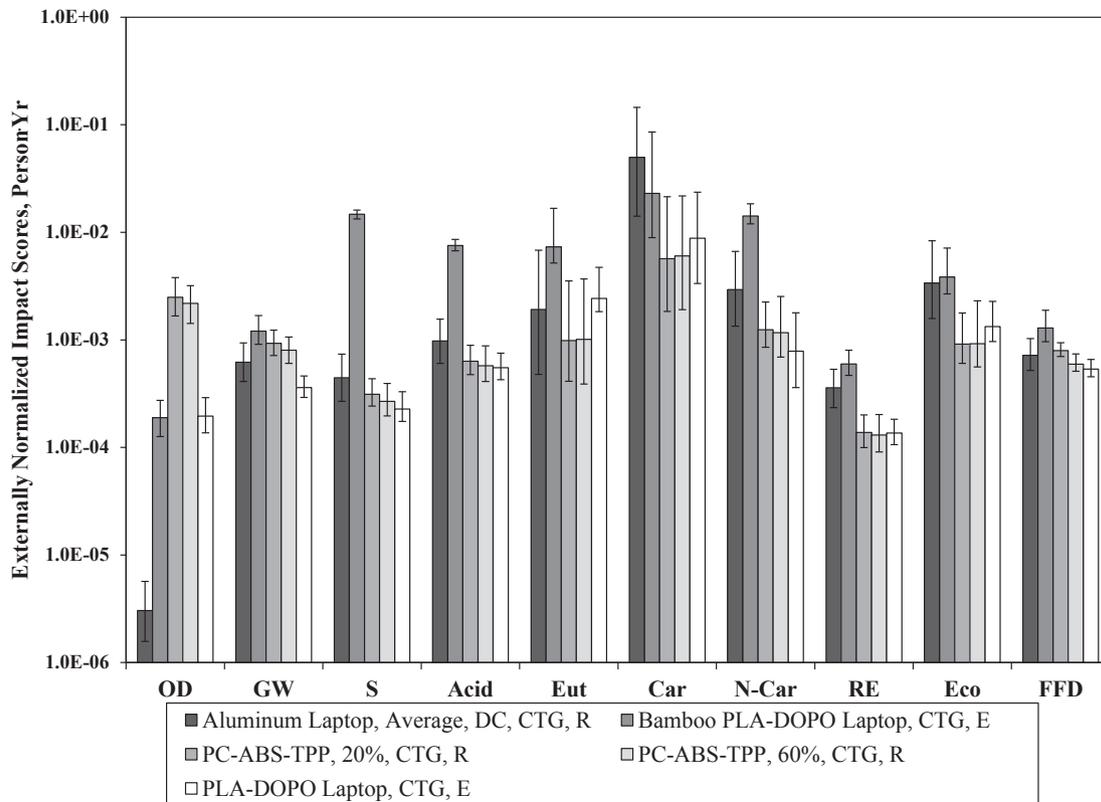


Fig. 10. Externally normalized impact scores for selected laptop with 95% confidence limits. Notes: CTG = cradle-to-grave, E = energy generation, R = recycle, LF = Landfill.

acidification, the range of uncertainty supports the interpretation that bamboo has the largest impact, followed by aluminum, and then plastics, with no meaningful distinction between plastics. Bamboo can be described as having the largest impact for eutrophication. However, the uncertainty for the other materials mean further identification of trends should be carefully considered. Human health impact from carcinogens has the largest uncertainties of all impacts with only a general impact trend of aluminum > bamboo > plastics possible. As with acidification, observed differences in fossil and bioplastics are marginal based on the uncertainty of the values. For respiratory effects, the significance of differences between the impacts of fossil and bioplastics are again questionable. The ranges of uncertainty for ecotoxicity only support an interpretation that bamboo and aluminum (in no order) have larger impacts than plastics.

The information obtained by this simultaneous material comparison will ultimately be more meaningful when policy makers can work with companies to understand the economic viability of addressing the identified sources of environmental impact. Additionally, it is important to note that this study did not look at the land and water use impacts of the materials evaluated. Future studies of bioplastic enclosures for consumer electronics should include analysis of land and water use impacts because they may be significant, especially if the market for bioplastics displaces fossil plastics. Such an expansion of the bioplastics market may constrain food production and drive up consumer prices. This effect should be evaluated if bioplastics are to be implemented as sustainable materials.

3.5.2. Flame retardants

While searching through the literature during the course of this study, research on flame retardants has focused primarily on

reducing the toxicity of the chemicals and given little attention to their impacts with regard to climate and resource management. The potential toxicity of these materials is obviously a major concern and should continue to be studied (US EPA, 2014b), especially the phosphorous-based materials that have been shown in recent hazard studies to pose some potential moderate risk. However, the subsequent discussion will demonstrate the need to consider these other impacts for flame retardants when developing environmentally sustainable products. In addition to the comparison of laptop enclosures, the cradle-to-gate impacts associated with manufacturing the required quantity of flame retardant for each enclosure were compared to determine the environmental relevancy of flame retardancy (not shown).

The impacts resulting from DOPO-Al(OH)₃ manufacturing are the largest of the four flame retardants. In addition to the production of aluminum hydroxide, the major contributing processes are the production of energy and the upstream feedstock trichloromethane. For BDP and TPP, the TPP generates lower impact scores in nine of the ten categories because the BDP process involves extra materials and energy for product extraction and purification. BDP actually has a negative contribution to ozone depletion because of the generation of hydrochloric acid as a by-product. The material with the least amount of impact is the BBAP solution used to treat bamboo. This can partially be explained by the much smaller mass of material required to treat the enclosure.

To better understand the importance of these results, Fig. 11 provides the contribution of flame retardant manufacturing to the total life cycle impacts for selected laptop enclosures. The use of BDP to treat PC-ABS is responsible for up to 32% of the life cycle impacts in 9 of the 10 impact categories with an average contribution of 15% for all impact categories. Interestingly, a material that

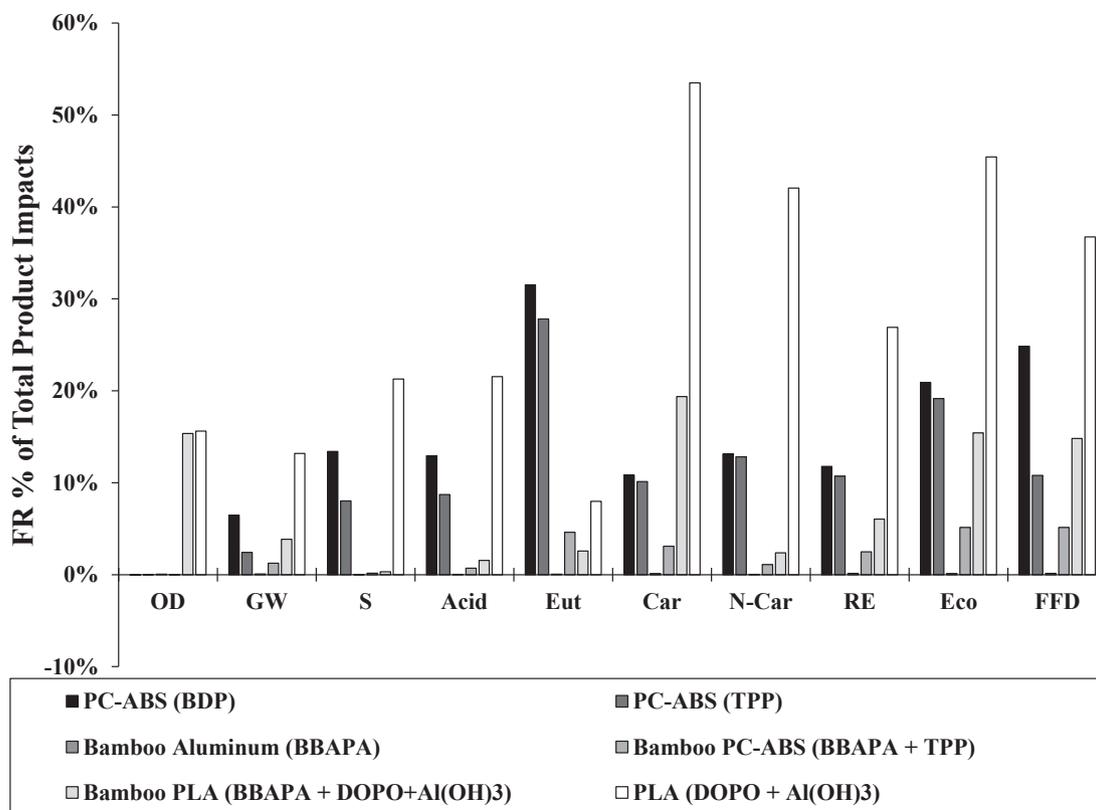


Fig. 11. Flame retardant contributions to the life cycle impacts of laptop enclosures.

is only 11.2% by mass of the laptop enclosure is responsible for 25% of the fossil fuel depletion because of the solvent extraction and purification steps required for product recovery. For TPP, which doesn't involve these processes, this value drops to 11%. BDP manufacturing does provide some benefit based on the large quantity of hydrochloric acid generated as an avoided product. Although the production of TPP generates hydrochloric acid, the quantity per mass of material is approximately one quarter of the amount generated for BDP and so the offset of ozone depletion impacts is not enough to provide a net benefit for the process. In general, the average impact contribution of TPP is less than half of the BDP at 11% and approximately the same as its mass fraction in the enclosure. Treatment of bamboo for flame retardancy and preservation when combined with a metal support accounts for only 0.1% (on average) of the impacts because a small mass of BBAP is needed. When a plastic support is used, the combined environmental impact contribution of flame retardant treatment for both the bamboo and plastic only increases to 2% for PC-ABS-TPP and 8% for PLA-DOPO. Although these contributions are small, they are overshadowed by the electricity and glue impacts associated with processing the bamboo and may become more significant as these parts of the life cycle are optimized. The use of DOPO-Al(OH)₃ in PLA has the largest average impact contribution at 28%. This negates many of the perceived benefits of using a bioplastic to make the laptop enclosure, especially given potential impacts from emissions related to degradation of the DOPO during use and/or EOL processes. For example, the decomposition of DOPO during combustion for electricity creates phosphorous pentoxide, which is readily converted to phosphoric acid in the atmosphere. The effects of the DOPO on potential composting applications are unknown, but will possibly negate potential benefits of bioplastics if they are negative. This last concern may be true of all phosphorous-based

flame retardants and needs further study to determine how to maximize the benefits of bioplastics.

4. Conclusions

The objective of this study was to better understand how to promote environmental sustainability for consumer electronics via materials selection for laptop enclosures. This is a first step towards full sustainability, which will only be achieved by simultaneously addressing the economic and societal implications of the various alternatives for consumer electronics. The evaluation of materials in this study can provide conclusive insights for accomplishing the stated goal.

The use of recyclable aluminum with only a 32% PCR content is currently not a better option than plastics. If this is representative of all metal enclosures, metal use can be improved by increasing the recycled content in the final product and offsetting the need for primary metal extraction. The same can be said for the effects of increasing the post-consumer recycled content of fossil plastics. The need for recycling has been well established and is not a novel finding. However, the results of this study help specifically demonstrate the tangible environmental benefits garnered by use of materials containing higher levels of post-consumer recycled content in CEDs if fossil plastics are to be used.

Bio-based plastics like PLA-DOPO provide a material option that is environmentally comparable to fossil plastics containing large PCRs based on the hypothetical life cycle modeled in this study. Further enhancements of the PLA-DOPO life cycle could be possible if recycling is considered and will depend on the development of a technically and economically viable EOL recovery and recycling infrastructure. This may be challenging given PLA can contaminate the recovery and recycle of other plastics and may require rigorous

source separation before recycling. Industries considering the use of bioplastics like PLA will have to address these concerns early in product development if they hope to maximize the benefits of renewable feedstocks.

For non-recycling EOL options, the benefit of energy generation from biomaterials will largely depend on the quantity and composition of the plastics, as well as the process used to generate the electricity. Incineration for energy recovery was included in this study and showed no real benefit because of the small quantity of waste material in the case of bamboo and the decomposition emissions in the case of PLA-DOPO. The impacts of alternative processing technologies like pyrolysis need to be evaluated to understand if they provide an EOL option that minimizes the volume of disposed waste without shifting environmental impacts.

The environmental sustainability of products relying on pressed bamboo materials will largely depend on improving the sub-processes such as strip gluing. Current adhesives like resorcinol phenol formaldehyde limit the environmental sustainability of materials because of the large impacts associated with manufacturing them. Furthermore, the combination of the small bamboo content and the inefficient energy and material usage during the CNC machining process defeated the intent to create a more sustainable alternative. These results highlight the caution that must be applied when designing sustainable consumer electronics and support the need to consider the holistic impacts of products when discussing their sustainability.

The final conclusion highlighted by this study is the need to develop more environmentally sustainable alternatives for flame retardants. Flame retardant enclosures for consumer electronics are challenging because the immediate need to prevent consumers from exposure to fire must be balanced with environmental impacts introduced by these materials. The manufacturing of these materials can represent a noticeable portion of the cradle-to-grave life cycle impacts even though they often constitute a small portion of the final product. If consumer electronics are to become environmentally sustainable, the application of green chemistry and engineering design principles to flame retardants is needed to develop suitable alternatives that are nontoxic and provide not only minimal manufacturing impacts, but support better EOL management of e-waste.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jclepro.2015.05.143>.

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