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DESIGN EVALUATION METHOD FOR THE DISASSEMBLY OF ELECTRONIC EQUIPMENT

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Abstract

Due to their short lifecycle, personal computers are being sent to the landfill at an accelerated pace. Their disposal has a hazardous impact on the environment thus necessitating the implementation of widespread recycling efforts. Currently, in the US, computer recycling businesses exist on a profit making model and not simply for the betterment of the environment. Therefore, efforts must be made to enhance profitability of these businesses so that they make money, this in turn will ensure recycling of more computers and reduce their environmental impact. This research is focused on developing guidelines to design computers so that they are profitable to recycle. We propose a simple yet practical way of determining recycling feasibility of a particular PC design by tracking the disassembly process as a function of the monetary gain for recycling companies. The proposed method of evaluating recyclability can serve as a powerful tool in the developmental stages of a computer design.

Keywords: design for disassembly, electronics recycling, end of life value, green design, product lifecycle.

1 Introduction

The last quarter of the twentieth century witnessed the introduction and rapid growth of technologies that were non-existent before; personal computers (PC), the internet and cell phones are a few good examples. The growth of the PC industry started in the early eighties and by 1989, an estimated 21 million personal computers (PCs) were sold worldwide - in 1998 this figure reached 93 million [1]. This exponential increase in the sale of PCs can be partly attributed to three factors. The first factor is the decrease in PC prices. For example, the IBM PC model 5150 (Intel 8088) with a speed of 4.47 MHz, introduced in 1981 was priced at $3000 (USD) [2], whereas currently (2002) a Dell Dimension 4550 Series with Pentium 4 Processor at 2.40 GHz can be purchased under $800 (USD) [3]. Secondly, the emergence of the internet in the early nineties resulted in accelerated PC sales within businesses and households all across the world. In 1990, 15% of US household owned PCs, this figure reached 50% in 1999 [4]. Thirdly, due to the rapid increase in raw processing power of desktop computers. According to Moore’s Law, the number of transistors on a silicon chip and hence its processing power, doubles every 18 months [5]. This resulted in frequent upgrades by end users, thereby significantly increasing PC sales.

This final factor has also attributed to the short life cycle of personal computer. Increasing sales has indirectly caused PCs to be sent to landfills at an accelerated pace. While about eight billion tons of industrial waste is generated annually in the United States containing more than 214 million tons of hazardous material, electronic equipment and computers constitute only 1.6% of this hazardous waste stream [6]. Researchers have cited different (often conflicting) reasons for recycling electronic equipment. Some suggest that landfill space availability is the primary reason for recycling electronic equipment [6]. Others argue that since electronic products are only a tiny fraction of the municipal solid waste stream, recycling electronic equipment does not solve the landfill space issue and that the main reason for recycling is to retrieve functional parts and precious metals [7]. However, it can reasonably be argued that whatever may be the motivation for recycling electronic equipment, eventually it is beneficial for the society to reuse and recycle this equipment to reduce their environmental impact and move towards achieving goals of sustainable development. A much cited 1991 study suggests that approximately 150 million PCs will end up in landfills by 2005 [8]. However, further studies conducted in 1997 by the same author, estimate that only 70 million PCs will be dumped by 2005 [8]. This reduction in number of computers being sent to landfills can be attributed in part to the creation of computer recycling firms.

Based on our research and interaction with these recycling firms we have classified the computer recycling business into two major categories: disassembly companies and processing companies. Disassembly companies are companies that collect computers from the end user and, depending on the functionality of the equipment, 1) resell them on an "as is" basis, 2) disassemble and reconfigure them to resell system and components, or 3) ship components made from the same material to processing companies. Processing companies are a step downstream of disassembly companies and have the capabilities to process disassembled parts to eventually recover raw materials (e.g. precious metal recovery). Additionally, processing companies, depending on the scope of businesses may perform some or all of the steps performed by the disassembly companies. It is important to note that these companies make decisions based on economics, not environmental concerns. Computers are disassembled and recycled only if it is profitable to the company and not because of the hazardous impact on the environment.

The scope of this research is to study and experiment with the disassembly of PCs to identify issues faced by recyclers. Since the steps performed in disassembly are dictated by the initial design, most of the recommendations are directed to computer manufacturers. It is proposed that if 'Design for Disassembly' guidelines are adopted early in the design process, it will improve the profitability of the disassembly process and the overall recycling operation for the recyclers. It will also benefit these manufacturers when product take-back laws are promulgated requiring manufacturers to collect equipment sold by them and to dispose them in an environmental friendly way.

2 Related recycling research

The need for recycling arises from the global goal of achieving sustainable development. In 'The Bruntland Report' of the United Nations Commission on Environment and Development (also known as The Bruntland Commission), sustainable development is defined as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs." [9]

Sustainable development in turn gave birth to many areas of research in academia, introduced new concepts in industrial design and even resulted in legislation which helps to implement the concept of sustainable development. Out of these areas, the focus of this research is in the area of Design for Disassembly (DfD). Disassembly is the process of removing constituent parts from assembled equipment or a sub-assembly. DfD is concerned with the initial design of products so that at their end-of life they are easier to disassemble. Product disassembly is gaining increased popularity and apart from its application to consumer electronics and other similar products, disassembly guidelines are being used for the design of wide array of products. Automobile manufacturers such as BMW and Volkswagen have established dismantling plants in Europe and US. Another emerging area for application of disassembly is weapons dismantling [10].

Research in the field of Design for Disassembly is rapidly expanding across the US [11] and Europe, researchers and designers are suggesting ways of designing equipment that makes it easier to disassemble them. Allada and Viswanathan [12], have proposed setting up dedicated facilities for disassembly of products. They have provided a framework based on which product groups having similar product structure and requiring similar disassembly resources will be combined to form a 'Disassembly Product Group', which then will be shipped to the proposed dedicated disassembly facilities. Ishii and Lee [13], propose that a 'Reverse Fishbone Diagram' will help designers to plan disassembly of products. They argue that the way 'Assembly Fishbone Diagram' helps design engineers to layout products with Design for Assembly considerations, a 'Reverse Fishbone Diagram' will serve as a graphical representation of the disassembly process and will facilitate the original designer to visualize the process of product retirement in the initial design stages. This fishbone diagram is used in the methodology presented here.

Zeid et al. [10] make a distinction between approaches to resolve disassembly issues and divided them into two major categories, design for disassembly (DfD) and planning for disassembly (PfD). They argue that goal of DfD is to design products so that they are easier to disassemble, whereas goal of PfD is the identification of efficient sequences to disassemble products. They propose the use of analogical problem solving (APS) to help designers to solve PfD problems, which are open ended and iterative in nature. Use of APS is based on the notion that solutions to similar problems encountered in the past, can be reused to solve PfD issues. Yu et al. [6], have proposed a decision making tool, which maximizes the recyclability of the end-of-life products and at the same time minimizes their environmental impact. The decisions in this respect are based on combination of environmental impact, recycling feasibility and intensity of resource recovery. Gupta and Veerakamolmal [14], propose use of a Design for Disassembly Index (DfDI). This index utilizes a disassembly tree (DT) which is a graphical representation of the product's structure. Use of product structure helps in determining the order in which components can be retrieved. This ultimately gives the disassembly and recyclability merits in comparing different designs.

3 Methodology

Our approach for developing guidelines that would be incorporated in the early design process is to disassemble eight obsolete computers from different manufacturers. Initially, three out of these eight computers were disassembled to gain familiarity with the disassembly operation and use of tools so that more representative disassembly times could be obtained. Data from the remaining five computers is used in the actual study.

These computers were collected from the university surplus warehouse and a nearby recycling facility. The main specifications of these computers are presented below.

1. Macintosh IIci by Apple® - CPU MC 68030 at 25 MHz.
2. Power Macintosh 7100/66 by Apple® - CPU PC 601 at 66 MHz.
3. Optiplex GS by Dell® - CPU Intel® MMX at 166 MHz.
4. DESKPRO by Compaq® - CPU Intel Pentium® at 133 MHz.
5. Unbranded with SBM logo - CPU AMD X5-133 ADW at 133 MHz.

Most disassembly steps were performed using a power screwdriver. For some of the fasteners (screws) that were inaccessible with a power screwdriver, a manual flat head and Philips head screwdriver was used. Disassembly times were noted down using a simple digital stopwatch and the weighing of each disassembled part was carried out using a laboratory weighing scale.

Disassembly times for these five computers were plotted in the form of a graph (as shown in Figure 1). The x-axis represents the disassembly time and the y-axis values are the net recovered worth for each step. This approach provided us with a simple yet useful way of evaluating the recycling profitability of different computers and computer manufacturers. The x-axis values are plotted as cumulative disassembly times. The net recovered worth was calculated using the difference between the values of recovered components (e.g. hard drive, CD drive and various cards etc.) or materials (e.g. plastic and steel etc.) and the money spent in disassembling them (including labor costs and overhead).

All of the numbers involved, such as component and material prices and the disassembly costs, are based on information gathered from a survey we prepared for recycling companies. The cost estimates used in this research are based on data gathered from this survey. The cost value of individual components is based on the price recyclers can get by reselling components to end users or small computer shops. Recycling companies also provided the price of selling materials or obsolete components in bulk to other recyclers which process these materials to recover raw materials.

To obtain the recovered value for a particular disassembled material, the weight of that material was multiplied with its price per pound Disassembly cost is determined by multiplying the time required to complete each disassembly step with the cost incurred during that time period. Disassembly cost is essentially the labor rate per unit time. For example if the disassembly labor rates are \$ 7/hr (\$ 0.00194/second) and if it took 500 seconds for a particular disassembly step, the cost incurred during this disassembly step would be \$ 0.972. These cost values were again, provided by the recycling companies. The net worth for a given step is obtained by subtracting the respective recovered value from the estimated disassembly cost.

Exogenous is defined as "something caused by factors that are outside the system". Parameters such as fluctuating resale market prices for raw material and components, bargain purchase of obsolete computers, worker efficiency or overhead costs are outside of the designer's control and therefore deemed exogenous parameters. These parameters can influence our results and the disassembly economics and profitability of a computer.

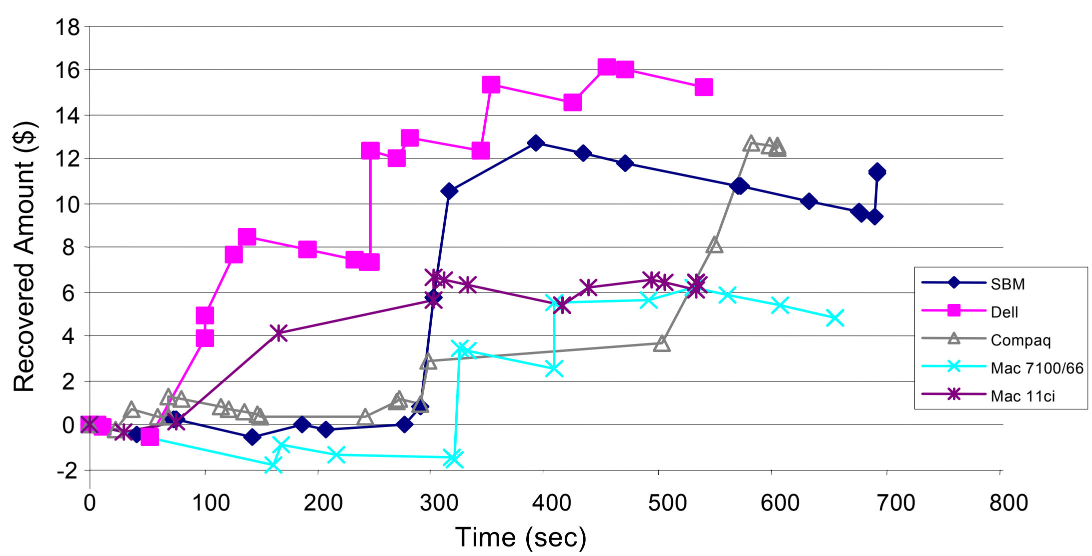

Figure 1: Net recovered worth for designs with normalized costs.

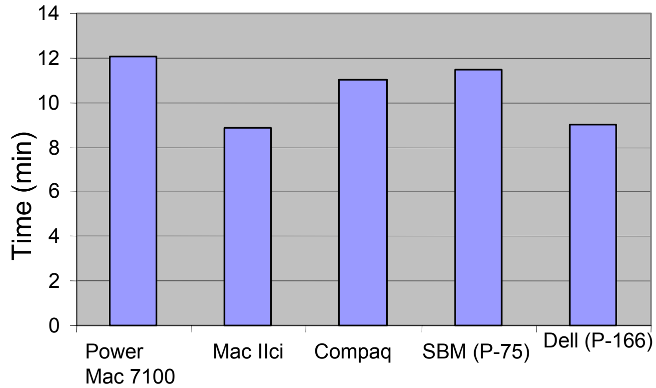

Figure 2: Disassembly times for designs form different manufacturers.

However, our approach of normalizing these results diminishes the effect of these factors and gives us net profit values comparable to that of recycling companies.

4 Results and discussion

The time taken for disassembly of each individual computer is presented in Figure 2. Even though the Mac IIci took the least time (8.88 minutes) this design did not generated the most revenue for the recycling companies as presented in Figure 1. This can partly be attributed to the fact that for this particular model the processor cannot be separated from the motherboard. Additionally, CD-ROM was not part of original Mac IIci design (introduced in September 1989), thereby reducing its recycling profitability. More importantly it shows that older computers represent a trend of diminishing returns for the recycling companies, hence making them a less attractive candidate for disassembly.

In Figure 1 the disassembly operation is plotted for recovered net worth and the disassembly time. We are able to identify certain immediate benefits emerging from this diagram. It is worthwhile to note that the costs used for generating points shown in Figure 1, are based on a fixed labor and overhead rate of $40/hr. This number is based on information gathered from recycling companies.

One noticeable trend in the disassembly plots is that almost all of the major revenues gains come from the recovery of components that can be resold. This leads to the recommendation that designs which allow for early component removal (in less disassembly steps) or a design in which the removal of a valuable component is independent of the removal of other parts will be a beneficial design for the recyclers. Also, this leads to the ideal that once the components have been cannibalized the remaining structural components can be thrown into a bin, to be shipped to processing recyclers. However, this approach will only be feasible if the remaining chunk is made of one or few materials so that it requires minimal further disassembly.

The above recommendation to design for early removal of parts also leads to the recommendation of a ‘best removal process’. In this approach we identified all of the steps, which resulted in generating revenues for the recycler and re-arranged the disassembly diagram to give precedence to these steps. However, physical disassembly constraints were still followed in doing so. For example a processor cannot be removed until the heat sink has been removed, even though the heat sink removal may not generate any revenue or may even turn out to be a cost to the recycler. Removing the heat sink is an unavoidable step to reach and remove the processor. The results for this rearranged disassembly sequence for DELL and SBM are presented in Figure 3.

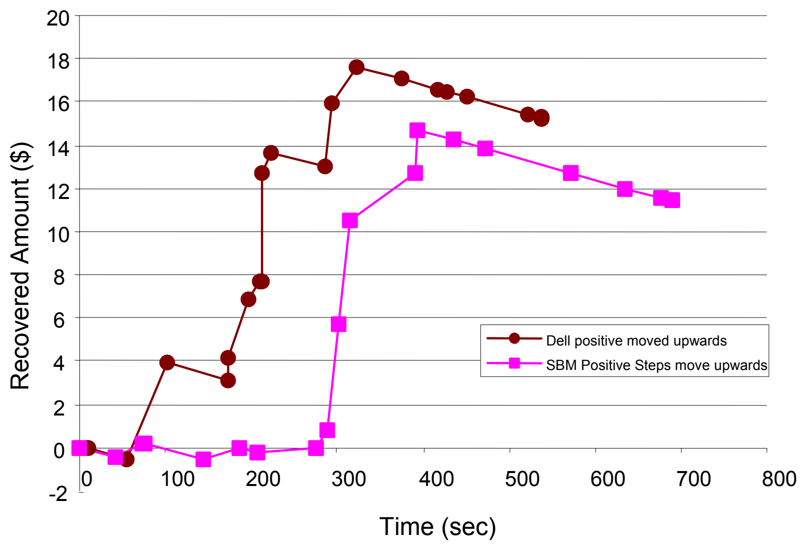

Figure 3: The 'best removal process' for two computers.

Based on this proposed 'best removal process' approach, the disassembly plot for the Dell OptiPlex shows that at 300 seconds all of the revenues generating steps have been performed as opposed to 550 seconds in the earlier design (see Figure 1). In the earlier case, the worker had to continue disassembly for a total of 550 seconds to recover all of the valuable parts. As proposed earlier, in the 'best removal process' the remaining disassembly steps after 300 seconds can be eliminated or greatly reduced only if the remaining assembly is comprised of one or fewer materials.

This approach can help designers visualize disassembly sequences and provide them with guidelines for rearranging PC layout to the benefit of recyclers. Furthermore, the method helps designers compare concept variants being considered for final production. Based on these plots, they can evaluate disassembly profitability and hence recycling feasibility of each concept variant and include such results in the decision making involved in selecting a variant.

This method of evaluating design disassembly profitability is not specific to computers and can be applied to other equipment and even component or subassemblies of electronic equipment or any other machinery which passes through the process of disassembly and recycling.

In addition to these disassembly plots, an important part of our experiments is the tabulation method, which we have created to record the disassembly process. This approach is somewhat similar to the reverse fish bone diagram concept presented by Ishii and Lee [13], with the addition and introduction of terminal and non-terminal nodes. This method, known as disassembly node diagram, classifies each removed part as either a **terminal or a non-terminal node**. Circles represent the terminal nodes in the diagram, which are actually independent components that can be either directly resold (for example, an OEM part like a power supply) or recycled (for example, parts constructed from a single raw material such as aluminum). A box represents a non-terminal node, which can be further disassembled until it results in a set of terminal nodes. The number within each box or a circle is the cumulative time for disassembly and the distance between two consecutive steps is the time spent in execution of that step. This method helps us to visualize and optimize the design of computers for ease of disassembly. Disassembly node diagram for Dell OptiPlex is presented in Figure 4.

A computer designed to have a greater number of direct terminal nodes will take less time for disassembly as opposed to a design having greater number of non-terminal nodes, which requires further disassembly to become a terminal node. It is apparent from our study that several parts could have easily been designed to incorporate this recommendation.

A casing cover, made out of steel was found to be a non-terminal node, because it has support strip made of aluminum. If this same casing cover was to be designed with considerations for terminal or non-terminal node concept, then the strip could easily have been designed of steel, making the part a terminal node. This simple change could have saved the disassembly worker from performing further disassembly to separate parts. This in turn not only saves time for the recycler but also saves them the effort and cost in handling different materials. We believe that designing computers with a greater number of terminal nodes and reducing non-terminal nodes will enhance the recycling feasibility of a design.

Plots presented in Figure 1, indicate that OptiPlex GS by Dell, appears to be the most profitable for the recyclers in terms of net recovered worth. We attribute the reasons for Dell OptiPlex to be the most profitable out of these five computers to the fact that it is designed with considerations to minimize the assembly time and this also proves to be beneficial in minimizing the disassembly time. To minimize assembly time, components have been designed to be installed as easily removable slide-in and slide-out assemblies and are attached

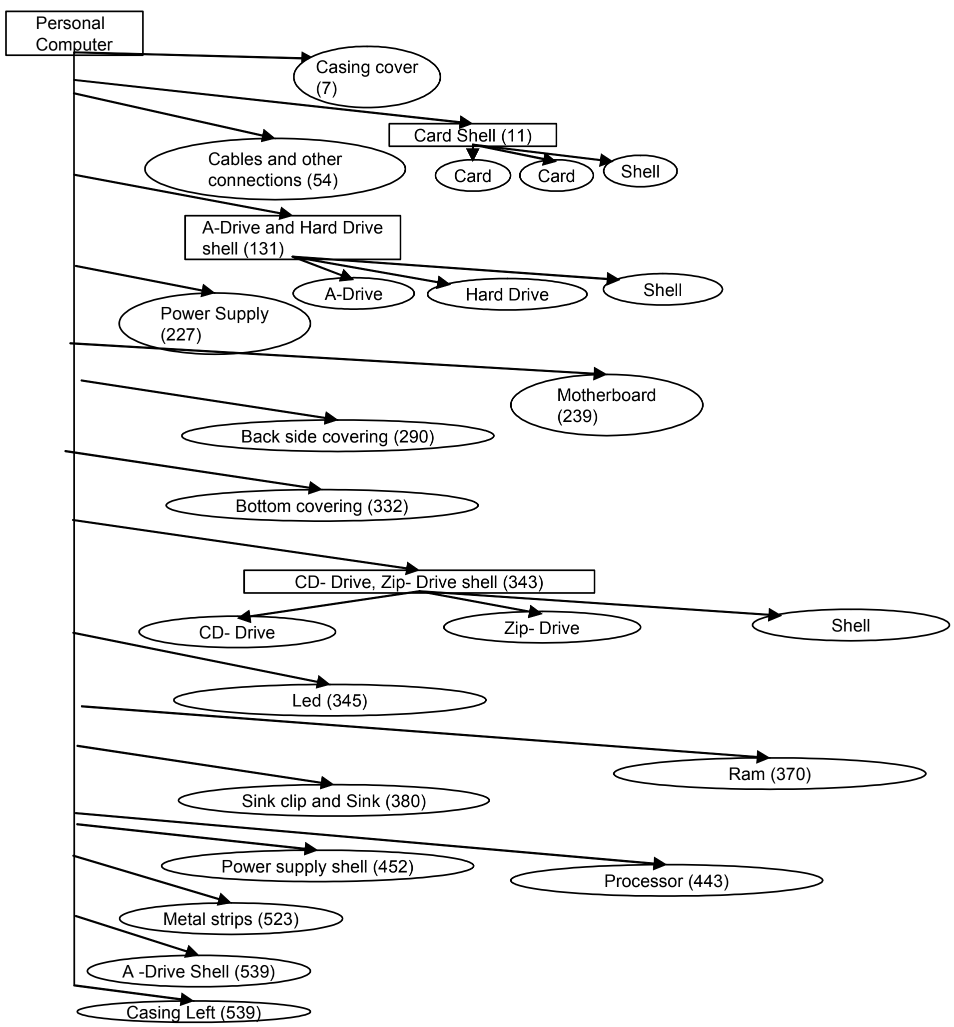

Figure 4: Terminal and Non-Terminal disassembly tabulation method.

to the main housing with as few as ten screws as opposed to 35 screws in some comparable designs. On the other hand, the DESKPRO by Compaq uses the same size screws for the assembly of every component. This helps in the disassembly process by eliminating use of different tools and also by eliminating wasted time in switching over from one tool to another.

Certain unique features were noticed in the designs from other manufacturers as well. Power PC 7100/66 by Apple is designed in such a way that the casing essentially is a rectangle prism with a removable top. The benefit of this design is that disassembly does not require any reorienting of the casing and all of the parts are removed in one direction, thereby saving valuable time and energy for the disassembly worker who is no longer required to reorient the part after every few disassembly steps.

It was felt that cognitive thinking time plays an important role as well for many disassembly steps since complex steps take more time. This leads to the recommendation that designs must be intuitive so as to reduce disassembly time. Also this will reduce the skill level required of the disassembly workers. This requirement of a low skill level was specifically mentioned by one of the recycling companies because all of these factors translate into reduced labor costs and hence reduced overall recycling costs for them. Also, this leads to the recommendation that a disassembly process description and diagram, specifying the disassembly sequence will prove extremely helpful to the worker in understanding the process and sequence of the removal of parts.

At many instances it was noticed that fasteners (screws) required to be removed were not visible and required effort in locating them. Also, screws for some designs were at inaccessible locations, requiring change of tool from power screw driver to small manual screw driver and re-orientation of casing to access them. These issues can be easily addressed by making or marking fasteners with bright colors and taking into account previously published Design for Disassembly guidelines that suggest placing fasteners/notches at such locations so that they are easier to access and do not require frequent reorienting of a PC during disassembly.

While disassembling computers it was noticed that the removal of the front panel in almost every design is somewhat difficult and takes time because it is difficult to access screws and requires reorienting to remove the panel. More importantly incorporation of many small components such as on/off buttons, LED's, internal speakers and logos on the front panel body make removal even more cumbersome. Though removal of the front panel does not necessarily generate revenue its removal is essential to reach other valuable parts underneath which may include CD, Zip and A drives. Therefore, it is recommended that apart from industrial and aesthetic design consideration, front panel design must be given significant disassembly considerations.

Though the Dell OptiPlex came out to be the most profitable design and only had ten screws as opposed to some designs having 35 screws, we noticed that even increasing the number of screws by a factor of three or four does not drastically hinder disassembly profitability. This is because removing even a dozen of screws using a power screwdriver only takes few seconds. The only consideration with the increased number of screws in a design is that they must be visible and easily accessible.

During our discussion with one of the recycling companies, it was mentioned that a PC in which epoxy has been used to join parts has almost no value for the recycler. Removal of epoxy requires time and effort and in many cases is not even possible without chemical processing, which does not make economic sense and renders the part un-recyclable in many cases. Therefore, the use of epoxy or other adhesives should be avoided. Rivets are another set of fasteners, which greatly slows down the disassembly process. Since it is very time consuming and difficult to remove rivets, it is recommended that the use of rivets is avoided. If they are used, they should be used to rivet the same materials.

One of the recycling companies mentioned that it is much easier to find buyers for parts (especially plastics) that have their type and specification information indicated (printed/embossed) on them. Based on this information they might be able to find buyers who are specifically looking for a certain type of plastic and hence may even be able to sell these materials at a higher price. With material specification information, processing companies can decide what processes to adopt for recycling a particular plastic and whether plastics or other parts are compatible to be processed together or not. Though this information may not be beneficial for the assembly or manufacturing of that equipment, it will be tremendously beneficial for recycling of that equipment.

5 Conclusions and recommendations

In the US, current recycling efforts are carried out by computer recycling businesses that are based on a profit-making model and not simply environmental improvements. Recycling businesses have a very low margin of profit and if recyclers anticipate that a prospective batch of computers will not generate any profits for them, that batch will not be recycled and will be sent to the landfill, irrespective of its hazardous environmental impact. Therefore, efforts must be made to enhance profitability of these businesses so that they make money. This in turn will ensure recycling of more computers and reduce their environmental effect.

Since profitability is one of the most important issues in computer recycling, we have plotted the disassembly time and the monetary gain from disassembled parts to give us the direct measure of economic feasibility. Based on this measure, we compared different models and determined which designs made more economic sense for disassembly. By noting down the disassembly process in terms of monetary gain for the recycling companies, we have proposed a simple yet very practical way of determining recycling feasibility of a particular PC design. This approach also leads to the 'best removal process', where a design can be modified to allow for recovery of valuable parts in the least disassembly steps thereby saving disassembly labor spent, recovering those parts. However, for this approach to be feasible, remaining structural components should be ideally of a single material or as small a number of different materials as possible.

Additionally, the disassembly node concept used for recording the disassembly process will serve as a useful technique to individually visualize each step and to study which steps are taking longer time for disassembly. Also, we believe that the proposal of designing for greater terminal nodes, if adopted by the initial designers, will further reduce the disassembly time. We introduced new Design for Disassembly guidelines resulting from our experiments in Section 4. These guidelines are presented below.

1. Design for intuitive disassembly procedure.
2. Avoid inaccessible location of fasteners.
3. Simple front panel design, with disassembly considerations.
4. Greater number of fasteners does not significantly effect the disassembly time.
5. Avoid use of epoxy and other glues.
6. Avoid fusing different materials together.
7. Avoid use of rivets.
8. Indicate material type on various parts.

The conclusions presented above were drawn by disassembling five computers from different manufacturers; however there still remain a number of major brand names which were not explored. Experiments of disassembling some of the major brand names and even unbranded computers may turn out to be useful in identifying further trends in design features to help reduce the overall disassembly time and effort. Ideally numerous computer models would be disassembled by many individuals and the times for disassembly would be averaged for each model. However, with limited resources available, we anticipate that the disassembly of a few dozen different designs will prove to be beneficial in identifying trends that can be refined to form a complete set of disassembly guidelines for computers in particular and other electronic equipment in general.

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