Disposition and End-of-Life Options for Products: A Green Design Case Study[1]

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Abstract

The ultimate fate of products is an important issue in conducting environmental life cycle assessments, setting public policy on product disposal and tracing materials flows over time. This case study illustrates a methodology for estimating the fate of such products, focusing on personal computers. The methodology can be applied to a wide range of consumer products.

Discarded or obsolete personal computers can be re-used directly, dissambled to re-use components, recycled to recover materials, or landfilled. Many computers are being recycled as markets for used computers and electronic equipment develop. Many are still being stored, despite the unprofitable nature of storage. Based on 1997 projections, our model suggests that nearly 150 million computers will be recycled in 2005. We predict that only 55 million will be landfilled. In addition, the equivalent of 15 million PCs will be landfilled from the unused portions of the 150 million recycled computers. In essence, the computers previously sentenced to death in landfills have been given a second life in newly established recycled electronic goods markets.

1. Introduction

Tracing the ultimate fate of products and their materials is often important in assessing the overall resource requirements for a product, comparing alternative designs that may differ in their ease of recycling, and in formulating public policies such as landfill restrictions or product take-back requirements for manufacturers.

Estimating the amounts of materials and product components that are re-used, recycled, landfilled or released to the environment is not as straightforward as it might seem on first glance. Some typical issues that arise include:

- Products are not homogeneous in size or composition. For personal computers, there are large differences between laptop and desktop machines, but even among desktop machines there are substantial size differences.

- The ultimate fate of products depends upon the time frame of analysis. Many products are stored for a period of time, so that the inventory of products increases over time. Personal computers stored in closets "in case of need" are a common example. Components may be re-used once in re-manufactured products, but these same components may be recycled or landfilled after a single re-use.

[1] This case study is based on Green Design Initiative Technical Report #97-10, available on the Internet at http://gdi.ce.cmu.edu/comprec/

- The rate of re-use and recycling for particular products may vary considerably in response to changing prices, corporate policies, public regulations and personal decisions. Forecasting these rates into the future is fraught with uncertainty.

- Recycling and re-use of product components is typically done for only a fraction of the mass of a product. For example, only 75% of the weight of automobiles are typically recycled; the remaining 25% is usually landfilled.

As a general framework, the recycling fraction of a particular product may be calculated as a product of the fraction of products returned for recycling, the fraction of materials in the product recoverable, and the fraction of materials actually recovered. For example, automotive lead-acid batteries have a 95% return rate, the recoverable lead in the battery mass is roughly 60 percent and the effeciency of the secondary smelter is roughly 95 percent. Thus, the material recovery fraction would be (0.95)*(0.60)*(0.95) or 54 percent [McMichael 98].

In this case study, we illustrate an analysis of the ultimate fate for a product, using personal computers as an example. We also consider public policy issues and possibilities to alleviate disposal problems. Personal computers are interesting because their sales growth in the two decades 1980-2000 is extremely high (historically, over 10% per year). We describe two different estimates for the fate of these computers. The first estimate was made in 1991, prior to the initiation of large-scale recycling operations. The second was made in 1997 and reflects a more complicated disposal process as well as the higher than expected sales of computers. These estimates were made with the aid of general purpose spreadsheet software. Some possible student assignments conclude the case study.

2. The Fate of Personal Computers: A 1991 Study

A 1991 Carnegie Mellon University student project study predicted that 148 million personal computers (PCs) would find their way into U.S. landfills by the year 2005 [CMU 1991]. The 1991 report was the result of a one-semester undergraduate Engineering and Public Policy project course at CMU and became widely cited. The organization and purpose of the project was to educate aspiring engineers as to the social impact of technology, and to help them understand the quantitative nature of the issue.

The study forecast flows of personal computers in each year based upon the diagram shown in Figure 1, where arrows represents changes in the status of particular computers. The study traced the flows of computers among the various categories for each year 1981-2005 with the aid of spreadsheet software. The study relied on three fundamental assumptions: 10 years of historical U.S. sales data with a forecasted 5% future growth rate, a simple one-stage model of end-of-life disposition, and some predictive assumptions on the future disposition rates of computers. A summary of the results from the initial model are included in the Appendix. However, the three fundamental assumptions did not accurately portray the end-of-life options for PCs as of 1997.

First, the sales data used in the study assumed only a modest 5% growth rate beyond 1991. However, the industry has seen remarkable growth— closer to 15% per year due to rapid operating system and processor upgrade cycles. In fact, 70 million PCs were shipped worldwide in 1997, 26 million of those in the United States. If the same predictive assumptions were used along with the actual sales data for the last 6 years, and with a future growth rate of 15%, the model would have predicted that 186 million computers would be landfilled by 2005. This number is roughly 25% higher than that without the rapid sales growth. (A summary of the results of updating the old model with actual sales data is in the Appendix).

Second, the 1991 model assumed all PCs would be obsolete in five years, then allowed for reuse, storage, recycling, or landfilling of the products. Storage was further defined, allowing three years of delay until all stored computers were landfilled. The one-stage model used in the original report (shown in Figure 1 below) is inappropriate since computers deemed obsolete by their initial owners often have subsequent value to others, and can remain in productive use for a few more years.

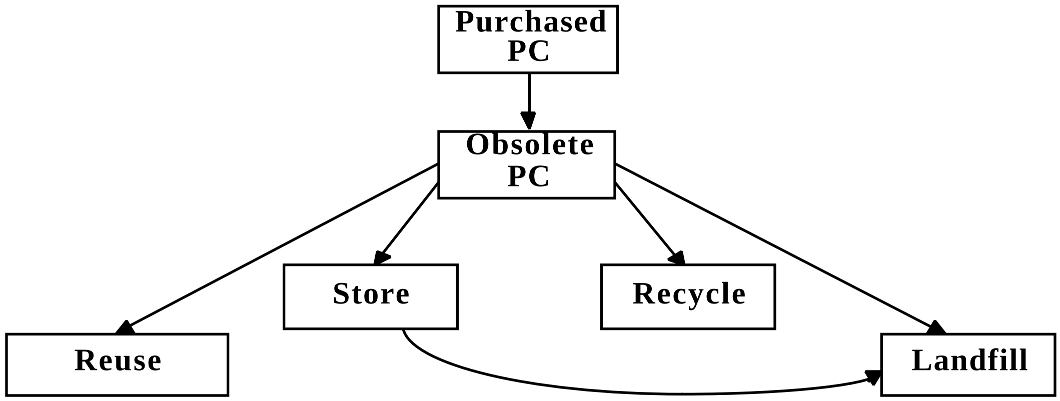

Figure 1 – Assumed Flow Diagram of Complete Computers in 1991 Study

The predictive assumptions used in the original study said that obsolete computers would be disposed as follows:

Parameter	Value
Lifetime of PC	5 years
% Obsolete Reused	10 percent
% Obsolete Recycled	1 percent
% Obsolete Stockpiled	80 percent
% Obsolete Landfilled	9 percent
Life of Stockpiled PC	3 years
% Stockpiled Landfilled	100 percent

Table 1 - Assumptions Used in 1991 PC Disposal Model

Six years have passed since the publication and broad citation of the 1991 study, and we can look at the changes in computer disposal. The single most significant change is the creation of many computer “recycling” firms. However, the "recycling" done by such firms often falls into the categories both of reuse and recycling as defined in the original model. Before proceeding further, we specifically define these two end-of-life activities. Reuse implies that the computer is put back in to service intact or with very minimal modification (such as adding memory). This could happen as a result of the computer being resold to a different user, being reassigned to a different user within a firm, or simply continuing to be used in another capacity by the purchaser. Recycling implies that the computer has in some way been disassembled and sold for raw materials or as separate electronic components.

Computer “recycling” firms both recycle and reuse products. Some firms actually take obsolete computers, make slight modifications, and place them in schools, non-profits, and charities for extended lifetime use (which is "reuse"). However, some firms actually "recycle" electronic equipment, extracting value from the components or high value materials like gold and other precious metals.

The emergence of these industries has diverted the flow of many computers from the municipal waste stream. However, hard numbers are not readily available which measure the aggregate numbers of computers being diverted into the reuse and recycling industries. In addition, consumers and businesses alike have shown a considerable unwillingness to throw away old electronic products. Instead, computers are often stockpiled in attics and storerooms until space is needed for another purpose. The existence of adequate storage space has contributed to the diversion of computers from landfills as well, as owners have had time to put off the disposition decision long enough for the recycling and reuse markets to mature.

The factors which are shaping the disposition of computers today are important in building an updated model of their fate. Following the three fundamental points of the initial study, we update the sales data to 1997 [Dataquest 9X], and assume the recent growth rate of 15% per year continues. Next, we propose a multiple-stage model, summarized below in Figure 2. Finally, as mentioned previously the actual number of computers being reused, recycled, stored, and landfilled is not available, thus estimates of these activities are made using both by extrapolation of individual recycling firm data, as well as by making qualitative assessments of the level of activity.

3. An Updated Model - 1997

The arrows in Figure 2 define the pathways of computers in the 1997 updated multi-stage model. A new computer is purchased, and eventually becomes obsolete. At that time, there are four options to the owner of the computer. First, it could be reused. This means that it is somehow used again after becoming obsolete to the purchaser— possibly a result of being resold or reassigned (or donated) to another user without extensive modification. Second, the computer could be stored by the original owner. In this case, it is serving no purpose except to occupy space. Third, the computer could be recycled. We define this to mean that the product is taken apart and individual materials or subassemblies are sold for scrap. (Recall our earlier comments about recycling firm activities). Finally, the computer could be landfilled.

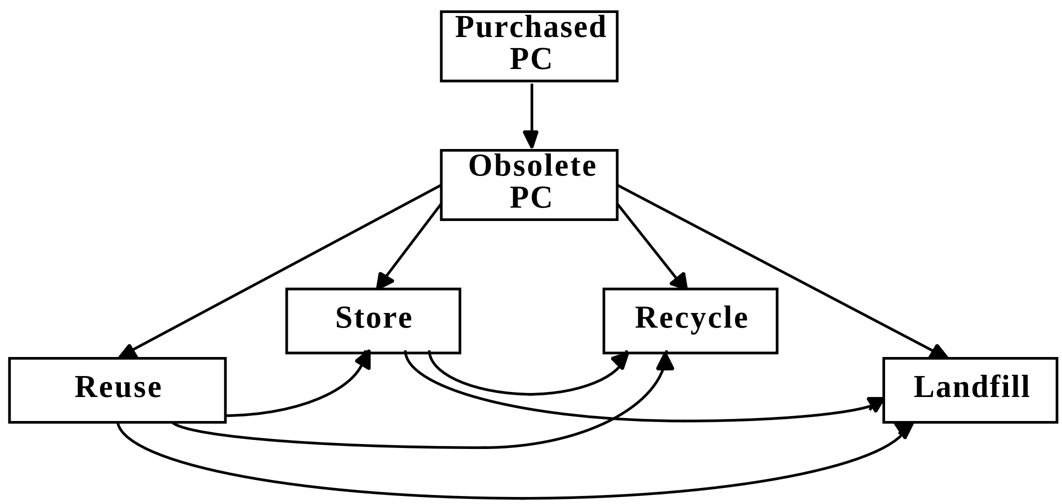

Figure 2 – Assumed Flow Diagram of Complete Computers in Updated Study

In our model, the reuse and storage options are only intermediate stages in the lifecycle of a computer. Only recycling and landfilling are terminal points. Notice that our model allows a computer to be purchased, reused, stored, and finally recycled or landfilled.

The final update is in suggesting the percentages of computers which follow the various end-of-life options. We continue to assume that computers generally become obsolete to the purchaser in five years. This assumption is one of the few assumptions carried over from the original model, and is supported inside the industry and outside by market research firms like Dataquest and International Data Corporation (IDC), who use it to predict product and processor upgrade paths in the personal computer industry. If not landfilled or recycled after becoming obsolete, reuse and storage allow for three more years in that capacity, implying the products are eight years old when leaving that step in the process. Stored computers are recycled or landfilled after eight years. Reused computers can be recycled or landfilled after 8 years, or they can be stored for three more years before then being landfilled or recycled, for a total of eleven years.

The first level of assumptions requires us to determine the percentages of obsolete computers being reused, recycled, stored, and landfilled. Since no strict data on this is available, two observations were used. First, the prior "doom and gloom" prediction of mass volumes of obsolete computers being landfilled by now has not been realized. Very few computers are seen to be entering the municipal waste stream. Second, articles and interviews of computer recycling firms show few computers less than five years old being processed. Thus, recycling and landfilling at the top level was assumed to be almost negligible. In addition, experience with corporate and individual users indicated roughly a 1:1 choice between reuse and stockpiling after five years. Thus, the remaining obsolete computers are assumed to be split evenly between the two options.

Reused machines are eight year old equipment which are now of no use to the owner. They are either recycled, stockpiled, or landfilled. Again, large quantities are not seen to be entering landfills and the percent being landfilled is assumed to be small. Similarly, large numbers of eight year old machines are not being recycled. Thus the majority are assumed to be stored for later disposition, with the remaining units recycled.

Finally, stored machines are assumed to have been deemed obsolete by the user, else they would have been reused. Similarly, they must have been seen to have some relative value— or they would have been recycled or landfilled earlier. Thus storing is merely an activity which the user does in order to potentially extract future value from obsolete computers. At this point (which happens between eight and eleven years after initial purchase) little chance of effectively reusing this equipment is seen. Most of these machines end up being transplanted to computer recycling firms, yet some are still landfilled. It should be noted that most likely this recycled or landfilled decision is more likely made on a volume basis rather than a unit basis. For example, a user might elect to throw away 25% of the original system, but recycle the remaining 75%. If anything, the percent landfilled is probably lower than this amount. About one-half of the contribution of landfilled computers annually in this model will come from stockpiled computers.

Based on these assumptions, the following parameters were assigned to variables in the model. Parameters used in the original model are presented as well.

Parameters	Old Value	New Value
Initial Lifetime of PC	5 years	5 years
% Obsolete Reused	10 percent	45 percent
% Obsolete Recycled	1 percent	5 percent
% Obsolete Stockpiled	80 percent	45 percent
% Obsolete Landfilled	9 percent	5 percent
Lifetime of Reused PC	3 years	3 years
% Reused Recycled	N/A	40 percent
% Reused Stockpiled	N/A	50 percent
% Reused Landfilled	N/A	10 percent
Lifetime of Stockpiled PC	3 years	3 years
% Stored Recycled	0 percent	75 percent
% Stored Landfilled	100 percent	25 percent

Table 2 - Assumptions Used in Disposition Models

Using this new formulation of the model, a very different picture of the computer disposition issue is seen. The original model predicted that cumulatively 340 million computers would be sold and 148 million landfilled in the U.S. (44 percent of those sold) by 2005. Our updated model predicts over 680 million sold but only 55 million computers landfilled in the U.S. (only 8% of those sold) by that time. Finally, we predict that 143 million will be recycled rather than the original 2 million. In short, the computers originally headed for landfills will be recycled. The number of computers landfilled will be roughly equal to the number sold through 1989, when recycling markets were just being formed and there were few end-of-life options for obsolete equipment. The Appendix shows a summary of the updated model.

4. Implications for Product Takeback

A more interesting statistic than either the number of computers recycled or landfilled is the number which are available for product takeback. Product takeback is an emerging international paradigm which requires that firms organize methods to reclaim their products at the end of their useful life. Seven European countries have some form of takeback legislation enacted already, and firms are becoming increasingly aware of the possibility that they will be required to comply. In this model, the number available for takeback is defined as those which have either been landfilled or are currently in storage. In 2005, despite increased recycling efforts, 80 million computers will still be available for takeback.

To more completely understand the environmental impacts of personal computer systems, they should be broken down into their major subcomponents: motherboards, cases, drives, monitors, and user input devices. This breakdown is basically unchanged since 1991, other than the fact that CD-ROM drives are now a standard part of all systems. This is the definition used in subsequent analysis.

It has probably become apparent to the reader that storing obsolete computers is inadvisable, since their value will only decrease over time, until they are worth only the sum of their raw materials. The residual value of materials in old electronic equipment soon after production is only 1-5% of the original cost of the equipment [MCC 96, Matthews 97]. Storing an old computer instead of quickly reusing or recycling it is not a profit-maximizing or cost-effective solution. Holding on to an obsolete computer without getting some benefit out of it is akin to holding on to a stock of a company which is known to be going bankrupt— in either case you end up with nothing, and have full knowledge of this fact ahead of time.

Further complicating the issue of storage is that many computers which are will beyond anyone's definition of "useful life" can only be disassembled for raw materials. Often, choosing this option requires paying a fee to a computer recycler just to comply with local regulations banning disposal. Thus, reuse and recycling need to be more forcefully promoted as options to maximize lifecycle values of machines.

5. Implications for Landfills

The updated model predicts that 55 million whole PCs will be landfilled by 2005. In addition, some portion of the 143 million recycled computers will also be landfilled. In this section, we estimate the mass of PCs and related material that will be landfilled over time.

The totals of PC sales include both desktop and laptop machines. A desktop machine weighs roughly 50 lbs. (23 kg) and occupies about 3 cubic feet (0.1 cubic meters) of space. A laptop machine weighs roughly 7.5 lbs. (3.5 kg) and occupies 0.14 cubic feet of space. As of 1997, the fraction of laptops in PC sales is 20% percent (and growing at an annual rate of 20%). Based on personal discussions with several recycling firms, we estimate that 10% of recycled PCs by weight are landfilled.

Compared with a 1991-era computer, these numbers are increasing, mostly because new technologies (e.g. CD-ROM) are being incorporated as standard components, and monitors are getting bigger. A computer system sold in 1991 was defined as weighing 30 pounds and occupying 2 cubic feet of space. Due to the increasing growth in sales, we assume that the typical system is more like the system of today, and use it in calculating landfill requirements.

Using our prediction of 55 million whole PCs being landfilled by 2005, we further state that 80% are desktop systems and 20% are laptops (conservatively following sales data). Thus the "weighted average" landfilled machine weighs 42 pounds (19.1 kg) and occupies a volume of 2.4 cubic feet. The 55 million whole PCs landfilled will require 135 million cubic feet of landfill space, and the 10% of scrap recycled computers will require an additional 35 million cubic feet by 2005, for a total of 170 million cubic feet. As a reference point, this volume is roughly one acre piled 4 thousand feet high.

6. Sensitivity Analysis

Clearly, many of the assumptions used in the model are uncertain. Sensitivity analysis can indicate what the effect of different assumptions or values of parameters might have.

The following table shows the result of independently making a +1% change in each of the percent distribution assumptions used in the model and equally compensating that increase across the other inputs. Note that these are not percentage point changes. For example, "% Obsolete Reused" is considered as increasing from 45% to 45.45%, while "% Obsolete Recycled and Landfilled" fall from 5% to 4.85%, and % Obsolete Stockpiled falls to 44.85%. The columns are the resulting percent changes which appear in the model as of year 2005 (cumulative for number recycled and landfilled, and as available for takeback in that year). Thus a 1% increase in the percent of obsolete computers reused leads to 0.10% less computers cumulatively recycled, 0.72% less cumulatively landfilled, and 0.06% fewer available for takeback.

Assumption Gradient	ΔRecycled	ΔLandfilled	ΔTakeback
Obsolete Computers			
% Obsolete Reused	-0.10 %	-0.72 %	-0.06%
% Obsolete Recycled	0.08%	-0.13 %	-0.03 %
% Obsolete Stockpiled	0.01 %	-0.56 %	0.56 %
% Obsolete Landfilled	-0.07 %	0.27 %	0
Reused Computers			
% Reused Recycled	0.20 %	-0.38 %	-0.12 %
% Reused Stockpiled	-0.01 %	-0.29 %	0.20 %
% Reused Landfilled	-0.04 %	0.16 %	0
Stored Computers			
% Stored Recycled	0.63 %	**-1.62 %**	-0.16%
% Stored Landfilled	-0.21 %	0.54 %	0.06 %

Table 3 - Sensitivity Analysis of Assumptions in Model

Of these results, only the 1.62% fewer computers landfilled as a result of increasing the percentage of stored computers being recycled (in boldface) seems significant. However, this result comes partially because of the already high magnitude of the initial assumption (75%, increased to 75.75%), which is almost twice the size of the next highest percentage in the model, and partly due to the fact that more than half of all obsolete computers pass through the storage stage.

One of the primary limitations of this model is the lack of flexibility with respect to assigning different parameter values for every year of computer sales in the United States. For example, it is clear that computers sold in 1980 faced a distinctly different set of end-of-life options than those sold in 1996, and did not have the same average useful life. However, the relatively low number of sales in early years are dominated by the large numbers in recent years, and this point becomes lost by volume.

Another limitation is the assumption of a continued 15% growth rate. This leads to a prediction in sales of 93 million units in 2005. However, the U.S. population will be roughly 300 million by then, so this would represent an unrealistic one computer sold for every 3 persons. However, given the time horizon of the model, adjusting sales growth to a more conservative 12% has little effect on the final environmental impacts. Under this rate, only 73 million new units will be sold in 2005, and the numbers of units recycled and landfilled fall less than 1% - to 142 million and 55 million, respectively. Note that this is almost entirely a result of the time horizon of 5 years until a computer becomes obsolete. So the sales growth rates affect only the years 1998-2000. If the model were extended an additional 5 years, there would be a much higher discrepancy.

7. Industrial Progress Since 1991

The 1997 model presents a much improved picture of the environmental impact of obsolete computers. However, the reduced impact has come more as a result of the emergence of third-party recyclers than from specific progress made by manufacturers. The 1991 study specifically outlined several areas where work needed to be done to improve the environmental quality of computer products. Following is a list of the design issues mentioned and progress to date in those areas.

Design for Environment Programs
The key to successfully improving environmental quality of any product is to make informed decisions at the design stage. So called Design for Environment (DFE) or Green Design programs maximize use of resources, and also ensure that corporate environmental goals are met in a timely manner. Most major computer manufacturers (Apple, HP, IBM) have environmental design programs in place and publicize their efforts. In addition, Compaq has been selected to receive the 1997 World Environment Center Gold Medal for International Corporate Environmental Achievement in recognition of the company's exceptional performance in environmental, health, and safety leadership and proactive stances towards meeting international regulation far ahead of their competitors.

Modular Design and Upgradeability
Modular Design and Upgradeability is intended to alleviate some of the need to constantly upgrade equipment, and thus, to reduce potential waste. Although most computers can be partially upgraded by swapping components like larger drives, few computers exist with appropriate price-performance upgrade paths, and even fewer are able to be traded in for newer models. The only options on the Intel-platform are generally limited to ranges of processor performance, and require relatively costly upgrades for little performance benefit (typically several hundred dollars for a modest gain).

However, Apple's PowerMac 7500 series was designed for upgradeability right out of the box. Even the original computer comes with the processor on a "daughtercard" attached to the motherboard. Upgrading is as simple as changing daughtercards and is very inexpensive - roughly $100 for twice the power. Although full upgradeability can never exist due to rapidly changing architectures, an option like this helps to extend the life of computers.

Component Reuse
In the absence of upgrade paths for most equipment, reuse needs to be seen as a viable option. Most subsystems (e.g. drives, memory, keyboards) are designed to last well beyond the 5-year useful life of the overall computer system. This is an awkward situation as the whole system sits idle while its subsystems could be reassigned, yet the purchaser paid more for components which will far outlast the system. Many of these components could be resold to increase the value.

Materials Selection
One of the more important reasons for concerning ourselves with materials selection is in preventing the use of toxic materials. Generally speaking, it will be impossible to remove all toxics from the design of computers. However, the initial report specifically mentioned a few toxics and their uses. We reconsider these examples and update the progress made. Overall, materials choices fall into three categories:

- Materials not necessary for operation (Class I)
- Materials necessary for operation and expensive to replace (Class II)
- Materials necessary but with no easy replacement (Class III)

Class I materials choices mentioned in the 1991 study included the Lead shielding for CPU cases. Much progress has been made in this area. Manufacturers have switched to cases which use more plastic for shielding, as well as using metals other than Lead. Class II materials included PCP in capacitors, Cadmium in batteries, lead solder on circuit boards, and Mercury in batteries and switches. Some progress has been made in this category, but mostly through reduction efforts. Cadmium is still present in rechargeable portable computer batteries, as are traces of Mercury, but each in lower quantities. Nickel-Cadmium (NiCd) technology continues to be the most widespread choice in the industry, although other options such as Nickel-metal-hydride (NiMH) exist. Lead solder is still a standard part of circuit board fabrication, but again, less is being used due to technology advances. Finally, Class III materials like Phosphorous in monitors, Copper-plastic interface cables, and Silicon and Arsenic in integrated circuits, are still standard in products. Little progress has been made in removing these materials from design other than through reduction. Thankfully, projections of widespread use of Gallium-Arsenide (GaAs) technology have proved premature.

An interesting side-effect of the continued use of metals in the design of computers is that they account for a high percentage of the end-of-life value of products. The more metals present (e.g. Aluminum), the higher the reclamation value for a recycling firm. Ironically, as metals are successfully replaced, there will be less incentive for recycling to occur. Metals account for over 70% of the residual value of computers [MCC 96, Matthews 97].

Aside from materials selection improvements, progress has been made in subsystem recycling. This advance has come in part through legislation like EPA's 1992 decision to ban the landfill disposal of cathode ray tubes (CRTs). As a result, monitor and CRT recycling has made great advances. This is significant because monitors contribute nearly 50% of the mass and volume of computer systems, and contain toxics Lead, Phosphorus, Cadmium, and Mercury. Glass, circuit boards, and wiring from both CRTs and standard televisions are reclaimed in great quantities every year (at least 85% of reclaimed monitors are recycled), reducing the volume of landfill waste from monitors [Envirocycle 97].

Even with these recycling technology advances, there are considerable obstructions to successfully entering the market. A company electing to reclaim old electronic products is classified as a "hazardous waste handler" by EPA regulations. Improvements need to be made which provide regulatory relief for companies which seek to both reduce landfill waste and improve environmental quality. EPA's Common Sense Initiative is a good starting point for changing the perception and classification of recyclers as hazardous waste facilities.

Labeling and Materials Recovery
Individual firms have followed International Standards Organization (ISO) guidelines with respect to labeling parts. IBM has labeled all plastic parts of their computers so that they can be easily identified at end-of-life, using ISO specifications as well as supplier information. Such efforts have, for the most part, caused manufacturers to realize the benefits in reducing the number of materials used (namely, plastics) in their products.

In addition, the electronic industry has made considerable progress in setting up reverse logistic networks and reclamation facilities to extract value from end-of-life equipment. Digital, Lucent, and IBM all have corporate- centers in place to process obsolete electronic equipment.

8. Policy Directions

In the last decade, many industry groups and worldwide environmental quality specifications have been created (e.g. Energy Star, Germany's Blue Angel, etc.) However it is still basically up to the user to preserve the environment at product end-of-life. Standards like Energy Star (EPA's Electronic Industry Pollution Prevention project) have definitely reduced the energy requirements of computers, but aside from reduced emissions in electricity generation, little product benefit has occurred.

For real environmental quality improvements to occur, one or more of the following issues will need to gain industry acceptance: green marketing, supplier management, promotion of recycling, and resource recovery. Each of these issues is now discussed in more detail.

Green Marketing
Products which are of higher environmental quality than their alternatives need to be allowed to be marketed as such without fear of FTC action. Many products in the industry fall into this category, such as IBM's PS/2e, which was designed to be more easily disassembled than other computers at the

time. So far, little benefit has been realized from green marketing. One factor preventing green marketing's success is a general degree of unwillingness amongst manufacturers to improve environmental quality if it costs more. Generally, firms are only willing to spend 0.1% more on a product to improve environmental quality [Lave 96]. While it is clearly no surprise that firms want to control costs, it will be difficult to differentiate products in the future without a commensurate investment in design.

Supplier Management
As international environmental quality specifications take hold, electronic firms will need to work in tandem with their suppliers to ensure that the final environmental footprint of the product is in accordance with all regulations. The primary means by which this will occur is by tightening the information linkages between suppliers and manufacturers. Original Equipment Manufacturers (OEMs) like HP and IBM are already querying subsystem manufacturers like Intel and Quantum regarding the materials, chemicals, and processes used. Subsystem manufacturers are now querying their own suppliers regarding the same issues. As these relationships grow, significant environmental benefits should be seen as the entire industry seeks to reduce environmental impacts.

Recycling Promotion
As mentioned above, used electronic equipment loses value quickly. Generally speaking, computers depreciate at a rate of 40% per year. Manufacturers are aware of this and realize the environmental burden of their products. Yet there has been no major effort to adopt an industry-wide initiative to promote computer recycling. The Electronics Industry Association (EIA) would be a natural choice to organize such a program.

Endorsing such a program could be as simple as adding a line in user manuals or attaching stickers to all new computers informing users (a majority of whom are replacing equipment) of the value in recycling obsolete electronics while still valuable. The longer a disposition decision is delayed, the more costly it will be to the company, until eventually they will have to pay for removal. This type of endorsement could serve two purposes: to publicize the firm's environmental awareness, and to increase the percentage of computers recycled.

Changes in government procurement and disposition procedures would be helpful as well. Currently there are restrictions in government procurement guidelines preventing purchase of recycled products. Also, many products purchased by the government can not be donated or otherwise reused, requiring long-term storage of obsolete equipment.

Resource Recovery and Product Takeback
Although several major manufacturers have the ability to reclaim materials from products, most such reclamation is being done by third-party groups. Although this inevitably meets the goal of preventing disposal, manufacturers thus have little incentive to try to design products that use non-virgin materials. Resource recovery programs are critical to closing the loop towards having a steady supply of non-virgin materials for manufacturers.

Large firms will sometime negotiate takeback pricing for old equipment (in the $50 range), but such a decision soon becomes moot as donation firms will give $100 or more tax credits for the same equipment. This fact underlies the economics of the situation— that personal computers are relatively expensive to completely recycle and there are small gains, whereas mainframe computers can be disassembled easily and with high returns. Note that this research has not even considered the potential environmental impacts or feasibility of software package recycling.

Firms with the logistics available to take back products should capitalize on this and incorporate outreach programs to fill capacity. Many firms donate old equipment to charity— why not promote recycling by launching "computer drive-off" programs, where empty trailers are left at schools to be filled with old equipment. In exchange for filling a certain number of trailers, the manufacturer provides "new" equipment to the school. Consumers have shown a remarkable willingness to provide computers for schools via grocery store receipt collection. Such programs could further inform the public about the incentives to recycling old equipment.

9. Conclusions

This case study illustrated how diverse data sources and rough estimates can yield estimates of the ultimate fate for consumer products. The study also shows how changes can effect such estimates over time. The growth rate of the computer industry was much more dramatic than expected in 1991. Consumers are buying more portable computers than ever (20% of sales and growing). Also, more computers are being stored by users making costly decisions about disposition. Finally, electronic reclamation businesses flourished with a constant stream of obsolete products, thereby reducing the numbers of units going to landfills, and increasing the number available for takeback. As mandatory takeback goes into effect around the world, such reclamation activities will become strategically valuable.

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Student Assignments

1. Using available data sources, update the 1997 Personal Computer disposal model to the current year, and add forecasts for the next five years.
2. Develop a “concept map” for the decision to dispose of a computer, with the various influences and inter-connections among influence labelled. How might these influences affect the assumed useful lifetime of personal computers?
3. Using the 1997 personal computer disposal model, estimate the amount of lead sent to landfills from leaded glass in cathode ray tubes. [Assume that a typical CRT tube contains 1.5 pounds of lead.]
4. Develop your own model of product disposal fates and amounts of landfilling for a particular consumer product, such as refrigerators, Nickel Cadmium rechargeable batteries, compact discs, or newspapers.

1991 EPP "Design Issues for Waste Avoidance" Study Model

Parameter	Units	Value
Lifetime of PC	years	5
% Obsolete Resold	percent	10
% Obsolete Recycled	percent	1
% Obsolete Stockpiled	percent	80
% Obsolete Landfilled	percent	9
Life of Stockpiled PC	years	3
Volume of PC	cu. ft	2
Power Cons of PC	watts	200
1 sq mile ft	acre ft.	640
1 Acre ft	cu. ft	43560

YEAR	NEW SALES (thousands)	NUM OBSOLETE (thousands)	NUM OBS RESOLD (thousands)	NUM OBS RECYCLED (thousands)	NUM OBS TO STOCKPILE (thousands)	NUM OBS LANDFILLED (thousands)	TOTAL LANDFILLED (thousands)	TOTAL STOCKPILED (thousands)
1981	1500	0	0	0	0	0	0	0
1982	2000	0	0	0	0	0	0	0
1983	2500	0	0	0	0	0	0	0
1984	3250	0	0	0	0	0	0	0
1985	4500	0	0	0	0	0	0	0
1986	6000	1500	150	15	1200	135	135	1200
1987	7500	2000	200	20	1600	180	180	2800
1988	9000	2500	250	25	2000	225	225	4800
1989	10000	3250	325	33	2600	293	1493	6200
1990	11000	4500	450	45	3600	405	2005	8200
1991	11500	6000	600	60	4800	540	2540	11000
1992	12600	7500	750	75	6000	675	3275	14400
1993	13600	9000	900	90	7200	810	4410	18000
1994	14700	10000	1000	100	8000	900	5700	21200
1995	15900	11000	1100	110	8800	990	6990	24000
1996	17100	11500	1150	115	9200	1035	8235	26000
1997	18100	12600	1260	126	10080	1134	9134	28080
1998	19100	13600	1360	136	10880	1224	10024	30160
1999	20100	14700	1470	147	11760	1323	10523	32720
2000	21100	15900	1590	159	12720	1431	11511	35360
2001	22100	17100	1710	171	13680	1539	12419	38160
2002	23100	18100	1810	181	14480	1629	13389	40880
2003	24100	19100	1910	191	15280	1719	14439	43440
2004	25100	20100	2010	201	16080	1809	15489	45840
2005	26100	21100	2110	211	16880	1899	16379	48240

TOTAL IN USE (thousands)	CUM LANDFILLED (thousands)	LANDFILL VOLUME (acre ft.)	LANDFILL VOLUME (sq mile ft)	CUM SALES (000s)	FRACTION LANDFILLED (%)	FRACTION LANDFILLED (% in use)
1500	0	0	0.0	1500	0	0
3500	0	0	0.0	3500	0	0
6000	0	0	0.0	6000	0	0
9250	0	0	0.0	9250	0	0
13750	0	0	0.0	13750	0	0
18250	135	6	0.0	19750	1	1
23750	315	14	0.0	27250	1	1
30250	540	25	0.0	36250	1	2
37000	2033	93	0.1	46250	4	5
43500	4038	185	0.3	57250	7	9
49000	6578	302	0.5	68750	10	13
54100	9853	452	0.7	81350	12	18
58700	14263	655	1.0	94950	15	24
63400	19963	917	1.4	109650	18	31
68300	26953	1237	1.9	125550	21	39
73900	35188	1616	2.5	142650	25	48
79400	44322	2035	3.2	160750	28	56
84900	54346	2495	3.9	179850	30	64
90300	64869	2978	4.7	199950	32	72
95500	76380	3507	5.5	221050	35	80
100500	88799	4077	6.4	243150	37	88
105500	102188	4692	7.3	266250	38	97
110500	116627	5355	8.4	290350	40	106
115500	132116	6066	9.5	315450	42	114
120500	148495	6818	10.7	341550	43	123

1991 EPP "Design Issue for Waste Avoidance" Study Model - With Updated Sales Data

Parameter	Units	Value
Lifetime of PC	years	5
% Obsolete Resold	percent	10
% Obsolete Recycled	percent	1
% Obsolete Stockpiled	percent	80
% Obsolete Landfilled	percent	9
Life of Stockpiled PC	years	3
Volume of PC	cu. ft	2
Power Cons of PC	watts	200
1 sq mile ft	acre ft.	640
1 Acre ft	cu. ft	43560

YEAR	NEW SALES (thousands)	NUM OBSOLETE (thousands)	NUM RESOLD (thousands)	NUM RECYCLED (thousands)	NUM SENT TO STOCKPILE (thousands)	NUM OBS LANDFILLED (thousands)	TOTAL LANDFILLED (thousands)
1981	1500	0	0	0	0	0	0
1982	2000	0	0	0	0	0	0
1983	2500	0	0	0	0	0	0
1984	3250	0	0	0	0	0	0
1985	4500	0	0	0	0	0	0
1986	6000	1500	150	15	1200	135	135
1987	7500	2000	200	20	1600	180	180
1988	9000	2500	250	25	2000	225	225
1989	10000	3250	325	33	2600	293	1493
1990	11000	4500	450	45	3600	405	2005
1991	12650	6000	600	60	4800	540	2540
1992	14548	7500	750	75	6000	675	3275
1993	16730	9000	900	90	7200	810	4410
1994	19239	10000	1000	100	8000	900	5700
1995	22125	11000	1100	110	8800	990	6990
1996	25444	12650	1265	127	10120	1139	8339
1997	29260	14548	1455	145	11638	1309	9309
1998	33649	16730	1673	167	13384	1506	10306
1999	38697	19239	1924	192	15391	1732	11852
2000	44501	22125	2212	221	17700	1991	13629
2001	51176	25444	2544	254	20355	2290	15674
2002	58853	29260	2926	293	23408	2633	18025
2003	67681	33649	3365	336	26919	3028	20728
2004	77833	38697	3870	387	30957	3483	23838
2005	89508	44501	4450	445	35601	4005	27413

TOTAL STOCKPILED (thousands)	TOTAL IN USE (thousands)	CUM LANDFILLED (thousands)	LANDFILL VOLUME (acre ft.)	LANDFILL VOLUME (sq mile ft)	CUM SALES (000s)	FRACTION LANDFILLED (%)	FRACTION LANDFILLED (% in use)
0	1500	0	0	0.0	1500	0	0
0	3500	0	0	0.0	3500	0	0
0	6000	0	0	0.0	6000	0	0
0	9250	0	0	0.0	9250	0	0
0	13750	0	0	0.0	13750	0	0
1200	18250	135	6	0.0	19750	1	1
2800	23750	315	14	0.0	27250	1	1
4800	30250	540	25	0.0	36250	1	2
6200	37000	2033	93	0.1	46250	4	5
8200	43500	4038	185	0.3	57250	7	9
11000	50150	6578	302	0.5	69900	9	13
14400	57198	9853	452	0.7	84448	12	17
18000	64927	14263	655	1.0	101177	14	22
21200	74166	19963	917	1.4	120416	17	27
24000	85291	26953	1237	1.9	142541	19	32
26920	98085	35291	1620	2.5	167985	21	36
30558	112798	44600	2048	3.2	197245	23	40
35142	129717	54906	2521	3.9	230894	24	42
40413	149175	66757	3065	4.8	269591	25	45
46475	171551	80387	3691	5.8	314092	26	47
53446	197284	96060	4410	6.9	365268	26	49
61463	226876	114085	5238	8.2	424121	27	50
70683	260907	134813	6190	9.7	491802	27	52
81285	300044	158651	7284	11.4	569635	28	53
93478	345050	186064	8543	13.3	659142	28	54

PC Disposition Model (6/2/97)

General Parameters	Units	Value
Original Lifetime of PC	years	5
Parameters for Obsolete Machines		
% Obsolete Reused	percent	45
% Obsolete Recycled	percent	5
% Obsolete Stored	percent	45
% Obsolete Landfilled	percent	5
Parameters for Reused Machines		
Lifetime of Reused PC	years	3
% Reused Recycled	percent	40
% Reused Stored	percent	50
% Reused Landfilled	percent	10
Parameters for Stored (Stockpiled) Machines		
Time Stockpiled	years	3
% Stored Recycled	percent	75
% Stored Landfilled	percent	25

Data Sources:
Dataquest Sales Data (1981-1995) -via Statistical Abstract of the U.S.
1996 Data Extrapolated with published 17% annual sales growth from 1995
All Numbers below in Millions
U.S. only!!

"Reused" = Reused, Resold, Reassigned
"Stockpiled" = Stored, not used
"Recycled" = Raw Mats Extraction

Landfill / Dimension Assumptions

Typical Desktop PC				
Weight	50	lbs	23.00	kg
Volume	3	cu. ft	0.10	cu mtrs
Typical Notebook Computer				
Weight	7.5	lbs	3.50	kg
Volume	0.14	cu. ft	0.00	cu mtrs
Weighted Average Computer (80/20)				
Weight	41.5	lbs	19.10	kg
Volume	2.428	cu. ft.	0.08	cu mtrs

			FATE of OBSOLETE PCs				FATE of REUSED PCs		
YEAR	SALES of NEW PCs	OBSOLETE PCs	REUSED	RECYCLED	STORED	LANDFILLED	RECYCLED	STORED	LANDFILLED
1980	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1981	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1982	2.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1983	6.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1984	7.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1985	6.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1986	7.03	1.50	0.68	0.08	0.68	0.08	0.00	0.00	0.00
1987	8.67	2.57	1.16	0.13	1.16	0.13	0.00	0.00	0.00
1988	10.00	6.19	2.78	0.31	2.78	0.31	0.00	0.00	0.00
1989	9.33	7.74	3.48	0.39	3.48	0.39	0.27	0.34	0.07
1990	9.85	6.39	2.87	0.32	2.87	0.32	0.46	0.58	0.12
1991	10.18	7.03	3.16	0.35	3.16	0.35	1.11	1.39	0.28
1992	12.54	8.67	3.90	0.43	3.90	0.43	1.39	1.74	0.35
1993	14.76	10.00	4.50	0.50	4.50	0.50	1.15	1.44	0.29
1994	18.40	9.33	4.20	0.47	4.20	0.47	1.26	1.58	0.32
1995	22.50	9.85	4.43	0.49	4.43	0.49	1.56	1.95	0.39
1996	26.33	10.18	4.58	0.51	4.58	0.51	1.80	2.25	0.45
1997	30.27	12.54	5.64	0.63	5.64	0.63	1.68	2.10	0.42
1998	34.81	14.76	6.64	0.74	6.64	0.74	1.77	2.22	0.44
1999	40.04	18.40	8.28	0.92	8.28	0.92	1.83	2.29	0.46
2000	46.04	22.50	10.13	1.13	10.13	1.13	2.26	2.82	0.56
2001	52.95	26.33	11.85	1.32	11.85	1.32	2.66	3.32	0.66
2002	60.89	30.27	13.62	1.51	13.62	1.51	3.31	4.14	0.83
2003	70.03	34.81	15.67	1.74	15.67	1.74	4.05	5.06	1.01
2004	80.53	40.04	18.02	2.00	18.02	2.00	4.74	5.92	1.18
2005	92.61	46.04	20.72	2.30	20.72	2.30	5.45	6.81	1.36
TOTALS:	682.13			16.26		16.26	36.76		9.19

FATE of STORED PCs		ANNUAL TOTALS					LANDFILL VOLUMES (mil. cu. ft.)		
RECYCLED	LANDFILLED	RECYCLED	LANDFILLED	STORED	IN STORAGE	AVAILABLE FOR TAKEBACK	FROM LANDFILLED	FROM RECYCLED	TOTAL
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.08	0.08	0.68	0.68	0.75	0.18	0.02	0.20
0.00	0.00	0.13	0.13	1.16	1.83	1.96	0.31	0.03	0.34
0.00	0.00	0.31	0.31	2.78	4.61	4.92	0.75	0.08	0.83
0.51	0.17	1.16	0.62	3.82	7.76	8.38	1.51	0.28	1.80
0.87	0.29	1.65	0.72	3.45	10.06	10.78	1.76	0.40	2.16
2.09	0.70	3.55	1.33	4.55	11.83	13.15	3.22	0.86	4.08
2.87	0.96	4.69	1.74	5.64	13.65	15.38	4.22	1.14	5.36
2.59	0.86	4.24	1.65	5.94	16.13	17.78	4.01	1.03	5.04
3.42	1.14	5.15	1.92	5.78	17.36	19.28	4.66	1.25	5.91
4.23	1.41	6.28	2.29	6.38	18.10	20.39	5.57	1.53	7.09
4.45	1.48	6.76	2.44	6.83	18.99	21.44	5.93	1.64	7.57
4.33	1.44	6.64	2.49	7.74	20.96	23.45	6.05	1.61	7.66
4.79	1.60	7.30	2.78	8.86	23.43	26.21	6.74	1.77	8.51
5.12	1.71	7.88	3.09	10.57	27.17	30.26	7.49	1.91	9.41
5.81	1.94	9.19	3.63	12.95	32.37	36.00	8.80	2.23	11.03
6.64	2.21	10.61	4.19	15.17	38.68	42.88	10.18	2.58	12.76
7.93	2.64	12.75	4.98	17.76	45.88	50.86	12.10	3.10	15.20
9.71	3.24	15.50	5.99	20.73	53.66	59.65	14.54	3.76	18.31
11.37	3.79	18.11	6.98	23.94	62.43	69.41	16.94	4.40	21.34
13.32	4.44	21.07	8.11	27.53	72.20	80.30	19.68	5.12	24.80
	30.01	143.06	55.46				134.66	34.74	169.40