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Assessing the benefits of design for recycling for plastics in electronics: A case study of computer enclosures

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Abstract

With the emergence of extended producer responsibility regulations for electronic devices, it is becoming increasingly important for electronics manufacturers to apply design for recycling (DFR) methods in the design of plastic enclosures. This paper presents an analytical framework for quantifying the environmental and economic benefits of DFR for plastic computer enclosures during the design process, using straightforward metrics that can be aligned with corporate environmental and financial performance goals. The analytical framework is demonstrated via a case study of a generic desktop computer enclosure design, which is recycled using a typical US "take-back" system for plastics from waste electronics. The case study illustrates how the analytical framework can be used by the enclosure designer to quantify the environmental and economic benefits of two important DFR strategies: choosing high-value resins and minimizing enclosure disassembly time. Uncertainty analysis is performed to quantify the uncertainty surrounding economic conditions in the future when the enclosure is ultimately recycled.

Keywords: Thermoplastics (A); Recycling (C); Performance indices (H)

1. Introduction

Designers in the electronics industry have been applying design for recycling (DFR) techniques since the early 1990s in an effort to improve the recyclability of electronic devices. The primary goal of DFR is the selection of design attributes that will allow a product's embodied bulk materials to be disaggregated and recycled in a cost-effective manner at the product end-of-life (EOL) stage. The environmental benefits of materials recycling have been well established; recycling not only reduces solid waste, but can also reduce the energy and pollutant intensity of raw materials production [1]. Until recently, DFR efforts in the electronics industry have largely been voluntary initiatives, driven by a manufacturer's desire to reduce its environmental impacts, to enhance its public image, or to comply with the DFR requirements of major product eco-labels. (Key eco-labels for electronics include the German Blue Angel and TCO'99 [2].) With the emergence of so-called "take-back" regulations for electronics—the most prominent example being the European Union's Directive on Waste Electrical and Electronic Equipment—electronics manufacturers are required for the first time to internalize the costs of EOL product recovery and recycling [3]. The application of DFR to electronic devices is therefore being elevated from voluntary practice to strategic business requirement.

Of particular importance to electronics manufacturers is the application of DFR to plastic enclosures (i.e., external product casings). As a class of materials, plastics typically comprise around 20% of the mass contained in electronic devices [4] and are thus one of the most abundant materials available in EOL electronics for recycling. In many

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electronic devices, such as televisions and personal computers (PCs), the enclosure represents by far the most prominent and mass-intensive use of plastics within the product. Most DFR efforts for plastics in electronics are therefore focused on enclosure design.

The most common approach to DFR for plastic enclosures has been the use of DFR heuristics or "rules of thumb" [5–7]. For example, one well-known heuristic instructs designers to use snap-fit connections in lieu of threaded fasteners to reduce the time (and hence cost) associated with manual enclosure disassembly. Another DFR heuristic instructs designers to avoid inseparable material additions in plastic enclosures (such as paints or molded-in metal parts), which can impair plastics recycling processes and/or diminish the quality of recycled plastics. An advantage of DFR heuristics is that they provide the enclosure designer with straightforward, essentially binary metrics that are easy to apply and interpret during the enclosure design process (i.e., either the designer follows a given DFR heuristic or does not).

However, a primary disadvantage of DFR heuristics is that, as qualitative metrics, they do not provide the designer with feedback on the expected "payoff" of DFR—that is, the environmental and EOL cost benefits that DFR is expected to deliver for a given plastic enclosure. Thus, the designer applying DFR heuristics must accept on faith that the enclosure design attributes chosen today will lead to environmental and economic returns in the future. As take-back considerations become increasingly important for electronics, there is a growing need to augment DFR heuristics with quantitative methods that forecast the expected environmental and EOL cost benefits of different DFR strategies. Such quantification would allow the enclosure designer to apply DFR with greater confidence, strategically choosing design attributes that maximize environmental benefits, EOL cost benefits, or both, depending on design goals and corporate take-back policies. Furthermore, such quantification would also prove critical in design tradeoff analyses, by allowing the designer of plastic enclosures to properly weigh the benefits of DFR in the face of competing design considerations (such as enclosure cost targets, device architecture and envelope constraints, and enclosure aesthetic requirements).

Quantifying the environmental and EOL cost benefits of DFR for plastic enclosures poses two particular challenges. First, straightforward metrics should be established, which can be easily incorporated into the enclosure design process and can provide the designer with quantitative feedback in units that are meaningful for decision making in a business context. Ideally, environmental metrics should be expressed in units that are compatible with corporate environmental metrics (e.g., energy use, solid waste generation, and carbon emissions) so that enclosure DFR strategies can be aligned with corporate environmental performance goals. Similarly, EOL cost metrics should ideally be expressed in monetary units so that the financial benefits of different enclosure DFR strategies can be assessed from a business perspective (i.e., their impact on the company's bottom line).

Second, uncertainty regarding future economic conditions when plastic enclosures are ultimately recycled must also be considered. A plastic enclosure designed today will, in general, not be recycled until several years in the future when market conditions (e.g., labor costs, energy costs, and scrap market prices for post-consumer plastics) might be significantly different than today. Thus, the uncertainty associated with EOL cost metrics should also be quantified, so that design attributes can be chosen that will ensure an acceptable likelihood of cost-effective enclosure recycling in the future.

Although much work has been published on quantitative methods for DFR in general, including methods for predicting product disassembly times [8,9], methods for scoring product demanufacturing complexity [10–12], and methods for predicting product disassembly costs [13,14], little work has been published that addresses the two challenges described above for the specific case of plastic enclosures. The most relevant work to date includes analyses by Huisman [15], Lee et al. [16], and Chen et al. [17]. Huisman analyzed the "eco-efficiency" of recycling major electronic devices (including PC monitors and televisions) on a regional scale in the European Union under different processing scenarios. (Eco-efficiency is a measure of environmental impacts generated per unit of economic cost [18].) These analyses predicted that, in general, products with large plastic enclosures that could be manually disassembled were the most eco-efficient designs. Lee et al. analyzed the disassembly costs (in US$) and EOL environmental impacts (in eco-indicator points [19]) for a coffee maker with a plastic enclosure. This analysis found that proper "design for disassembly" led to cost-effective materials recycling, which delivered environmental savings. Chen et al. developed an economic and environmental cost-benefit model for DFR of generic products, which was applied to the case of an automotive dashboard made of plastic and steel. Results predicted that the economic viability of recycling dashboard materials increased as dashboard disassembly time decreased. While such work has provided valuable quantitative evidence of the benefits of DFR for plastic components in different products, a considerable gap in the literature still exists for analyses and case studies that (a) quantify both the environmental and EOL cost benefits of DFR for plastic components using straightforward metrics, and (b) do so with an explicit treatment of future economic uncertainty. This paper attempts to address this data gap for the specific case of plastic PC enclosures.

This paper summarizes the results of analytical work to assess the environmental and EOL cost benefits associated with DFR strategies for plastic PC enclosures. The goal of this work was to develop models for quantifying the expected "payoff" associated with various DFR heuristics, which could be used to augment heuristic approaches during the enclosure design process. Specifically, a systems modeling framework was developed to characterize both the environmental impacts and the costs associated with a typical take-back system for plastics in EOL computers. Environmental impacts are characterized using two straightforward metrics—life-cycle energy use and life-cycle greenhouse gas (GHG) emissions per enclosure—which were chosen due to their relevance for decision-making in a business context. This modeling framework is applied to a case study, which considers a generic desktop PC enclosure that is recycled in the United States using manual disassembly and sorting processes. Desktop PCs represent one of the highest volume applications for plastic enclosures in the electronics industry—nearly 145 million desktop PCs were manufactured in 2004 alone [20]—and thus provide both an interesting and relevant case study. The case study quantifies the expected environmental and EOL cost benefits associated with two important enclosure design attributes—enclosure disassembly time and enclosure resin selection—and employs uncertainty analysis to explore how predicted EOL cost benefits might vary under future economic scenarios.

Section 2 of this paper describes in detail the systems modeling framework and environmental and economic metrics employed in this analysis. In Section 3, the details of the case study PC enclosure and assumed take-back system are summarized. Section 4 presents and discusses the case study results. Conclusions are offered in Section 5.

2. Analytical framework

Fig. 1 depicts the systems modeling framework developed for the case study analysis. The systems modeling framework is comprised of a sequence of simplified unit process models that characterize the major processing steps in the life cycle of a typical plastic PC enclosure, from plastics manufacture through enclosure recycling and/or disposal. A unit process is defined as a discrete processing step for which processing costs, energy consumption, and environmental emissions (e.g., air emissions and solid waste generation) can be quantified on a per kilogram basis. Each unit process step in Fig. 1 is assigned a unique identifier (j); unit processes ($j = 3$) through ($j = 11$) represent a typical process sequence employed in US take-back systems for EOL PCs. In a typical US take-back system, EOL PCs are collected and transported to an electronics demanufacturing facility (denoted by the dashed boundary in Fig. 1), where plastic enclosures are manually disassembled and either discarded or processed further for recycling. Enclosures to be recycled are typically sorted by resin type, shredded, and stored before being sold and transported to a plastic scrap recycler. The plastic scrap recycler purifies, extrudes, and pelletizes the plastics into near virgin quality pellets for reuse in new products. Demanufacturing operations also include receiving and staging of EOL PCs for disassembly, and pre-shipping activities (e.g., the palletization and loading of plastic scrap) prior to scrap transport. Mass flows throughout the processing system in Fig. 1 are described in terms of the enclosure mass (m), a demanufac-

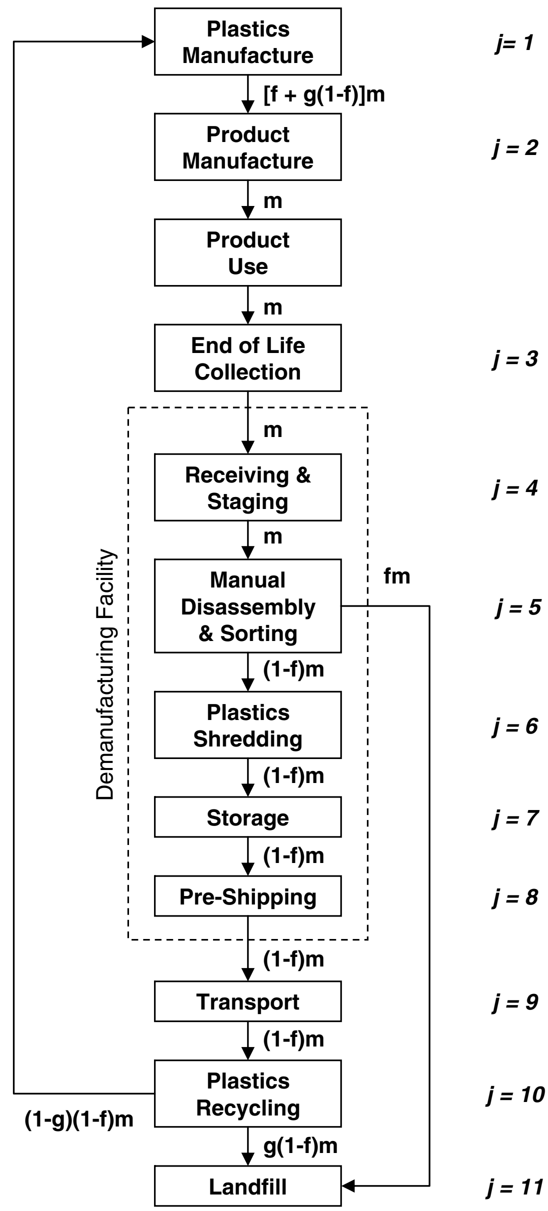

Fig. 1. Systems modeling framework to characterize environmental and EOL cost benefits of PC enclosure recycling.

turing waste fraction (f), and a recycling waste fraction (g). The demanufacturing waste fraction accounts for PC enclosure components that are discarded due to design attributes that preclude recycling, such as "designed in" recycling inhibitors (e.g., paints or molded-in metals) or the lack of resin identification labels that facilitate manual sorting by resin type [5]. The recycling waste fraction accounts for process waste generated during mechanical recycling operations for plastics, for example, the 5–15% melt filtration purging loss typically associated with extrusion and pelletization in plastic recycling [21].

There are several key assumptions associated with the unit process systems model depicted in Fig. 1. First, it was assumed that manual methods would be employed to disassemble the PC enclosure and to sort enclosure components by resin type for recycling. Although more advanced technologies exist for liberating and sorting plastics from EOL PCs, including continuous product shredding systems [22] and density-based resin sorting techniques [23], manual methods still predominate at PC demanufacturing facilities in the United States. Second, the case of closed-loop recycling was considered, in which recycled plastics from PC enclosures serve as feedstock for injection molded components of comparable quality in new PCs (hence the mass flow loop from plastics recycling to plastics manufacture in Fig. 1). Closed-loop recycling is generally considered to be the most environmentally-favorable form of plastic recycling [24], and thus serves as a convenient upper-bound for estimating the environmental benefits of PC enclosure recycling. Although still somewhat rare in practice, closed-loop recycling is technically achievable and could be realized by an electronics manufacturer through contractual arrangements with plastics recyclers as part of its corporate take-back strategy. Third, it was assumed that the PC enclosure mass would be 100% plastic (i.e., that the mass of attached non-plastic materials is negligible) and free of flame retardants. Fourth, it was assumed that all plastic waste generated at the demanufacturing facility would be sent to a landfill.

The environmental impacts associated with the processing system in Fig. 1 were estimated using two environmental metrics: primary energy use and greenhouse gas (GHG) emissions. Although the processing system in Fig. 1 will generate other environmental impacts, such as solid waste and energy-related emissions of criteria air pollutants, the analysis presented here focuses solely on primary energy use and GHG emissions. These metrics are commonly used as performance measurements in corporate energy efficiency and GHG reduction programs, and can therefore align enclosure DFR efforts with corporate environmental goals. Eq. (1) was used to characterize the primary energy use associated with the life cycle of a single plastic PC enclosure (E_{LC}), based on the sequence of unit process models in Fig. 1. Similarly, Eq. (2) was used to characterize the GHG emissions associated with the life cycle of a single plastic PC enclosure (GHG_{LC}). Greenhouse gas emissions in Eq. (2) are expressed in terms of kilograms of carbon dioxide equivalents (kg CO_2e), based on the 100-year global warming potential of energy-related air emissions as specified by the Intergovernmental Panel on Climate Change [25].

$$E_{LC} = m\left[\frac{[1+(n-1)(f+g(1-f))]}{n}(\varepsilon_1+\varepsilon_{11}) + \sum_{j=2}^{5}\varepsilon_j + \frac{(n-1)(1-f)}{n}\sum_{j=6}^{10}\varepsilon_j\right] \tag{1}$$

$$GHG_{LC} = m\left[\frac{[1+(n-1)(f+g(1-f))]}{n}(\gamma_1+\gamma_{11}) + \sum_{j=2}^{5}\gamma_j + \frac{(n-1)(1-f)}{n}\sum_{j=6}^{10}\gamma_j\right] \tag{2}$$

where ε_j is the specific primary energy use of unit process j (MJ/kg), γ_j is the specific GHG emissions of unit process j (kg CO_2e/kg), f is the demanufacturing waste fraction, g is the recycling waste fraction, m is the PC enclosure mass (kg), and n is the number enclosure life cycles for environmental impact allocation.

Because the environmental impacts associated with the closed-loop recycling system in Fig. 1 occur continuously over multiple enclosure life cycles, it was necessary to allocate a proportionate share of ongoing environmental impacts to a single PC enclosure life cycle. A simple allocation approach was employed in which the total impacts associated with n enclosure life cycles are allocated equally to each PC enclosure in Eqs. (1) and (2). In practice, polymer degradation limits the number of times the plastic in a given enclosure can be recycled in a closed-loop fashion (to roughly 3–5 enclosure life cycles), and thus the variables (E_{LC}) and (GHG_{LC}) have practical minimum values. When the demanufacturing waste fraction (f) is equal to 1, Eqs. (1) and (2) estimate the environmental impacts associated with disposing of 100% of PC enclosure mass via landfill. The environmental benefits of closed-loop PC enclosure recycling can therefore be quantified by comparing the results of Eqs. (1) and (2) under various recycling scenarios (where $f < 1$) to results obtained for the 100% landfill scenario (where $f = 1$).

The EOL costs of PC enclosure recycling were quantified in this analysis from the perspective of the electronics demanufacturer. In general, whether or not a plastic PC enclosure is recycled at EOL is primarily a question of economics: plastics are more likely to be recycled when the demanufacturer has an economic incentive to generate plastic scrap that is salable to plastic recyclers. Conversely, plastics are more likely to be disposed of rather than recycled when the demanufacturer cannot generate plastic scrap that can be sold to plastic recyclers profitably. In practice, exceptions to this behavior exist, most notably when a demanufacturer charges a processing fee that is designed to subsidize unprofitable operations such as glass and plastics recycling. Such subsidies for unprofitable operations could also be incorporated into corporate take-back contracts designed to ensure plastics recycling. However, since the goal of DFR is the selection of design attributes that facilitate cost-effective product recycling, the primary objective of DFR for a given plastic PC enclosure should be to maximize the income a demanufacturer can expect to receive from recycling that PC enclosure. Eq. (3) defines the enclosure demanufacturing income (I_D), which was defined in this analysis to characterize the expected income associated with PC enclosure recycling in the assumed processing system of Fig. 1. The plastic scrap price variable (r) in Eq. (3) represents the prevailing scrap market price for the PC enclosure resin at the time of recycling.

$$I_{\mathrm{D}} = m\left[(1-f)(r-\sum_{j=6}^{9} c_j) - c_4 - c_5 - fc_{11}\right] \quad (3)$$

where c_j is the cost of unit process j (\$/kg), m is the total mass of plastic PC enclosure (kg), f is the demanufacturing waste fraction, r is the plastic scrap price (\$/kg).

Enclosure demanufacturing income (I_{D}) can serve as an effective DFR cost metric when enclosures are designed for an established take-back system, by providing the designer with an estimate of the expected take-back costs to be incurred by the company for enclosure recycling. However, Eq. (3) can also be used to assess the ad hoc recyclability of a given enclosure design (i.e., for scenarios in which the company's products are recycled outside of its established take-back systems), based on the observation that greater expected demanufacturing income (I_{D}) will increase the chances of profitable enclosure recycling.

3. Case study data

Together, Eqs. (1)–(3) were employed in a case study to characterize the environmental and EOL cost benefits of two important design attributes for plastic PC enclosures: enclosure disassembly time and enclosure resin selection. These two design attributes were chosen based on a series of interviews and site visits with electronics demanufacturers, who indicated that, in general, plastic PC enclosures that are easy to disassemble and that contain resins with high scrap market value are more likely to be recycled. The goal of this case study was to make explicit the benefits of DFR heuristics aimed at minimizing disassembly time and maximizing resin value for a typical PC enclosure design, using the analytical framework outlined in Section 2. Table 1 provides the details of a generic plastic desktop PC enclosure that was chosen for this case study analysis. The case study enclosure was based on a teardown analysis of 500-MHz Pentium III workstation enclosure, which is representative of many plastic desktop PC enclosure designs currently on the market. The enclosure was comprised of eight separate plastic components, which were free of contaminants (such as paints or molded-in metals) and had a total combined mass (m) of roughly 2.6 kg.

Table 1
Case study PC enclosure components

#	Enclosure component description	Mass (g)
1	Left side panel	740
2	Right side panel	725
3	Front panel	400
4	Base	350
5	Top panel	290
6	Expansion bay door	40
7	Expansion slot cover	25
8	Expansion slot cover	15
	Total enclosure mass (m)	2585

It was assumed that the PC enclosure would be demanufactured and recycled using a typical US take-back system employing manual disassembly and sorting techniques for plastics, as defined by the unit process sequence depicted in Fig. 1. To establish representative costs for a typical US demanufacturing facility for use in Eq. (3), site visits and phone interviews with facility managers were conducted, as well as a review of publicly-available data sources. It was assumed that demanufacturing operations would occur at a facility with 10–15 workers, an annual throughput of roughly 10 million pounds (4.5 million kg), 5000 m^2 of facility space, and 2000 annual hours of operation. These data are representative of a medium-sized electronics demanufacturer in the United States [26].

The unit process costs (c_j) in Eq. (3) were estimated using a two stage approach. First, key facility-level costs were defined and characterized for the case study demanufacturing facility, which are summarized in Table 2. Table 2 details major facility-level costs typical of a medium-sized demanufacturer, and provides an estimated range for each cost in the United States as of 2004. Facility-level costs were broken down into the following key categories: (1) facility lease, taxes, and maintenance costs; (2) building energy costs (i.e., electricity and natural gas costs for building lighting, heating, and cooling); (3) administrative costs, which include such overhead costs as management and administrative staff salaries, office supplies, and custodial services; (4) labor costs; (5) equipment capital and maintenance costs; (6) consumable materials costs (e.g., pallets, gaylord boxes); (7) process electricity (e.g., electricity costs for forklifts and plastics shredding); (8) transport costs for shipping scrap plastics to recyclers; and (9) waste disposal costs. The estimated cost ranges were identified using published data sources whenever such data existed (data sources are noted in Table 2). When published data did not exist, estimates were made based on feedback obtained through site visits and phone interviews. The key assumptions and data sources associated with each cost range are also provided in Table 2 (assumptions are listed below each facility-level cost, indented). Energy costs were broken down into building energy costs and process energy costs to facilitate allocation of process energy costs to specific unit processes within the demanufacturing facility. Table 2 does not list equipment capital and maintenance cost for non-plastics processing equipment (such as printed circuit board shredders) as these costs are not applicable to demanufacturing operations for plastic enclosures.

Second, the facility-level costs summarized in Table 2 were allocated to demanufacturing unit processes to arrive at estimates for the unit process costs (c_j) in Eq. (3). Activity-based costing techniques were used in this allocation procedure, in which facility-level costs were assigned to an individual unit process based on its consumption of key facility resources (e.g., floor space, labor time, and materials) [33]. The resulting unit process costs estimates are summarized in Table 3.

Table 2
Facility-level cost estimates for a medium-sized US electronics demanufacturer (2004)

Demanufacturing facility cost	Unit	Estimated range	Data source
Facility lease, taxes, and maintenance	\$/yr	203,700–533,600	
Facility rent	\$/m^2 yr	29.10–66.70	[27]
Tax, maintenance overhead rate	%	40–60	
Electricity (building)	\$/yr	8700–41,500	
Industrial electricity rate	\$/kWh	0.03–0.10	[28]
Facility electricity consumption	kWh/m^2 yr	58.1–82.9	[29]
Natural gas (building)	\$/yr	2600–47,600	
Industrial natural gas rate	\$/m^3	0.08–0.46	[28]
Facility natural gas consumption	m^3/m^2 yr	6.5–20.7	[29]
Administrative	\$/yr	300,000–500,000	
Labor	\$/yr	213,000–613,200	
Labor rate (total compensation)	\$/h	7.60–17.25	[30]
Hourly workers	workers	10–15	[26]
Supervisor salary (total compensation)	\$/yr	55,000–75,000	[30]
Equipment capital and maintenance	\$/yr	18,000–27,000	
Plastics shredder	\$/yr	10,000–15,000	
Forklifts	\$/yr	8000–12,000	
Materials	\$/yr	30,000–50,000	
Electricity (process)	\$/kWh	0.03–0.10	[28]
Scrap transportation	\$/kg	0.01–0.03	
Freight cost	\$/t km	0.18	[31]
Transport distance	km	50–150	
Waste disposal	\$/kg	0.02–0.10	
Landfill tipping fee	\$/kg	0.01–0.08	[32]
Disposal bin rental and haul	\$/kg	0.01–0.02	

Table 3
Summary of estimated unit process costs distributions (2004)

Unit process cost variable	Unit process description	Cost distribution (\$/kg)	
		Mean	95% C.I.
C_4	Receiving and staging	0.06	0.04–0.08
C_5	Manual disassembly and sorting ($t_d = 30$ s)	0.14	0.10–0.18
	Manual disassembly and sorting ($t_d = 60$ s)	0.22	0.16–0.28
	Manual disassembly and sorting ($t_d = 90$ s)	0.30	0.22–0.38
	Manual disassembly and sorting ($t_d = 120$ s)	0.37	0.27–0.48
C_6	Plastics shredding	0.07	0.05–0.09
C_7	Storage	0.05	0.02–0.09
C_8	Pre-Shipping	0.04	0.02–0.05
C_9	Transport to plastics recycler	0.02	0.01–0.03
C_{11}	Waste transport and disposal	0.05	0.03–0.08

Table 3 expresses the unit process cost estimates in the form of cost distributions (mean values and 95% confidence intervals). The cost distributions in Table 3 were derived to account for the fact that, while the facility-level cost ranges in Table 2 are representative of medium-sized electronics demanufacturing facilities in the United States, the facility-level costs at individual demanufacturers can vary significantly with geography. Such geographical variations can occur based on regional differences in the costs of labor, energy, waste disposal, and real estate. To characterize this variability, cost probability distributions were derived for the facility-level costs in Table 2 using state-specific cost data compiled from each respective data source. The facility-level cost probability distributions were derived based on the assumption that the probability of occurrence for a given US state's facility-level cost scenario (i.e., the cost of labor, facility rent, electricity, natural gas, and waste disposal in that state) was proportional to that state's share of total US population. The cost distributions in Table 3 were generated by applying Monte Carlo analysis (10,000 runs) when allocating facility-level costs to demanufacturing unit processes via activity-based costing.

In this case study, four different enclosure disassembly times (t_d) were considered: 30 s, 60 s, 90 s, and 120 s. In Table 3, it can be seen that estimated unit process costs for manual disassembly and sorting rise with increasing values of (t_d). The increased costs associated with higher values of (t_d) are due to the increased share of facility labor resources necessary for enclosure disassembly, which results in higher activity-based costs for that unit process.

To analyze the effect of enclosure resin selection, three different resin types were considered in this case study: high impact polystyrene (HIPS), acrylonitrile butadiene styrene (ABS), and polycarbonate/acrylonitrile butadiene styrene

(PC/ABS). These resins are typical selections for plastic PC enclosures and provide good examples of lower-cost (HIPS, ABS) and higher-cost (PC/ABS) enclosure resin selections.

An important consideration when using Eq. (3) to predict enclosure demanufacturing income (I_D) is the fact that a PC enclosure designed today will not be demanufactured and recycled until the PC reaches EOL several years in the future (typically anywhere from 2 to 7 years). Thus, the case study analysis also considered uncertainty with respect to how unit process costs (c_j) and plastic scrap price (r) might change in the future. As a simplifying assumption, it was assumed that all unit process costs would rise with inflation. However, it could not be assumed that the plastic scrap price (r) for a given resin would also rise with inflation, because scrap market rates for plastics have varied greatly over time in response to such factors as sporadic demand and fluctuating petroleum prices. This case study therefore considered three future economic scenarios for plastic scrap prices: (i) a ‘‘base price’’ scenario, in which 2004 plastic scrap prices would also rise with inflation, (ii) a ‘‘high price’’ scenario, in which 2004 plastic scrap prices would return to their historical (10-year) peak, and (iii) a ‘‘low price’’ scenario, in which 2004 plastic scrap prices would fall to their historical (10-year) low.

Table 4 summarizes the data that were used to estimate the plastic scrap price (r) for HIPS, ABS, and PC/ABS in Eq. (3) for each of the three case study scenarios. For each resin, the current (2004) virgin price, 10-year high virgin price, and 10-year low virgin price were identified from published data sources [34] and converted to 2004 dollars (i.e., adjusted for inflation). Next, scrap price ranges (in 2004 dollars) were derived for each scenario based on the assumption that, on average, scrap prices for clean (i.e., contaminant free), flaked HIPS, ABS, and PC/ABS will range from 15% to 25% of virgin resin prices. This assumption was based on online surveys of average scrap market prices in 2004 for clean HIPS, ABS, and PC/ABS flakes [35,36]. Uniform distributions were assumed for the scrap price ranges listed in Table 4 as a simplifying assumption.

Table 5 summarizes data that were employed in this case study to characterize unit process energy use and GHG emissions in Eqs. (1) and (2). The data in Table 5 were obtained from published life-cycle inventory studies on virgin resin production and processing [37], electronics demanufacturing and plastics recycling operations [38], and waste management processes [39]. The energy associated with disposing of plastics (ε_{11}) includes both the resin's caloric energy content (higher heating value basis) [40]—which represents wasted energy that could otherwise be recovered thermally—and the energy consumed by landfill processes (collection, compacting, etc.). Uncertainty distributions were not derived for the estimates in Table 5 due to a general lack of life-cycle inventory data sets (from which ranges could be established) in the public domain.

It was also assumed in this case study that PC enclosure components with a mass of 25 g or less would be discarded (a common practice for small plastic components), and thus that the demanufacturing waste fraction (f) for the case study PC enclosure equaled 0.03. The recycling waste fraction (g) was assigned a value of 0.15 to account for melt filtration purging loss during plastic recycling operations [21].

4. Results and discussion

Fig. 2 displays the environmental results of the case study analysis, which were generated via Eqs. (1) and (2)

Table 4
Summary of scrap revenue rate estimations by case study scenario

Resin	Virgin price (2004 \$/kg)			Scrap price variable	Plastic scrap price range (2004 \$/kg)		
	2004	10-year high	10-year low		Base scenario	High scenario	Low scenario
ABS	1.99	2.91	1.70	r_{ABS}	0.30–0.50	0.44–0.73	0.26–0.43
HIPS	1.68	1.68	1.19	r_{HIPS}	0.25–0.42	0.25–0.42	0.18–0.30
PC/ABS	3.54	4.70	3.37	$r_{PC/ABS}$	0.53–0.89	0.71–1.18	0.51–0.84

Table 5
Summary of estimated unit process energy use and GHG emissions

Unit process energy variable(s)	Primary energy use (MJ/kg)			Data source(s)
	HIPS	ABS	PC/ABS	
ε_1	50.9	55.5	77.1	[37,40]
$\sum_{j=2}^{5}\varepsilon_j$	34.7	34.5	39.8	[37,38]
$\sum_{j=6}^{10}\varepsilon_j$	12.5	12.5	12.5	[38]
ε_{11}	42.0	40.2	33.8	[39,40]
Unit process GHG emission variable(s)	GHG emissions (kg CO_2e/kg)			Data source(s)
	HIPS	ABS	PC/ABS	
γ_1	3.0	3.4	4.8	[37]
$\sum_{j=2}^{5}\gamma_j$	1.2	1.3	1.8	[37,38]
$\sum_{j=6}^{10}\gamma_j$	0.7	0.7	0.7	[38]
γ_{11}	0.1	0.1	0.1	[39]

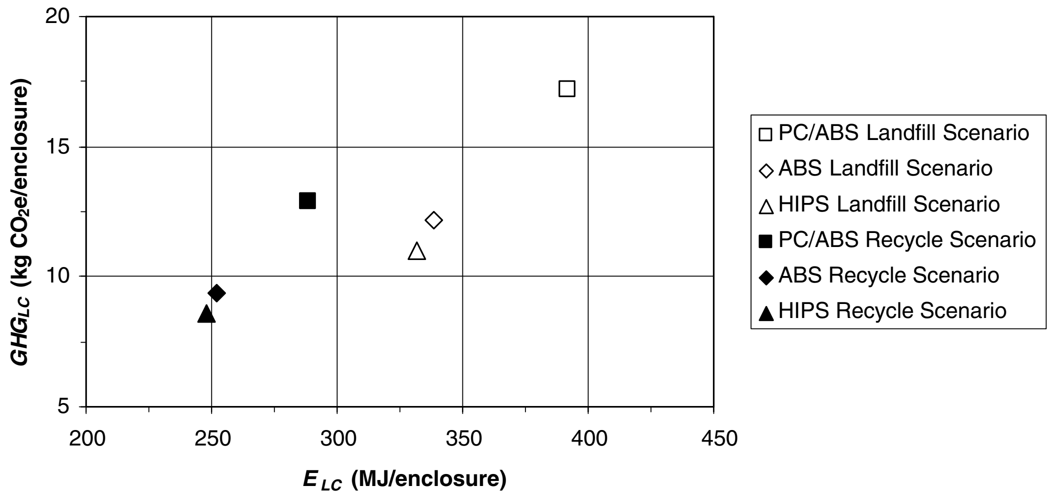

Fig. 2. Environmental modeling results: landfill and recycle ($n = 2$) scenarios.

using the modeling data described in the previous section. Results are shown for the 100% landfill scenario ($f = 1$) and the case study recycling scenario ($f = 0.03$) for the three resin types considered in this analysis. Results for the recycling scenario are displayed for the case of ($n = 2$), which assumes that the plastics in the case study PC enclosure will only be recycled once. Thus, the data in Fig. 2 provide a lower bound on the environmental benefits associated with plastic PC enclosure recycling, as closed-loop recycling over additional life cycles ($n = 3$, 4, etc.) would lead to additional per enclosure savings in energy use and GHG emissions.

By comparing results for the landfill scenario to the recycling scenario for a given resin type, it is possible to quantify the expected primary energy and GHG emissions savings associated with PC enclosure recycling. For example, if the case study PC enclosure were made of PC/ABS, Fig. 2 indicates that enclosure recycling would save roughly 100 MJ of primary energy and 5 kg of CO_2e emissions per enclosure compared to the landfill scenario. If the case study PC enclosure were manufactured as a high volume product, as most models of PCs are, the annual savings associated with enclosure recycling could potentially be significant. For example, if 10,000,000 case study PC enclosures made of PC/ABS were manufactured, theoretically 1 PJ of energy (equivalent to over 160,000 barrels of oil) and 50,000 tonnes of CO_2e (equivalent to the annual GHG emissions of 11,000 average US automobiles [41]) would be saved if all enclosures were recycled once in a closed-loop fashion. The results in Fig. 2 reinforce the importance of designing plastic PC enclosures that are financially attractive for recycling, by providing the enclosure designer with quantitative evidence of the potential environmental savings that are at stake. As discussed in Section 1, such quantification will be critical in design optimization and design tradeoff analyses for plastic PC enclosures as the environmental aspects of product take-back systems become increasingly important. Such quantification will also be critical in assessing and communicating the importance of enclosure DFR in corporate energy efficiency and GHG reduction initiatives. Results such as those in Fig. 2 can therefore serve as valuable complements to DFR heuristics in enclosure design.

The results in Fig. 2 also demonstrate the significant differences in the environmental "footprint" associated with the different enclosure resin types considered in this analysis. While recycling is clearly beneficial for each resin type, the primary energy use and GHG emissions associated with a PC enclosure made of HIPS or ABS are considerably less than for a PC enclosure made of PC/ABS. Interestingly, sending a HIPS or ABS enclosure to the landfill is expected to result in similar GHG emissions as recycling a PC/ABS enclosure (when $n = 2$), due to the significant energy use and GHG emissions associated with manufacturing PC/ABS components (see Table 5). Thus, if maximizing environmental benefits is included the enclosure designer's DFR goals, the designer should ideally choose resins that minimize the per-enclosure environmental footprint.

The economic results of the case study analysis are displayed in Figs. 3–5, for the base price, high price, and low price scenarios, respectively. The results in Figs. 3–5 were generated via Monte Carlo analysis (10,000 runs) using Eq. (3), the case study unit process cost distributions in Table 3, and the plastic scrap price distributions in Table 4 for each future economic scenario. Results for the expected value of enclosure demanufacturing income (I_D) for each assumed enclosure disassembly time (t_d) are plotted by resin type. For all values, the 99% confidence interval is displayed as well as the probability (%) that a given combination of resin type and disassembly time (t_d) will lead to positive enclosure demanufacturing income ($I_D > 0$) at EOL in the United States. (Probabilities of less than 1% are omitted from Figs. 3–5.) It should be noted that the results in Figs. 3–5 are only valid for the case study data assumptions and modeling distributions discussed in

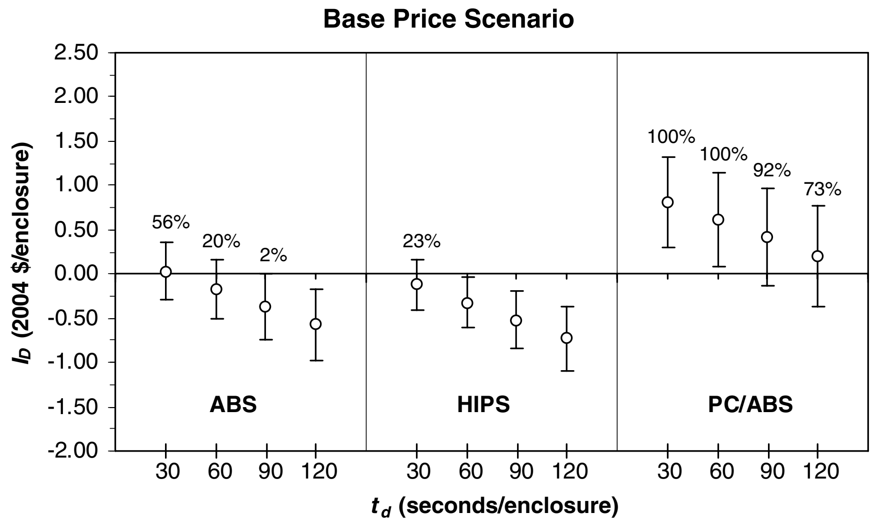

Fig. 3. Economic modeling results: recycling base price scenario.

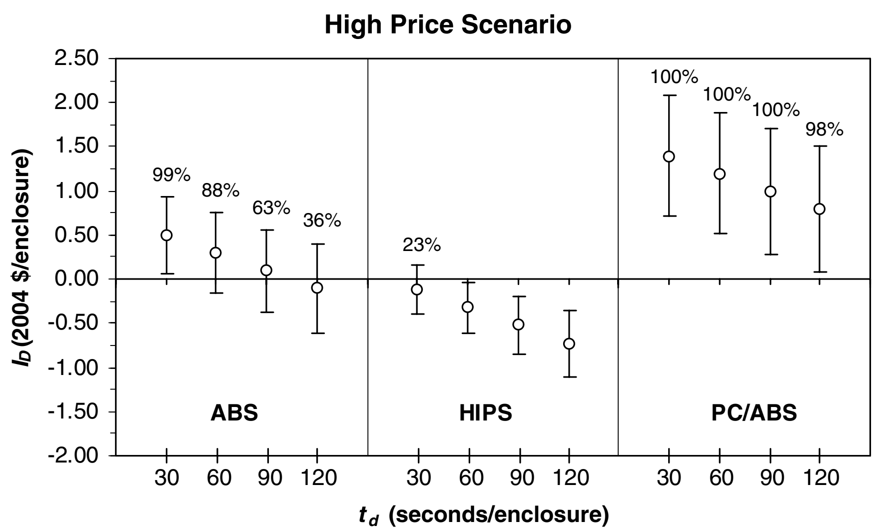

Fig. 4. Economic modeling results: recycling high price scenario.

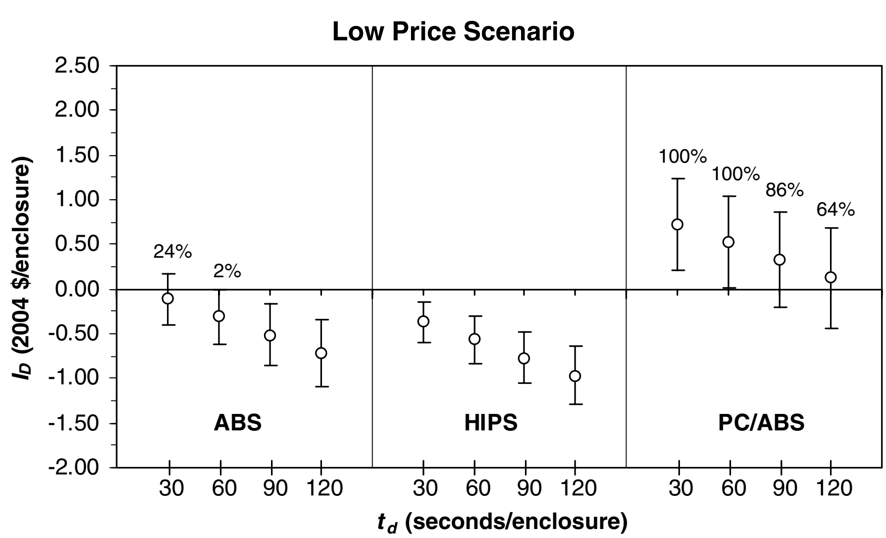

Fig. 5. Economic modeling results: recycling low price scenario.

Section 3; however, alternate data scenarios could easily be evaluated using the analytical framework presented in this paper.

The results in Figs. 3–5 show that, in all three future economic scenarios, lower disassembly times lead to greater expected values of demanufacturing income regardless of resin selection. The results suggest that DFR heuristics aimed at reducing enclosure disassembly time can be particularly effective and provide quantitative feedback on the EOL cost "payoff" of disassembly time minimization. However, the results also show that it is the combination of enclosure resin type and disassembly time that is most important, and that low disassembly times alone do not guarantee profitable enclosure recycling. It can be seen that for all three future economic scenarios, the case study PC enclosure made of HIPS is least likely to generate positive demanufacturing income, even when enclosure disassembly time is minimized. Conversely, the case study PC enclosure made of PC/ABS is most likely to generate positive demanufacturing income, even at the highest enclosure disassembly time considered in this analysis. Thus, while minimization of enclosure disassembly time should always lead to EOL cost reductions, choosing a high-value resin in addition to disassembly time minimization is seen as the most robust DFR strategy in the face of future economic uncertainty. If the case study PC enclosure were recycled in an ad hoc fashion at product EOL, those designs with low or negative values of expected demanufacturing income would be the least likely to be recycled.

Most significant, however, is that the results of Figs. 3–5 would allow the designer to incorporate quantitative methods into DFR for plastic PC enclosures. As discussed in Section 1, such quantification is critical for design optimization and design tradeoff analysis, and for aligning DFR strategies with corporate financial goals. In the case study example, the designer could estimate that by reducing the disassembly time of a PC/ABS enclosure from 120 s to 30 s (via such DFR strategies as the use of snap-fits, the use of disassembly symbols, or the minimization of fasteners), the expected profitability of enclosure recycling in the United States would increase by around $0.60 in all three scenarios, while the likelihood (i.e., probability) of profitable recycling would also increase significantly. Or, if the designer were limited by architectural or cost constraints to a PC enclosure design with a minimum disassembly time of 60 s, the designer could estimate that by switching from ABS to PC/ABS, the expected demanufacturing income would be raised by around $0.80. However, the results of Fig. 2 also suggest that this switch would come at an environmental penalty, as PC/ABS has a greater per-enclosure environmental footprint than ABS. Additionally, the enclosure designer would also have to consider the up-front costs of choosing a higher-value resin, as this would lead to higher raw materials costs in enclosure manufacturing. However, results such as those in Figs. 3–5 would allow the enclosure designer to weigh the EOL cost benefit gained by increasing up-front enclosure cost, and therefore could provide a quantitative means of evaluating DFR strategies for plastic PC enclosures in design tradeoff analyses.

5. Conclusions

This paper presented the results of analytical work to quantify the benefits of DFR for plastic PC enclosures using systems modeling and uncertainty analysis techniques. The case study results demonstrated how the analytical framework can help enclosure designers quantify the expected environmental and EOL cost benefits of different DFR strategies during product development. The analytical framework presented here can therefore augment DFR heuristics with a quantitative dimension for improved decision-making. The use of uncertainty analysis provided EOL cost estimates that acknowledged future uncertainty in economic conditions, which would further allow the designer to evaluate not only the expected outcome but also the likelihood of success associated with a given DFR strategy. Further analyses of the type presented in this paper could provide designers with critical aid in optimizing the benefits of DFR for plastic enclosures and in evaluating enclosure attributes in design tradeoff analyses, especially as take-back considerations are becoming increasingly important for electronics manufacturers. Furthermore, such analyses could also provide the enclosure designer with a means of aligning DFR strategies with corporate environmental and financial performance goals, as well as with a compelling economic and environmental case for implementing DFR in the face of competing enclosure design considerations.

Although only primary energy use and GHG emissions were considered as environmental metrics in this paper, the analytical framework is capable of quantifying other important environmental impacts, such as airborne and waterborne pollution and solid waste, for which modeling data are available. The economic data considered in the case study were based on an average, medium-sized US demanufacturing facility, but the analytical framework could easily be adapted to analyze other facility scenarios by inserting the appropriate cost data. Moreover, the analytical framework could be applied to other high-volume electronic devices with large plastic enclosures suitable for manual disassembly, such as TVs and cathode ray tube PC monitors. For companies with established take-back infrastructures, the facility cost data in Eq. (3) could be compiled from contracted demanufacturing partners, which would provide a more precise characterization of expected EOL processing costs for a given take-back system. For more robust decision making, uncertainty analysis could also be applied to the environmental analysis (not included here due to lack of data) and additional (or more extreme) future economic scenarios could be considered.

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