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E-Waste Stream Analysis and Design Implications

The quantity and age of the incoming stream of "feedstock" from product take-back systems are known as the major sources of the uncertainty that complicates the e-waste recovery. This paper presents the results of an analysis of data from an incoming stream for an e-waste collection center and analyzes the quantity and age of e-waste by product type and brand. The analysis results point out receiving of outdated products and processing of multiple generations, and brands of products at the same time are among main obstacles to the e-waste recovery. The potential role of product design in overcoming those obstacles is discussed with emphasis on design for upgrade, repurpose, and commonality.
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Keywords: e-waste, end-of-life, take-back, product recovery, design for reuse, design for commonality

1 Introduction

Recovering end-of-life products has become a promising solution to the waste problem in the consumer electronic industry. Such recovery considers the entire product lifecycle from cradle to "grave" and back to the cradle again. Used products, components, or materials are given a second life through reuse, which, in turn, can reduce the quantities of electronic waste (i.e., e-waste) that must be disposed and bring about economic and social benefits as well [1–3].

Over the past two decades, many design methods have been developed to make e-waste recovery easier and more profitable. These methods involve, for example, designs for disassembly, recycling, reuse, and remanufacturing. One difficulty with these methods is that the nature of the incoming e-waste stream is highly variable. Unlike traditional manufacturing processes, which impose tight control of raw materials, recovery processes must deal with an incoming stream of raw materials (e-waste) that varies widely in terms of design, returning volume, age, and condition [4–7]. However, little research has focused on the nature of the e-waste itself, so what actually happens in the real world still remains uncertain. This lack of knowledge poses an obstacle to the improvement of design methods for e-waste recovery.

In an effort to gain a better understanding of the nature of the incoming e-waste stream, this paper presents the results of an analysis of the data collected from an e-waste collection center. With empirical evidence, the characteristics of the e-waste stream are examined, and based on the results, the design and managerial implications for more profitable e-waste recovery are discussed. The *quantity* and the *age* (or timing) of e-waste are the primary variables of concern in this analysis. These variables are known to be the major sources of the uncertainty that complicates e-waste recovery [4–6]. More specifically, this analysis helps to answer the following research questions:

- What is the origin of e-waste for a single e-waste drop-off center? How many units of e-waste are returned to the center per day? Is there any difference in returning quantities among various product types and brands?
- How old is the incoming stream of e-waste? How variable is the age of the e-waste? How long (or what percentage of the age) is the storage time? What are the differences in the ages among the various product types and brands that are returned?
- How does the nature of e-waste complicate e-waste recovery? What are the design and managerial implications for making e-waste recovery easier and more profitable?

The rest of the paper is organized as follows. Section 2 reviews the previous literature, and Sec. 3 describes the data collected and the analysis results. Section 4 summarizes the findings and highlights the design and managerial implications. Finally, the conclusions drawn from the analysis are presented.

2 Literature Review

E-waste recovery converts the used electronics into a set of marketable products, components, or materials. It includes taking back of used electronics from consumers, reprocessing the collected units following appropriate end-of-life options (i.e., reuse, refurbishing, component reuse, material recovery, and disposal), and distributing recovered products, components, or materials to customers [8]. Since more companies have been choosing recovery instead of disposal as their primary strategy for waste management, engineering methods for maximizing recovery profits are now being sought by industry.

Since the detail processes for the e-waste recovery depend on what the products are and how they are designed, many case studies have been published, which provide product-specific recovery processes and address their economic and environmental impacts. Bhuie et al. [9] conducted a survey to understand and compare the economics of recycling cell phones and computers. In a similar study, Geyer and Blass [10] examined the economics of cell phone reuse and recycling processes. Neira et al. [11] also investigated the environmental and economic outcomes of different end-of-life options for cell phones. Kerr and Ryan [12] presented a case study of Xerox photocopiers in Australia to show the effects of remanufacturing processes on reducing resource consumption and waste generation over the product's lifecycle. Ferrer [13] raised the awareness of the existence of potential markets for remanufactured computers and showed how remanufacturing of personal computers (PCs) extends their useful lives. Grenchus et

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al. [14] analyzed the composition and economic value of end-of-life information technology (IT) equipment and discussed decisions that can maximize the profit from its recovery.

The better understanding of the recovery process has leveraged the development of the design for recovery, which aims to improve the recovery process and its outcome by means of the design enhancement. In the field of design for recovery, several methods have attempted to improve product design by focusing on a specific recovery operation or an end-of-life option. For instance, focusing on the disassembly operation, Das et al. [15] presented an approach to estimate disassembly effort and cost, and Takeuchi and Saitou [16] proposed design for product-embedded disassembly, which designs a built-in disassembly pathway for a product. Mat Saman et al. [17] focused on the material recovery and proposed a method for evaluating the ease of recycling of a product. Hammond and Bras [18] presented design metrics for assessing the ease of remanufacturing of a product design, and Kimura et al. [19] suggested product modularization to facilitate the reuse of parts. Other design methods have aimed at evaluating product design alternatives at the design stage from the recovery point of view. Most of these studies first developed an optimal recovery plan and then evaluated product design based on the plan and its economic and/or environmental outcomes. For example, Pnueli and Zussman [20] represented a product structure using an AND/OR graph and suggested algorithms to find optimal disassembly and recovery plans from the graph. Kwak et al. [21] proposed a linear programming model to evaluate the recovery profit by a simultaneous consideration of the product design and the recovery network design. Mangun and Thurston [22] presented a decision-making model that considers component reuse, remanufacturing, and material recovery for a product portfolio. Zhao et al. [23] developed a decision-making model that considers multiple lifecycles. The model identifies optimal lifecycle lengths and optimal recovery plans for multiple products.

With well-defined recovery processes, many methods of design for recovery have emerged and improved the recovery of e-waste. However, these methods have had difficulties in estimating the quantity, quality, and age of e-waste. The lack of knowledge about these characteristics hampers the efforts of many researchers and designers to understand the e-waste problem and its current status. Although there have been several studies on the e-waste stream [24–26], they have more focused on what mass of e-waste is returned and how it can be processed, rather than identifying the numbers and types of e-waste components that are returned. Also, the analyses showed the e-waste status at the level of a state, a nation, or the globe, but not at the level of a single collection center. This paper adds a new set of results to the previous results. With a set of real data, this paper presents a more detailed level of analysis, i.e., the data are from a single e-waste drop-off center where individual consumers voluntarily return their used electronics; the quantity and age of e-waste are examined by product type as well as by brand.

3 Data Analyses and Key Findings

3.1 Data Collection. This section gives an overview of the data collection for the analysis. A waste collection center in Goose Island, Illinois (Chicago, USA) is the data source under consideration. The facility is one of the waste drop-off centers operated by the City of Chicago. Individual consumers return their used items to the facility with no reward or charge, and the facility sends the items to third-party companies for reuse, recycling, and proper disposal. PC Rebuilders and Recyclers (PCRR), based in Chicago, is one of the companies dedicated to the e-waste recovery. The company accepts consumer electronics (e.g., computers, monitors, printers, and televisions (TVs)) from the Goose Island facility and recovers them by means of reuse, refurbishing, component reuse, and material recovery. For the purpose of monitoring, PCRR records a set of information for each incoming product, which includes the following:

- Arrival date and time: Date and time when the product arrived at the Goose Island facility.
- Product type: Product category to which the product belongs (e.g., laptop).
- Brand: Original manufacturer of the product (e.g., Apple, Sony, Dell).
- Year and month manufactured: Year and month when the product was manufactured.
- Age: Period of time between when the product was manufactured and when it arrived at the Goose Island facility (the end of its life).
- Zip code: Zip code of the individual consumer who disposed the product.
- Distance: Distance between the Goose Island facility and the location of the individual consumer.

The dataset analyzed in this paper is the actual information that PCRR collected for 23 months, from November 2007 to September 2009. The product types covered in this analysis are limited to desktops (the central processing unit (CPU) only, hereafter referred to as the CPU), laptops, monitors, printers, and TVs. These products were chosen because they account for the majority (more than 90%) of the incoming e-waste stream. Accordingly, about 9500 lines of e-waste data were prepared for the analysis.

In addition to the general information, PCRR also collects another set of information on the hard drives of desktop computers. It contains:

- Date manufactured: Date the hard drive was manufactured.
- Date last used: Date the hard drive (or the computer) was last used.
- Read date: Date the hard drive was read by PCRR.
- Years used: Number of years between the date manufactured the date last used.
- Years stored: Number of years between the date last used and the date read.
- Age: Number of years between the date manufactured and the date read; the sum of years used and years stored.

From October to December 2009, PCRR examined 63 hard drives from individual consumers and 638 hard drives from corporations. This paper also uses the data from the hard drive log to investigate consumers' behavior in returning e-waste.

The data used for this paper provide a snapshot of the quantity and the age of e-waste, which helps to clarify the role of product design in improving e-waste recovery. However, it should be noted that the data represent current situation of an e-waste drop-off center, and the resulting statistic values in the following sections can change based on items, such as time, market environment and the location, type, and size of facility.

3.2 Quantity of E-Waste. How many units of e-waste and what types of e-waste are returned to a collection center are important issues in the e-waste recovery, since they largely affect the efficiency (economies of scale) of recovery processes and the profitability of the e-waste recovery. This section analyzes the quantity of e-waste, especially the origin of e-waste and the difference in returning quantity among various product types and brands.

The Goose Island facility under consideration is a single drop-off center where individual consumers return e-waste with no reward or charge. Figure 1 shows the geographic locations from which the e-waste came to the Goose Island facility (i.e., where the consumers live). As shown in the first panel, most e-waste comes from an area that is within 10 miles of the recovery facility. The second panel for zip code shows a similar result; most e-waste is from a limited area near the facility (zip code: 60622).

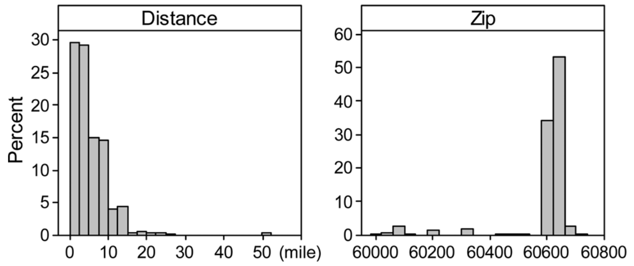

Fig. 1 Histogram of distance, zip code, and arriving time for incoming products

One possible question here might be if those returning patterns are different for different product types. In general, monitors and TVs are bulkier than CPUs, laptops, and printers. Since they are often difficult to move or deal with, it is plausible to say that the average distances of monitors and TVs should be less than the other product types. However, Table 1 demonstrates that the distances are about the same for all product types, which means that consumers' willingness to return a product is not affected by product type, when it comes to the distance. Likewise, it turns out that the zip code for each product type follows similar patterns to those in Fig. 1. It seems that the coverage of a single collection center is not different for different product types.

Figure 2 and Table 2 show how the number of units collected per day is distributed for each product type. Unlike the distance, the incoming quantity per day shows quite different patterns, depending on the product type. First, the mean incoming quantity per day changes significantly. Monitors have the highest frequency with a mean of about 17 units per day, while laptops have the lowest with a mean of almost three units per day. Second, the variances are different. Especially, CPUs and monitors show wider distributions (i.e., higher variability) with standard deviations of almost 11 and 14, respectively. Their greater variances imply more difficulty of predicting the incoming quantity of e-waste, which might make it more difficult to plan and manage the recovery process.

An interesting fact observed in all product types is that only a few brands account for most of the incoming e-waste stream. For example, Fig. 3 shows a Pareto Chart of the percentage of various brands of CPUs received. Figure 3 illustrates that only five major brands, out of a total of 123 brands, account for more than 75% of the total units that were disposed. Table 3 demonstrates that a similar phenomenon exists for other products. About the 5–15% of all brands account for 75–80% of the total incoming quantity.

3.3 Age of E-Waste. Age is another important characteristic of e-waste because it is closely related to how obsolete a product is and whether the product is reusable or not. In the consumer electronic market, reusability of a used product depends more on its technological obsolescence than its reliability. As a testament, most of the e-waste entering PCRR is known to have good reliability. Taking the computer as an example, the failure rates for hard drives and memory are only 10% and 2%, respectively. Processor failures are extremely rare. Nevertheless, 40–60% of computers are considered nonreusable, because they are too old to be reused. In other words, their functional specifications are too obsolete or outdated. The age of e-waste is an important condition that largely affects the profitability of e-waste recovery. Therefore, this section analyzes the age of e-waste in order to help to understand the current situation and find a way to improve it.

Table 1 Descriptive statistics: distance

Type	Mean	St dev.	Min.	Median	Max.	IQR[a]
CPU	5.53	5.28	1	3.69	57.95	5.54
Laptop	5.38	5.45	1	3.59	50.37	5.39
Monitor	5.60	5.47	1	3.69	60.65	5.50
Printer	5.49	5.52	1	3.69	50.37	5.35
TV	5.47	5.47	1	3.69	50.37	5.61

[a]Interquartile range (IQR) = upper quartile (Q3)—lower quartile (Q1) = 75th percentile—25th percentile.

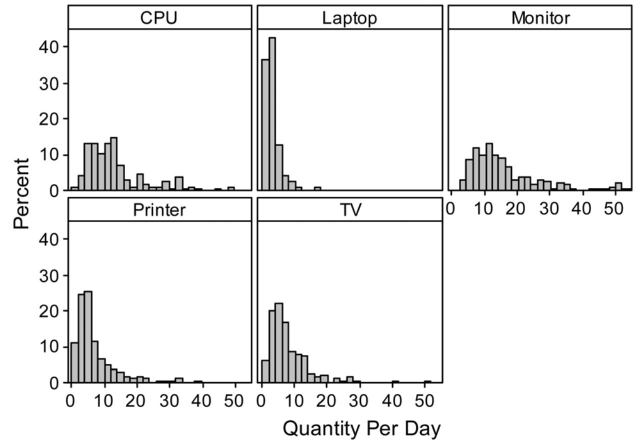

Fig. 2 Histogram of incoming quantity per day for different product type

Figure 4 and Table 4 show the age distribution of e-waste for each product type. Different product types show different means and variances of age. CPUs, laptops, and monitors had mean ages of approximately 9, 11, and 10 years, respectively. Printers exhibit the shortest mean age of about 9 years, while TVs exhibit the longest, i.e., about 15 years. TVs also show the highest variability in age with a standard deviation of almost 7 years. Regardless of product type, the age is distributed over a wide range. This wide range of age implies that the e-waste recovery must deal with multiple generations of products simultaneously. For instance, recovering TVs involves a range of products from 1 year old to 33 years old. If the technological obsolescence cycle of TVs is 3 years [27], the range of products corresponds to more than ten generations of products.

An interesting point is that the mean age of each product type is more or less different from its typical wear-out lifespan in Table 5. Especially, a huge difference between the two life characteristics was observed in CPUs and laptops. On the other hand, only a negligible difference was found in monitors and TVs. A wear-out lifespan is an estimate of the longest period of time that a product can perform the original functions. Thus, it can be regarded as the upper estimate of the actual usage time (i.e., the time period between the initial purchase and the last use of the product). With this interpretation, Table 5 implies two points. First, the time when the consumers return the e-waste may be different from the time when they stop using it. In other words, people store their used products for a while before finally discarding them. Second, the length of storage time varies depending on the product type. CPUs and laptops seem to be stored for a longer period of time than monitors and TVs. It seems that the storage time is affected by whether the product contains proprietary data, the size of the product and the ease of storage, and the original price.

Table 2 Descriptive statistics: quantity per day

Type	Mean	St dev.	Min.	Median	Max.	IQR
CPU	13.38	10.91	1	10	77	8
Laptop	2.63	2.21	1	2	17	2
Monitor	16.61	13.96	2	12	88	12
Printer	7.43	9.05	1	5	68	5
TV	7.61	6.73	1	6	51	7

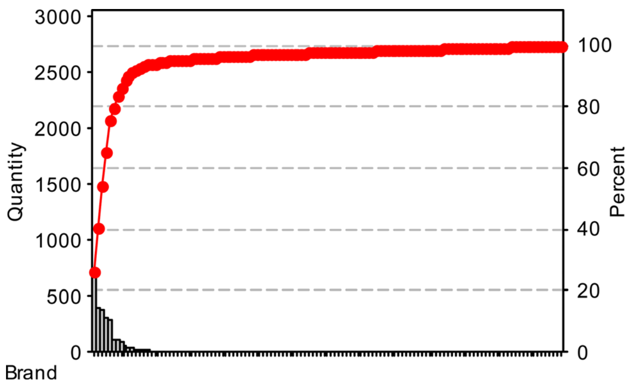

Fig. 3 Pareto chart of brand of CPU Box

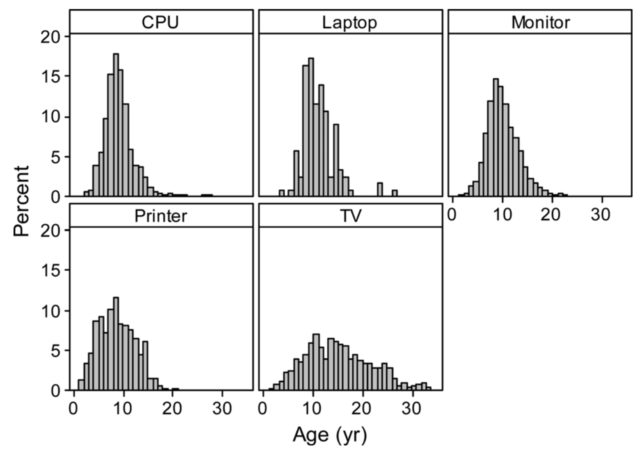

Fig. 4 Histogram of age for different product type

The hard drive data also give support to the point that people actually store their e-waste before disposal. Table 6 summarizes the age, used year, and stored year of hard drives from commercial users and individual consumers. Figure 5 shows the histograms of stored year and stored ratio of hard drives. It turns out that both commercial users and individual consumers store their computers for a while before disposal. The average number of years stored is approximately 1.4 years for commercial users and 1 year for individual consumers. Stored ratio is the ratio of stored year to the age, which represents how much of the total lifetime is spent in storage. The average stored ratio is 0.22 for commercial users and 0.19 for individual consumers. The Kruskal–Wallis test on the stored ratio indicates that, with the p-value of 0.016, the median stored ratios for commercial users and individual consumers are different (see Tables 9–10 for detailed results). Thus, it can be concluded that individual consumers tend to use computers for a longer period of time and store them for a less period of time than commercial users. The results of the correlation analysis presented in Fig. 6 and Table 7 give additional implications on the relationship between the age, used year, and stored year. First, the older age of a product implies that it was used for a longer period of time. There exists a strong positive correlation between the used year and the age. Second, a computer used longer tends to be stored for a shorter period of time. A significant negative correlation exists between used year and stored year. Third, the stored year has very little relationship with the age of product. The correlation between the age and stored year is very weak and, therefore, insignificant. Therefore, an older product does not necessarily mean it was stored for a longer period of time.

In summary, previous results illustrated two facts about the age of e-waste. First, different product types have different ages. Second, people store their e-waste before disposing it, and this behavior increases the age of returning e-waste. Figure 7 gives another implication on the age of e-waste by stratifying the e-waste data according to the brand. Figure 7 shows two interval plots of age, one for the mean age and the other for the standard deviation of age. An interval in these plots depicts the 95% confidential interval (CI) of the mean or standard deviation for the corresponding product type and brand. If intervals in a plot overlap, it indicates that the means (or standard deviations) are not significantly different. Since both plots in Fig. 7 have nonoverlapping intervals, it can be concluded that different brands have different means and variances of age. Also, Fig. 7 demonstrates that such trends are general. Both CPUs and monitors have the same conclusion and, even though not included in the paper, the other product types also share the conclusion. Table 8 describes the related statistics in detail.

Irrespective of the product type, the e-waste from brand A has a greater mean and variance of age compared to the e-waste from brands D and G. This indicates that brand A products are so old that they might have more obsolescence issues, hence less potential for reuse. Moreover, brand A requires that a wide variety of products across multiple generations be processed simultaneously. However, the ages of brands D and G are relatively young on average, which implies the better chance of reuse when assuming all other conditions (e.g., reliability and demand) are equal. In addition, they might have a smaller variety of products owing to the smaller number of generations.

4 Design and Managerial Implications

The data analysis shows how the quantity and age of e-waste is distributed and how those characteristics differ with product type and brand. In addition, the analysis results revealed the characteristics of e-waste that hinder the improvement of e-waste recovery processes. With the summary of the findings, this section describes the obstacles to the e-waste recovery and how design and managerial efforts can contribute to overcome them, thereby making the e-waste recovery easier and more profitable.

4.1 Reducing the Storage Time. An obstacle to end-of-life recovery is that the returning e-waste is usually too old to be reused as is. For instance, the average age of returning desktops (CPUs) is about 9 years, while the average replacement cycle and wear-out lifespan of desktop are known to be 3–4 years and 5–6 years, respectively [27,29–31]. Only few people would want to use such an outdated computer. Accordingly, many computers inevitably head to material recovery, which is in general less profitable and less environmentally benign than reuse or refurbishment [32,33]. The fortunate part is that there is a possibility of

Table 3 Number of the major brands for different product type

Type	Major brands[a]	Total brands
CPU	5–6	123
Laptop	5–6	35
Monitor	10–15	198
Printer	13–17	96
TV	4	41

[a]The brands which account for 75–80% of the total incoming quantity

Table 4 Descriptive statistics: age (year)

Type	Mean	St dev.	Min.	Median	Max.	IQR
CPU	9.16	3.05	1.92	8.82	27.72	3.04
Laptop	11.10	3.39	3.10	10.46	26.67	3.97
Monitor	9.95	3.24	1.24	9.48	29.44	4.03
Printer	8.73	3.61	1.13	8.47	20.24	5.51
TV	15.21	6.70	1.56	14.49	33.91	9.76

Table 5 Mean age versus wear-out life span

Type	Wear-out life span [27–31]	Mean age
CPU	5–6	9.16
Laptop	3–5	11.10
Monitor	8–10	9.95
Printer	5–8	8.73
TV	15	15.21

reducing the age of returning e-waste. In the previous analysis, the age data implied that people often keep their products indefinitely even though they are no longer used. The analysis of hard drive data also showed that CPUs have been stockpiled at home or in the office, on average, for the 15–20% of their lives. If the storage time were decreased by any means, younger e-waste with higher potential for reuse will be taken back. Therefore, managerial effort to encourage timely disposal is desirable. Giving an economic incentive to consumers might also work.

4.2 Design for Upgrade, Design for Repurpose. Design efforts are also important to overcome the age obstacle. More specifically, two design approaches are available. The first approach is the design for upgrade, which reduces the degree of obsolescence of a product. When products become obsolete (e.g., the computer memory is too small to run current software), people either choose to upgrade (e.g., add additional memory to the computer) or buy a new computer with more memory. If product design allowed an easier upgrade, more people might choose to upgrade and postpone the replacement, which, in turn, would decrease the amount of e-waste. The analysis results show evidence that consumers are willing to upgrade their products if upgrading is easy. Table 2 shows that there is a difference between the number of CPUs and monitors disposed by consumers. The Kruskal–Wallis test on the quantity of return per day also indicates that, with the p-value of 0.008, the median quantity of returns for CPUs and monitors are different (see Tables 11–12 for detailed results). In addition, Table 8 shows that the age of CPUs and the age of monitors are different as well, because consumers use monitors longer than they use CPUs. General desktop computers have a modularized structure. CPUs and monitors are designed as separate modules and no sophisticated knowledge or skills are required to connect/disconnect them. This example illustrates that people have a willingness to upgrade just one portion (or module) of product if the design of the product supports the upgrade. Hence, design strategies that respond to this willingness, i.e., making it easier for consumers to upgrade memory, operating systems and software, and user-interface elements, would be a promising way of elongating the life of a product and reducing e-waste. Also, "piggybacking," which enables renewed functionality through the integration (or add-on) of a secondary device or component [34], would encourage consumers to use the equipment longer. It should be noted that designing to facilitate upgrading benefits e-waste recovery as well when people finally dispose of the product. To be competitive in the second-hand market, a used product must be equipped with more recent functions and features. Products that have been designed to be more easily upgraded have much higher potential for reuse and refurbishment.

Table 6 Descriptive statistics: age, used year, and stored year and ratio of hard drive

	Mean	St dev.	Min.	Median	Max.	IQR
Commercial						
Age	6.22	1.66	1.49	6.41	10.37	2.81
Used year	4.84	1.88	0.04	4.95	8.99	2.42
Stored year	1.38	1.42	0.00	0.98	9.01	1.33
Stored ratio	0.22	0.21	0.00	0.16	1.00	0.21
Consumer						
Age	6.36	2.05	1.18	6.36	10.60	3.13
Used year	5.33	2.47	0.08	5.33	10.40	4.40
Stored year	1.03	1.03	0.03	0.72	4.59	1.47
Stored ratio	0.19	0.22	0.00	0.12	0.98	0.25

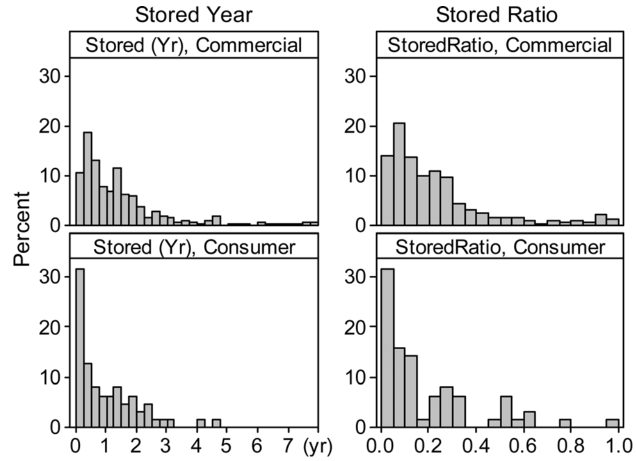

Fig. 5 Histogram of stored year and stored ratio of hard drive

The second design approach to overcome the old age of e-waste is to create demand for older products (more specifically, their parts) by designing another product that can utilize the parts from them. The second item does not necessarily have to have the same identity as the original product. For instance, memory and processors from old computers can be reused in making gaming machines or dolls. Repurposing the e-waste is a representative design strategy in this regard. An example is LCD monitors. LCD monitors can be reused in its original application as a monitor or can be reused in another application as a TV. This possibility creates additional demands for used LCD monitors.

4.3 Design for Commonality Across Multiple Generations and Brands. An important fact about e-waste recovery is that it requires that multiple generations and brands of products be processed at the same time. Table 4 describes that e-waste has a wide range of ages for all product types. Considering the pace of technological advances and design changes, the range of age implies that the incoming stream of e-waste contains multiple generations of products with different designs. The problem is that such design diversity can complicate e-waste recovery. Hard drive designs from different age products are a case in point. Currently, two types of hard drives are available in the market, i.e., parallel

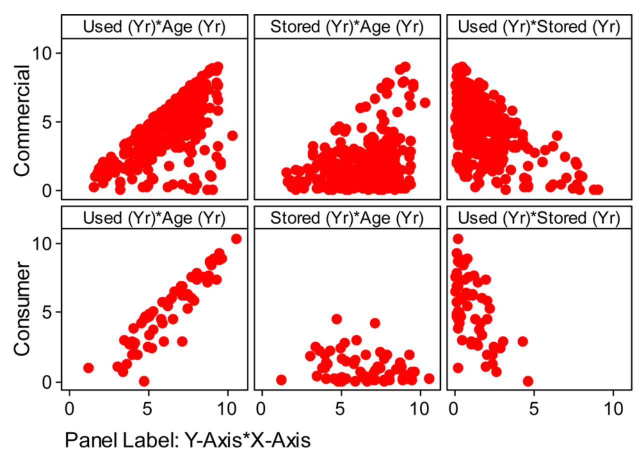

Fig. 6 Scatter plot of hard drive life characteristics

Table 7 Correlation analysis result

	Used year	Stored year
Commercial		
Age	0.715 (0.000)	0.223 (0.000)
Used year		−0.519 (0.000)
Consumer		
Age	0.913 (0.000)	−0.199 (0.118)
Used year		−0.581 (0.000)

Cell contents: Pearson correlation coefficient (*p*-value)s

ATA (PATA, old technology) and serial ATA (SATA, new technology) drives. Before being reused or refurbished, every computer must undergo a data destruction process that eliminates all personal and confidential information. In case of PCRR, the company uses a machine that reads and deletes multiple hard drives at once. However, the difference between PATA and SATA drives requires that different machines be developed and operated, which increases the recovery costs. Furthermore, old computers cannot accommodate the new SATA drive, and some new computers are not compatible with the old PATA drive. As a result, the reuse of hard drives is limited.

Recovering value from a variety of products is influenced by individual product designs and by the interactions between designs, i.e., the interchangeability of components or the commonality of recovery processes. The variance of age is a good indicator of why multiple generations of products must be considered simultaneously in the design stage. Unfortunately, current approaches for design for reuse and recovery have focused on improving single-product designs. Therefore, more design methods must be developed to consider and improve multiple generations of products simultaneously.

According to Bras [35], Simpson [36], Perera et al. [37], and Kwak and Kim [38], increasing part commonality across product variants can benefit the e-waste recovery in two ways. First, component reuse can increase as the interchangeability of components across product variants increases. Second, the economies of scale

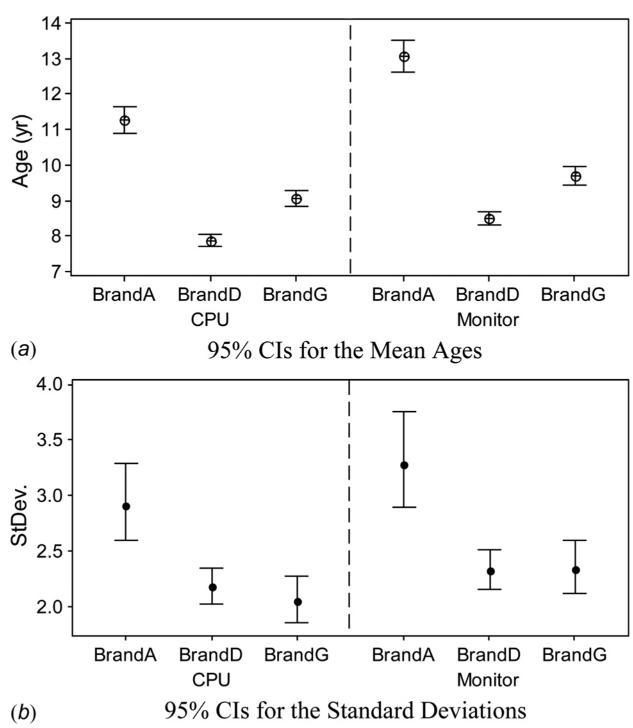

Fig. 7 Interval plot of age: mean and standard deviation for different brand

Table 8 Descriptive statistics: age (year) of CPU and monitor for different brand

	Brand A	Brand D	Brand G
CPU			
Mean	11.27	7.87	9.06
St dev.	2.90	2.18	2.05
Min.	4.72	1.92	2.30
Median	10.54	7.81	8.84
Max.	22.89	21.61	22.54
IQR	3.84	2.74	2.01
Monitor			
Mean	13.07	8.49	9.69
St dev.	3.27	2.32	2.34
Min.	6.06	1.39	3.14
Median	13.08	8.39	9.28
Max.	26.30	21.66	18.44
IQR	4.52	2.54	2.73

can increase as multiple variants can share tools and worker skills necessary to conduct recovery operations. Pandey et al. [39] proposed the concept of temporal commonality that may exist between generations and would greatly influence reuse decision making. In this regard, design for commonality across multiple generations might be employed. To be specific, a product could be designed to be compatible and expandable with components from older-generation products. Many recovery systems store e-waste by first disassembling it into groups of components. Some e-waste is too old to refurbish, even though it is fully functional. However, newer products might be designed so that they can reuse older-generation components. For example, a PC designed to have two slots for hard drives can reuse old 20-GB hard drives to meet the minimum hard drive specification for the refurbished PC, for instance 40 GB. Similarly, PCs with multiple slots for memory expansion can facilitate the reuse of 256-MB memory from older-generation products, while satisfying minimum specifications for refurbishment (for example, 512 MB). Another way to design for commonality across multiple generations is to increase process commonality. For instance, designing products to share similar disassembly structures can help increase the economies of scale in disassembly operations [40].

From a similar context, standardization across multiple brands is also desirable. Brand is another source of the design diversity of the incoming e-waste stream. As shown in Table 3, e-waste recovery involves multiple brands of products at the same time. Laptop batteries are an example of an opportunity to benefit overall e-waste recovery by improving commonality across multiple brands. Laptop batteries from different brands do not have standard dimensions or shapes, which makes them difficult to reuse for other laptops. Considering component compatibility, such as dimensions, interface, and architecture, can increase the reusability of this component between different brands.

4.4 Design for Commonality That Considers Different Age Characteristics. Different brands have differences in the means and variances of the age of e-waste, so different strategies for design for commonality are recommended. Figure 7 and Table 8

Table 9 Test for equal variances: stored ratio versus type

95% Bonferroni confidence intervals for standard deviations				
Type	*N*	Lower	St dev	Upper
Commercial	638	0.201488	0.214164	0.228476
Consumer	63	0.180484	0.216957	0.270926

Levene's test (any continuous distribution): test statistic = 3.61, *p*-value = 0.058.

Table 10 Kruskal–Wallis test: stored ratio versus type

Kruskal–Wallis test on stored ratio				
Type	N	Median	Ave rank	Z
Commercial	638	0.1613	356.8	2.41
Consumer	63	0.1150	292.4	−2.41
Overall	701		351.0	

$H = 5.80$ DF = 1 $P = 0.016$
$H = 5.80$ DF = 1 $P = 0.016$ (adjusted for ties)

Table 12 Kruskal–Wallis test: quantity per day versus type

Kruskal–Wallis test on stored ratio				
Type	*N*	Median	Ave rank	Z
CPU	197	10	183.1	−2.66
Monitor	199	12	213.7	2.66
Overall	396		198.5	

$H = 7.06$ DF = 1 $P = 0.008$
$H = 7.07$ DF = 1 $P = 0.008$ (adjusted for ties)

show that different brands exhibit different means and variances for age. The difference in the mean ages indicates that different brands might have different level of obsolescence and ease of reuse and refurbishing. If the mean age of a brand tends to be too old, then the company can focus on material recovery or component reuse beginning in the design stage. On the other hand, the difference in the variances of ages indicates that the degree of design variety and its variability differ for different brands. This underscores the importance of differentiated commonality strategies. If there is a high variability of ages in incoming returned products, longer term "generational commonality" must be considered for higher profit in product recovery. If, on the other hand, there is a lower variability of ages, in incoming products, then "contemporary commonality" (i.e., commonality only for a few generations) is better suited for product recovery. In this case, manufacturers would not need to consider longer term generational commonality.

4.5 Design for Component Reuse and Material Recovery for Minor Brands. Different brands also have different characteristics in terms of quantity of return, so different design strategies are recommended. Figure 3 illustrates the fact that most e-waste comes from a limited number of brands. This indicates that only those brands might be able to meet the minimum-volume requirement to make reuse or refurbishing a viable business. Reusing and refurbishing a product involves various operations, such as inspection, disassembly, repair, testing, packaging, and redistribution. All processes are highly dependent on the e-waste product's design, so different tools, skills, and resources are required for different products. To practice economies of scale, therefore, reuse or refurbishing efforts are usually focused on a product with a high frequency of return (i.e., greater quantity). Also, the major consumers in the second-hand market (e.g., schools, nonprofit organizations, and charitable organizations) tend to prefer a set of identical (at least similar) products. Furthermore, a higher return implies that the product was more popular in the market and is likely to be so in the second-hand market. With this background, major brands with high disposal quantities are usually considered for reuse, while minor brands are usually sent directly for material recovery. One possible design strategy that minor brands can employ to increase reuse is to design products that are intended for component reuse. By increasing part compatibility with major brand products, it is possible to facilitate the reuse of components. However, it should be admitted that the initial cost of implementing the strategy could be burdensome for the minor brands with limited resources. For the successful application of the strategy, cooperation from major brands and governmental supports might be demanded.

Table 11 Test for equal variances: quantity per day versus type

95% Bonferroni confidence intervals for standard deviations				
Type	*N*	Lower	St dev	Upper
CPU	197	9.7944	10.9064	12.2910
Monitor	199	12.5397	13.9562	15.7179

Levene's test (any continuous distribution): test statistic = 3.61, *p*-value = 0.058.

Another design strategy is design for material recovery. The value from material recovery is affected by the types of materials in a product and how easy it is to refine them. Thus, minor brands can consider design strategies, such as increasing material compatibility in a product, using less-toxic and easily degradable materials, and improving modularity and disassemblability so that materials can be easily separated and refined.

4.6 Design for Ease of Return. Finally, this analysis poses a question on the effect of the e-waste drop-off center. Expecting consumers to return their products by themselves seems to have some limitations. In Fig. 1, most e-waste is from a limited area within a 10-mile radius of the facility. Figure 2 indicates that the average quantity of e-waste for each product type is less than 20 units, which might be too small to make any business from it. Thus, a company might need either to increase the number of collection centers or to develop another way of collecting e-waste. Taking e-waste back through mail is a widely used method for small goods and electronics. It can cover a much wider area than take-back through drop-off. However, large, heavy, and/or fragile products are not appropriate for take-back by mail. Whether product design can help to overcome these limitations and facilitate take-back through mail is an open question.

5 Conclusion

This paper addressed the characteristics of e-waste that are known to be highly influential in recovering the e-waste in a profitable manner. These characteristics and their interactions have not been well-defined and still remain uncertain. In an effort to gain a better understanding of the key characteristics of e-waste, this paper presented an analysis of data collected from an e-waste collection center. Especially, the *quantity* and *age* of the e-waste were analyzed by product type and brand.

The analysis results revealed current obstacles to e-waste recovery. The old age of e-waste is among main obstacles to e-waste recovery. Receiving of outdated products makes reusing the e-waste infeasible and/or unprofitable. The paper highlighted design for upgrade (designing products that support easier upgrade) and design for repurpose (designing products and applications that can utilize the parts from e-waste) as the potential role of product design in overcoming the age obstacles. Processing of multiple generations and brands of products at the same time is another major obstacle to e-waste recovery. Different brands have different characteristics in terms of age and quantity of returning products. In order to improve the recovery rate and profitability, it is important to consider the e-waste characteristics and apply a design strategy that fits the characteristics well. Possible design strategies were discussed in this regard, including design for commonality across multiple generations and brands and design for component reuse and material recovery for minor brands.

Future research should address the specific cause of product obsolescence. One line of research would be to determine more specifically why customers purchase new computer products. The reasons will range from technical obsolescence (for example, speed or memory being inadequate for new software or certain Internet applications), physical obsolescence (inability to obtain needed replacement components), compatibility with co-workers or peers, or equipment failure. Understanding trends in customer preferences is essential to guide the decision making in product recovery.

Another potentially productive line of research would be to develop models to predict future trends in the e-waste stream. If the current waste stream problem and resulting legislation had been anticipated earlier, we might have avoided the current disposal problem. Will variability in the e-waste stream in terms of age decreases or increases over time? Will customers upgrade more frequently, since prices have decreased and better/less expensive means of data back-up are available, or will more consumers practice direct reuse by deploying obsolete units to lower level functions, such as demoting a primary PC to a printer server for a home network? These are valid research questions for the future in the sustainable product research area.

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