Waste 2.0

Environmental issues in the use of refurbished computers for development

A Plan B Paper

In Partial Fulfillment of the Master of Science, Technology and Environmental Policy Degree Requirements

The Hubert H. Humphrey Institute of Public Affairs
The University of Minnesota

Steven E. Cayford

May 20, 2009

Elizabeth Wilson, Ph.D.
Paper Adviser

Date

Contents

1 Introduction **1**

2 Context **4**
2.1 Defining electronic waste 4
2.2 Legal setting 5
2.3 Logistics of computer reuse and refurbishing 6
2.4 Economic scale of the sector 11

3 Environmental aspects of disposal and recycling **16**
3.1 Electronic waste contents 18
3.2 Effects of processing 20

4 Benefits and Costs **27**
4.1 Assessing refurbished computers 27
4.1.1 Values by price 28
4.1.2 Estimating lifetimes 30
4.1.3 Estimating capacities 33
4.1.4 Computer donation lag time 37
4.1.5 Maintenance and configuration costs 38
4.1.6 Processing as economic development 40
4.2 Alternatives 42
4.2.1 New computers 42
4.2.2 Purpose-built computers 43

5 Conclusion **45**
5.1 Recommendations 46

1 Introduction

An increasingly common strategy for promoting development over the past decade or more has been that of donating used computers to organizations in developing countries. Some organizations, such as Computer Aid International and World Computer Exchange, do this as a non-profit venture while companies such as Free-Com and Device Global do so on a for-profit basis (Bridges.org, 2004).

In either case the fundamental process is the same: people or organizations in the more developed countries donate their used computers after the machines have reached their expected usable lifetime. This lifetime is usually three to four years for computers donated by companies and perhaps more for those donated by individuals. Considering that computers have an overall average lifetime of perhaps eight years, this leaves four or five years of functionality in the machine. Rather than dispose of this functional equipment, the machines are donated to organizations that sort them, do various amounts of refurbishment, and then ship them overseas.

Of course those who donate used machines are not doing it solely out of altruism. Development of computer equipment progresses so rapidly that machines that are only four years old possess just a fraction of the capability of new machines and will quickly begin to experience problems with the latest versions of software applications written for newer generations of computers. Rather than expend maintenance energy on computers increasingly unable to handle the latest software, computer owners consider upgrading every three or four years simply part of the cost of ownership.

The computers being shipped overseas are by definition obsolete, and yet they are still functional. Considering the financial constraints in developing countries it clearly makes sense from a private economic perspective to purchase obsolete but functional computers at low cost—or even better, to receive the machines free or for the cost of shipping.

Since the fundamental principles of personal computer operation have changed little over the last 20 years, older computers still exhibit similar educational potential both for end users and technical staff. The used machines may not run the latest software, but they run some software and that is better than nothing. They may break down at a higher rate than new computers, but to ingenious computer lab managers in developing countries, failing equipment is simply an opportunity to teach hardware maintenance skills.

On the face of it, shipping used computers to organizations in developing countries is a win win proposition. Those donating the machines have them taken off their hands—generally at no cost—and get warm recognition for helping to "bridge the digital divide," while those on the receiving end get usable equipment at low cost.

But this private economic perspective is too simplistic and overlooks the possibility of external societal costs. Ultimately the donated computers will be scrapped when no more use can be coaxed out of them. What happens to them at that point? Are they dumped in a landfill and left to leach out toxic material into the ground water? Are they broken down for recyclable materials, exposing local communities and those doing the processing to toxic dust and smoke? What environmental costs may they impose on the society they were intended to assist? And how can these environmental costs be balanced against the societal benefits of the computers?

Further inspection of the transportation of used computers reveals that the non-profit scenario described above makes up only a small portion of the overall trade. The larger portion of the sector is driven by the private economic interests of companies and individuals seeking to profit from the exchange of used computers. Private, profit-seeking companies may be more prone than non-profit organizations to ignore the environmental and societal externalities of the trade. As a report by the Basel Action Network (BAN) says, "[t]he reality is that this burgeoning new trade is not driven by altruism, but rather by the immense profits that can be made through it, and those involved are oblivious to or unconcerned with its adverse consequences." (Puckett, 2005, p. 2) Within the for-profit sector there is a division between a few large companies like Freecom and Device Global, which appear to see their mission much as the non-profits do, and innumerable small outfits interested in just shipping computers for profit.

Although it may be impossible to quantify the effects of computer end-of-life issues to the degree necessary to compare them with the economic benefits incurred from computer use, it is only reasonable for the donating entities, processors, and recipients to consider these issues when deciding what machines to donate, process, and accept.

This paper describes the primary benefits and costs of using refurbished computer equipment for development and places these costs and benefits in the context of the electronic waste issues. The paper does not reach strictly quantifiable conclusions, but frames the issues and indicates what concerns stake-holders should consider when deciding whether and to what extent to utilize refurbished computers.

This approach necessarily examines the societal costs and benefits in addition to private concerns, which may hold weight for those interested in using refurbished computers for development and are interested in societal changes, not simply private benefits—particularly government and non-profit agencies.

2 Context

2.1 Defining electronic waste

Electronic waste goes by several different names, reflecting a range of definitions. "Electronic waste," "e-waste," and "waste electrical and electronic equipment" are the most commonly used terms. The casual meaning of the terms is usually a reference to material containing circuit boards and associated peripheral equipment. This generally includes computers, monitors—whether cathode-ray tubes (CRT) or liquid crystal displays (LCD)—keyboards, mice, computer power supplies, and hard-copy peripherals like printers and scanners.

The European Union's Directive on Waste Electrical and Electronic Equipment (WEEE) uses the definition "equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields." (European Parliament, 2003, §3.a) Clearly, this is a broader definition that would include most household appliances as well as a variety of other machines.

This paper uses the general term "electronic waste" to refer to the high-tech portion of such equipment: those products containing integrated circuits (computers, monitors, cell phones, etc.) and their peripherals.

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal does not explicitly consider electronic waste, referring instead to the contents of waste products that render them hazardous. However, most electronic waste by either the common definition or the legal terms of the European Union are classified as hazardous by the Basel Convention terms. Most of the plastics in electronic goods contain polychlorinated biphenyls (PCBs) as well as polybrominated biphenyls (PBBs) and polybrominated diphenyl ethers (PBDEs), used particularly for their flame-retardant attributes, in addition to numerous other chemicals. The CRTs used in older computer monitors contain several pounds of lead in each monitor. Newer flat-panel LCD monitors contain mercury—primarily in the fluorescent tubes that back-light the displays. Printed circuit boards and batteries may contain lead and cadmium. Other components include "[c]opper, antimony, beryllium, barium, zinc, chromium, silver, nickel, and chlorinated and phosphorus-based compounds..." (Grossman, 2006). Most of these materials are included in the Basel Convention list of controlled substances. Other materials such as the polyvinyl chlorides (PVCs) used for insulation generate hazardous materials when they are burned or otherwise break down.

Many of the materials in electronic equipment have a substantial value in the recycling market, with lead, copper, mercury, silver, and gold used in printed circuits being some of the more valuable elements. However, due to the combination of components and their miniaturization, extracting the valuable materials is not always an easy task.

2.2 Legal setting

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal was adopted by the international community under the auspices of the United Nations Environment Program in 1989. The Basel Convention did not create an outright ban on the movement of hazardous wastes, it simply required that source and recipient states formally agree to each shipment in writing. This gives the recipient country the opportunity to refuse any incoming shipments of hazardous waste as defined by the Convention.

Poorer countries continued to find it difficult to block arriving shipments of waste, however, so several countries and environmental groups proposed a total ban on international trade in hazardous wastes. In 1994, the parties to the Convention agreed on a ban on all hazardous waste from OECD countries to non-

OECD countries. In 1995 this agreement was attached as an amendment to the original Basel Convention. The amendment has not been ratified, but the European Union and many countries have proceeded to implement the restrictions (Williams et al., 2008).

The United States, although a signatory to the original Convention, never ratified the Convention and has been opposed to the ban amendment. Other countries that opposed the ban amendment include Japan, Canada, Australia and New Zealand (McKenna, 2007).

While the Convention clearly applies to electronic waste, it is not always clear when used electronic equipment fits the definition of waste. Equipment that does not work and is not able to be fixed should be classified as electronic waste. Equipment that is still relatively new and functions well should evidently not be considered waste even if it is second hand. The grey area of the Convention lies in the distinction between equipment needing only "repair, refurbishment, or upgrading," which is not considered waste, and that requiring "major reassembly," which is considered waste (McKenna, 2007).

This ambiguity in the definition of electronic waste raises questions about some of the secondhand and refurbished computers donated for development work. While the non-profit organizations and the better known for-profit providers appear conscientious about testing equipment before shipping it, there is still natural attrition during shipping. In addition, older equipment will not have a very long expected life before it breaks down and inevitably needs the disposal or major reassembly indicative of electronic waste according to the Basel definition.

2.3 Logistics of computer reuse and refurbishing

This paper focuses on the activity around re-use and refurbishment of secondhand computers. While a great deal of used computer equipment is shipped to China

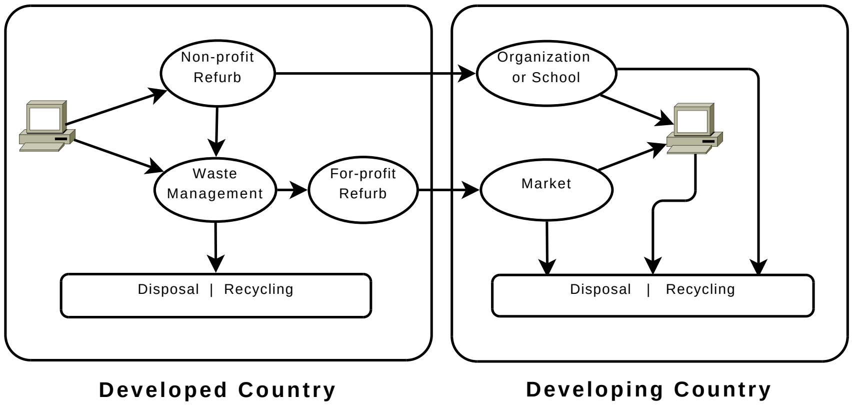

Figure 1: Schematic overview of refurbished computer flows.

and South Asia, the majority of this equipment appears to be intended for recycling and material recovery (Schmidt, 2006; Puckett, 2005). The majority of machines intended for re-use and refurbishment currently are shipped to sub-Saharan Africa. Accordingly, this discussion will focus primarily on the issues as they apply to the African continent. However, the experience of the South Asian recycling sector is used as a reference because it provides a useful example of possible developments in Africa should more substantial recycling efforts develop.

When considering the trade in used and refurbished computers there are two distinct sub-sectors: for-profit and non-profit. While fulfilling similar roles, these two sub-sectors exhibit different behaviors and motivations so merit separate consideration. The general flow of used computers through these parallel refurbishing and transportation chains is illustrated by the schematic diagram in Figure 1.

A great deal of public attention has been directed to non-profit computer refurbishers—particularly in the form of requests for donations. Non-profit organizations such as Computer Aid International in the U.K. or World Computer Exchange in the United States operate largely on the efforts of volunteers in developed countries. Companies or individuals may donate their used computers, assuming the machines meet the minimum specifications of the organization. The machines are then received, stored, refurbished, packed, and shipped by volunteers who donate their time and expertise. In some cases, the refurbishing operations may be operated as a local technology education project. Organizations receive donated computers from a wide range of sources: businesses, universities, colleges, schools, and local and national government entities (Computer Aid International, 2008).

The degree of refurbishment and testing done on the donated computers appears highly variable across organizations. Processing costs the organizations volunteer time and it increases the need for storage and processing space and the need to dispose of equipment that does not pass muster. Recycling unusable equipment requires either money to pay recyclers or volunteer time to do the recycling in-house. The more environmentally responsible the recycling effort, the more costly it is likely to be. Disposing of CRT monitors responsibly can be a particularly expensive task.

Unfortunately, this lack of consistency can make it difficult to measure outcomes and may result in unsuitable machines being shipped to developing country organizations. The Basel Action Network argues this point, saying that "[c]haritable re-use organizations are operating without universally agreed standards to ensure that their donations are appropriate [. . .]. It is very important to begin to develop standards for charitable re-use" (Puckett, 2005).

Shipments of used computers to organizations in developing countries are commonly made by boat and are packed into standard international shipping containers to minimize the costs of transportation. A typical 40-foot shipping container may hold up to 400 sets of computers including CRT monitors and peripherals. Accordingly, shipping large allotments in a single container is the most cost-effective means of transportation. Recipient organizations interested in receiving fewer than 400 units are encouraged by the providers to combine their requests with other local organizations in order to be able to ship a full container (World Computer Exchange, 2009). Individually packing each computer unit in protective material decreases the amount of potential damage resulting from shipping, but drives up the costs for packing materials and volunteer time. Organizations must balance the increased cost of shipping against the cost of equipment damage and the acceptable failure rate of received computer shipments.

Most providers charge recipients for shipping and some portion of the processing expenses. These charges can vary substantially depending on the computers' ages and models, in addition to shipping fees. Considering the constraints on the recipients' finances and the dependence of the providers on donated funds and volunteer time, there is likely a great deal of pressure to minimize processing and shipping costs.

Cost issues are even more pronounced in the case of for-profit companies. For-profit processors may receive computers as a donation—either directly from the machines' owners or from a recycler's triage process—but they cannot count on donated funds or volunteer time. This situation increases the importance of keeping costs down for for-profit entities since the full amount of processing and shipping will be charged to the recipients.

The for-profit portion of the sector appears to be much larger than the non-profit side (Puckett, 2005; Computer Aid International, 2008; World Computer Exchange, 2009). Also the constraints on the recipient organization are likely much less. Non-profit providers prefer to ship to other non-profit or community organizations or educational institutions and may require the submission of formal plans for the computers' use. For-profit shippers are unlikely to have such concerns.

It is reportedly common among for-profit providers to include a fairly high failure rate in the terms of the contract. These rates may be as high as 75 percent in some cases (Puckett, 2005). Less reputable shippers may not be held to any explicit rate at all. Since it is difficult to enforce contract terms in the international market, the temptation to unload unusable electronic waste on the recipient in lieu of refurbished computers can be substantial. BAN reports that naïve purchasers in developing countries have sometimes found themselves in possession of a shipping container of electronic waste rather than the computer equipment they expected with little recourse for compensation (Puckett, 2005).

Once burned by a bad deal, an importer is unlikely to work with the same source again, so in most cases the amounts and types of equipment are agreed upon in advance. This agreement results from a process of negotiation in which the importer attempts to get as many quality pieces of equipment in the shipment as possible in exchange for accepting some amount of waste. According to Charles Schmidt, "It costs an average of $5,000 to ship a 40-foot container full of used electronics from the United States to Africa . . . ." Given the prices for used good equipment, "it doesn't take many working units to cover shipping costs. Indeed only 40 good Pentium III computers pays for an entire container, leaving a comfortable margin for profit even if the container is loaded with mostly unusable waste" (Schmidt, 2006).

While comparable figures for the non-profit providers are unavailable, personal experience and the providers' guarantees indicate that the failure rates among non-profits are much lower. Computer Aid International includes additional computers with any shipment over 20 machines "to pre-compensate in the event of any machine being damaged in transit" (Computer Aid International, 2009). This would suggest a failure rate closer to 5 than 25 percent. However, regardless of specific rates, any shipment of used computers likely will contain some amount of broken or potentially unusable equipment. An Association for Progressive Communications report points out that this means that "[b]y implication, NGOs that have been refurbishing PCs for educational or other developmental purposes have been taking part in the recycling continuum" (Finlay, 2005).

2.4 Economic scale of the sector

It is difficult to get much information on the scale of the trade in used computers and the refurbished computer market in developing countries. Part of the difficulty is that the international Harmonized Tariff Schedule does not designate codes for used electronics or electronic waste (Puckett, 2005). As a result, shipments of used electronics destined for refurbishment and re-use as well as electronic waste destined for recycling or dumps often are listed as new electronics or as scrap metal (Puckett, 2005).

In many countries—particularly those that have ratified the Basel Convention or the Basel Ban Amendment—the trade may be illegal or operate in a grey area of the law. The Basel Convention allows for trade in usable equipment or equipment destined for refurbishment or re-use, but classifies equipment in need of "major reassembly" or destined for disposal as electronic waste (McKenna, 2007). This definition allows for some wiggle room in describing shipments and provides another motivation for miscategorization of shipments of used electronics. A handful of US states (including California, Maine, Maryland, and Washington) have passed laws along the lines of the Basel Convention (McKenna, 2007), but since the federal government has not ratified the Convention, exporting electronic waste from most states is not illegal. However due to public opinion, most recyclers that export waste do not advertise the fact, and in some cases companies have been found to export waste despite their claims to the contrary (Puckett, 2005).

The lack of reliable data has lead most researchers to rely on secondary evidence to attempt to understand the scale of the used electronics market. Most researchers have attempted to estimate the entire category of used electronics, not just the computer sector.

Elizabeth Grossman, for example, attempted an estimate by observing that in the United States, between five and seven million tons of electronic equipment become obsolete every year (Grossman, 2006). She compared this to reports from the US Environmental Protection Agency (EPA) and the recycling industry noting that only 9 to 12 percent of electronic waste is recycled domestically and concluded that between four and five million tons of electronic waste must be exported from the US annually. This estimate may be high, as it does not seem to account properly for equipment that ends up in domestic landfills or incinerators or what is left in storage. On the other hand, the US Government Accountability Office estimated that relatively few of the televisions rendered obsolete in the US every year found their way to landfills or incinerators and concluded that they were likely still in storage (Stephenson, 2005). A 2008 study by the US EPA estimated that about 77 percent of computer CRT monitors collected by recyclers were shipped overseas, accounting for about 130,000 tons of equipment (US Environmental Protection Agency, 2008). However the EPA study was based on amounts openly reported by legitimate recyclers.

Certainly, the potential source for refurbished and secondhand computers is huge. One estimate is that for every three computers purchased, two become obsolete (Nnorom and Osibanjo, 2008). A 2004 study predicted that worldwide, 150 million computers would be recycled over the next year, while an equal number would be sent to landfills. (Bhuie et al., 2004, p. 77)

Nigerian researchers Nnorom and Osibanjo have argued that the disposal of electronics is driven by the production of new electronics so disposal should roughly track production. Their conclusion was that the global increases in production of electronics of 4.4 percent and 6.8 percent in 2002 and 2003 would be reflected in the waste streams (Nnorom and Osibanjo, 2008). These researchers further argued that due to the high costs of recycling in more developed countries, the main route of disposal of this electronic waste is "through export to developing countries in the name of 'bridging the digital divide.' "

Attempting an estimate of the trade from the demand side may be even more difficult than from the supply side because the destination countries are usually poor and do little formal reporting of imports of used electronics. As with the source countries, trade in electronic waste may be illegal in developing countries. As a result, trade in electronic waste is unlikely to be reported as such.

An investigative report by the Basel Action Network (BAN) in 2005 attempted to estimate the number of shipments of used computers and monitors to the Nigerian port of Lagos. BAN's report, based on survey data from the computer refurbishing market in Lagos, concluded that 500 shipping containers of used computer equipment arrived in the port every month. Assuming an average content of about 400 sets of computers and monitors per shipment, this comes to 200,000 sets arriving in Lagos per month or 2,400,000 sets per year (Puckett, 2005). A rough estimate of 50 pounds per computer and monitor set would give a total of about 60,000 tons of imported used computer equipment per year arriving in Lagos.[1] Most of this trade appears to be from for-profit shippers, and the report found equipment failure rates from 25 to 75 percent.

It is likely that the number of shipments of computer equipment to the port of Lagos is higher than to other cities in Africa. In fact Lagos serves as a wholesale used computer market for many other countries in the region (Puckett, 2005).

[1] This estimate assumes that CRTs and computers are received in roughly equal numbers. If this assumption is wrong, the overall tonnage should remain the same as the average weight of computers and monitors are similar, but the quantity of some hazardous components would be affected. Most notably, a greater proportion of CRTs would increase the amount of lead in the shipments as described in Section 3.1.

However, the numbers for the city of Lagos may help researchers arrive at a rough estimate of the scale of the used computer trade in Africa as a whole. These numbers also show the magnitude of the electronic waste problem in Lagos, because the unusable portion of the computer equipment that arrives there is unlikely to leave the area.

Computer Aid International, perhaps the largest non-profit computer provider, shipped 28,712 computers to educational and community organizations in the 2007–2008 financial year (Computer Aid International, 2008). World Computer Exchange reported shipping 3,526 computers in fiscal year 2008 (World Computer Exchange, 2009), with about half shipped to sub-Saharan Africa and the others to countries in South Asia, South America, and the Caribbean. Clearly the number of machines provided by non-profits is substantial, but significantly smaller than the overall number of refurbished machines purchased per year in developing countries.

Researchers in South Africa have estimated that the number of active personal computers (PCs) in the African continent range from 1.5 million to 7.5 million—making the ratio of computers to people between 1:500 and 1:100 (Finlay, 2005). This estimate seems remarkably low give the calculation of 4.8 million second-hand computers entering Lagos each year—even if only 25 percent of them are usable—and estimates that between 1.2 million and 1.5 million computer are imported into South Africa every year (Finlay, 2005). The e-Waste Association of South Africa (eWASA) claims that, based on interviews with refurbishers in the country, “PC refurbishers currently import anything from 20,000–100,000 units a year into South Africa.” (Liechti and Finlay, 2008, p.23) The eWASA estimate for the total number of *new* PCs imported into South Africa annually is 1,020,000, which aligns roughly with the 1.2 million estimate above.

In the case of South Africa, there is a substantial amount of electronic waste exported to Europe or Asia for further processing. The capacity of recyclers in South Africa is not developed enough to recover all of the material components. As a result, “[s]hredded plastics that may still include some metals, such as copper, are sent to China, where hand-sorting allows for a finer extraction of re-usable materials. PC boards, when they are extracted, are sent to Rotterdam.” (Finlay, 2005, p. 9)

In addition to Nigeria and South Africa, known destinations in Africa for used computers include Mombasa, Kenya; Dar es Salaam, Tanzania; and Cairo, Egypt (Schmidt, 2006). However, due to the lack of data few conclusions can be reached about the nature or volume of the trade.

3 Environmental aspects of disposal and recycling

Most analyses of the use of secondhand and refurbished computers in developing countries concentrate solely on the private benefits and costs. This is appropriate for those interested in stocking their labs with equipment and purchasing computers for their own organizations. However, in the overall context of development this type of analysis ignores the environmental effects external to the private exchange. For government entities or organizations interested in broadly promoting development through the provision of information technology, consideration of these external environmental effects should play a more important role. This section will look at what types of environmental impacts occur as a result of the disposal and recycling of computers.

In general, computers are not dangerous in the context of normal, day-to-day handling despite the numerous toxic chemicals and materials that make up their components. The vast majority of toxic materials in computers are embedded in solid parts and do not present an exposure risk to people from daily use. The risk associated with hazardous components is most pronounced when computer equipment is disposed of in inadequately protected landfills or when parts are processed for recycling.[2]

When computer equipment is disposed of or recycled the hazardous contents can be released into the environment or new hazardous chemicals can be created from the processing itself. Some forms of processing required for recycling use toxic solvents that are then discharged into the environment. While processing seems to be the major cause of the release of hazardous material, disposal is not

[2] A few compounds can, however, affect people through normal daily use. Most notable are some brominated flame retardants, especially deca-BDE, a form of polybrominated diphenyl ether (PBDE) that is used in plastic computer casing and parts as a fire retardant. One study in 2004 showed that dust samples taken from the surface of computers showed elevated levels of deca-BDE and other neurotoxins (McKenna, 2007).

always a better alternative. Equipment that is dumped in unlined landfills—as is the case in most developing countries—can react with water and leach chemicals and heavy metals into the area's surface- or ground-water.

Few people in the recipient areas are aware of the dangerous nature of electronic wastes. A report from the Association for Progressive Communications (APC) notes that in a survey of 18 African countries, "with the exception of South Africa, electronic waste (e-waste) was given little or no priority in the countries surveyed. Instead, the problems with waste management were far more basic, and included a lack of awareness of hazardous waste, and inadequate legislation, controls and facilities to deal with waste" (Finlay, 2005).

As the quantity of electronic waste increases it is likely that more intensive recycling processes will be used to recover the valuable contents. Much of the more hazardous electronic waste processing—such as heating circuit boards to recover metals—is currently confined to China and South Asia. An investigation by the Basel Action Network in 2005 found little evidence of this type of processing in Nigeria (Puckett, 2005). Instead, the recycling efforts were focused on recovering working components from otherwise unusable computers and dumping the rest in landfills. However, because electronic waste contains valuable recyclable elements it seems highly likely that more intensive processing will begin to develop in the future if it has not done so already. In the United States, the value of the material recoverable for recycling—about 55 percent of the total computer contents—was about $34 in 2004. Even trace elements of minerals can be quite valuable. For example, the typical desktop computer is composed of about 0.0016 percent gold, 17 times the concentration found in raw gold ore (Nnorom and Osibanjo, 2008).

Material	Percent of total weight of PC & CRT (~26 kg)
Silica	25.0
Plastics	23.0
Iron	21.0
Aluminum	14.0
Lead	7.0
Copper	7.0
Zinc	2.2
Tin	1.0
Mercury	1.0
Nickel	0.8
Silver	0.02

Table 1: Approximate contents of a computer and CRT monitor (Bhuie et al., 2004).

3.1 Electronic waste contents

A general breakdown of the primary components of a combined computer and cathode-ray tube (CRT) monitor is shown in Table 1. The largest component by weight is silica, primarily in the form of glass CRT tubes. A variety of plastics comprise the second largest item, used in computer and CRT cases, connectors and insulating materials. Iron and aluminum are used for structural components and copper is used in electrically conducting wires—particularly in the magnetic coils in the yoke of CRT screens. Other than plastic, these materials are not ones that are commonly thought of as hazardous, however in an open landfill these metals can leach into surface- and ground-water with possible health implications for those who drink the water. Some heavy metals bioaccumulate in plant and animal tissue in which case they may be passed on to people through the food chain.

Lead is one of the materials of greatest concern in electronic waste. Much of this is found in CRTs, which are known to be one of the largest contributors of lead in municipal waste. In 2000, CRTs (including both televisions and computer monitors) contributed about 29 percent of the lead in municipal solid waste in the United States (Nnorom and Osibanjo, 2008). CRTs contain between two and four kilograms of lead each, about 8 percent of the monitor by weight (Nnorom and Osibanjo, 2008). Most of this lead is embedded in the glass of the CRT itself where it provides shielding from the x-rays produced by the cathode-ray generator. As the use of CRTs drops off in favor of flat-screen LCD panels the amount of lead in electronic waste should decrease, but it will be years before the currently installed base is disposed of. There may even be an increase in CRT disposal in the short term as consumers in the United States replace analog CRT televisions with digital ones. A smaller source of lead in electronic equipment is the lead-tin solder used to connect electronic components to the printed circuit boards. Lead is also found in the form of lead sulphate in the PVC plastic sheathing used for cable insulation.

The electronics industry has been under pressure from international legislation and markets to move to lead-free alternative materials (Nnorom and Osibanjo, 2008). As a result, most of the concern over lead applies to the printed circuit boards in older electronics and, of course, older CRTs. Unfortunately some substitutes for lead solder have been shown to be a potential source of hazardous contaminants themselves. One common replacement solder alloy may leach excessive amounts of silver (Nnorom and Osibanjo, 2008).

Mercury is an extremely toxic heavy metal used in a variety of electronics. One of the most notable uses is in the fluorescent tubes used for back-lights in liquid crystal displays (LCDs) such as in flat panel screens and laptops. This unfortunately means that as the proportion of lead waste decreases due to the industry's shift away from CRTs, the proportion of mercury waste may increase. Other common uses of mercury are in batteries and switches.

The plastic that makes up a large portion of computers and CRTs is usually impregnated with brominated flame retardants (BFRs). These are usually in the form of polybrominated biphenyls (PBBs), polybrominated diphenyl ethers (PBDEs), or tetrabromobisphenol-A (TBBPA) (EMPA, 2008). These compounds are added to the plastic cases and cable housings to make them more fire resistant. BFRs can escape the plastic through evaporation or leaching and can be found in the dust on computer parts, however the more serious concern is the chemicals that are released or created when the plastic is burned. Under pressure from legal agreements like the European Union's Restrictions on the Use of Certain Hazardous Substances (RoHS) Directive, manufacturers are phasing out the use of BFRs, but again, it will be years before this change works its way through the waste stream (Bhuie et al., 2004).

In addition to these materials there are numerous other compounds found in small or trace amounts in electronic equipment. Table 2 lists many of the additional hazardous substances and the components in which they can be found.

3.2 Effects of processing

Although some of the hazardous contents of electronic waste will leach out into ground- and surface-water after dumping, much more is released into the environment from the processing used to recover recyclable material. The workers themselves experience most of the exposure resulting from this processing although the surrounding area and population will also be affected when newly exposed material dumped in landfills increases leaching, and fumes and smoke pollute the air around processing centers. While by no means exhaustive, the following examples illustrate how hazardous materials in a relatively safe contained form are released through processing.

A common practice for recycling copper from CRT monitors is to break off the

Hazardous substance	Found in
Halogenated compounds:	
Polychlorinated biphenyls (PCBs)	Condensers, transformers
Tetrabromo-bisphenol-A (TBBA), polybrominated biphenyls (PBBs), polybrominated diphenyl ethers (PBDEs)	Fire retardants for plastics (thermoplastic components, cable insulation) TBBA is presently the most widely used flame retardant in printed wiring boards and casings.
Chlorofluorocarbon (CFC)	Cooling unit, insulation foam
Polyvinyl chloride (PVC)	Cable insulation
Heavy metals and other metals:	
Arsenic	Small quantities in the form of gallium arsenide within light emitting diodes
Barium	Getters in CRTs
Beryllium	Power supply boxes that contain silicon controlled rectifiers and x-ray lenses
Cadmium	Rechargeable NiCd batteries, fluorescent layer of CRT screens, printer inks and toners, photocopying machines and printer drums
Chromium VI	Data tapes, floppy-disks
Lead	CRT screens, batteries, printed wiring boards
Lithium	Li batteries
Mercury	Fluorescent lamps that provide back-lighting in LCDs, some alkaline batteries and mercury wetted switches
Nickel	Rechargeable NiCd batteries or NiMH batteries, electron gun in CRTs
Rare earth elements (yttrium, europium)	Fluorescent layer of CRT screens
Selenium	Photo drums in older photocopying machines
Zinc sulphide	Interior of CRT screens, mixed with rare earth metals
Others:	
Toner dust	Toner cartridges for laser printers and copiers
Radioactive substances:	
Americium	Medical equipment, fire detectors, active sensing element in smoke detectors

Table 2: Hazardous substances found in electronic waste (EMPA, 2008).

yoke at the end of the tube where the spools of copper wire are located. The rest of the tube is then often dumped in open dumps or rivers. (Finlay, 2005) The lead in the CRT glass is exposed to water and may leach into the environment. Keith et al. (2008) show that potential lead leaching from whole, unbroken CRTs is minimal, however when the glass is broken into smaller pieces the leaching increases. "Lead leaching from broken CRT glass and [printed circuit boards] therefore poses significant health and environmental hazards" (Keith et al., 2008).

Processing of printers releases the toner that can then be recycled or resold. In Guiyu, China, for example "[w]orkers without any protective respiratory equipment or special clothing of any kind open cartridges with screw drivers and then use paint brushes and their bare hands to wipe the toner into a bucket." (Finlay, 2005)

Electronic components are commonly recovered from circuit boards by heating the board to melt off the lead-tin solder that connects chips and other components to the boards. Daily exposure to the lead-tin solder fumes is likely damaging to the workers' health (Finlay, 2005). The processing also affects the surrounding community. Huo et al. (2007) investigated blood lead levels in children living in Guiyu and found that "[l]ead contamination from e-waste processing appears to have reached the level considered to be a serious threat to children's health around the e-waste recycling area." Blood lead levels in children are particularly concerning as it can stunt growth and impair neural development. Blood lead levels have been shown to be inversely associated with IQ levels and academic scores (Huo et al., 2007). Cadmium may also be released into the environment through this type of processing. Significantly elevated blood cadmium levels were also found in the children of Guiyu in an additional study (Zheng et al., 2008). Cadmium is a known carcinogen and can accumulate in the body and cause long-term renal damage (Zheng et al., 2008).

In addition to simply releasing hazardous compounds, electronic material is often burned or otherwise treated in a way that creates new, potentially hazardous compounds. For example, in order to recover copper wire the plastic insulation is often burned off. While the insulation is not particularly hazardous in its initial form, when burned it is likely that "the emissions and ashes [...] will contain high levels of both brominated and chlorinated dioxins and furans—two of the most deadly persistent organic pollutants (POPs). It is also highly likely that cancer-causing polycyclic aromatic hydrocarbons (PAHs) are also present in the emissions and ash" (Finlay, 2005). Wang et al. (2005) studied soil and river sediment samples from Guiyu for levels of PBDEs and found that "[u]ncontrolled recycling and disposal of e-wastes by simple dismantling, acid treatment, and open burning have resulted in severe soil contamination and migration of PBDEs into the river system." PBDEs have been shown to bioaccumulate in fish and can then affect people through eating fish (Luo et al., 2007). Tissue samples from tilapia and bighead carp from rivers near Guiyu have been found to have high concentrations of PBDEs (Luo et al., 2007).

Once most of the components have been stripped off by melting the solder, the remaining circuit boards may be burned and the ashes sifted for traces of valuable metal such as gold and palladium. The burning circuit boards likely release large quantities of heavy metals, dioxins, beryllium and PAHs (Finlay, 2005). Li et al. (2007) sampled ambient air quality in Guiyu and the surrounding region for levels of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) and polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs). They found both PCDD/Fs and PBDD/Fs at very high pollution levels and concluded that the "total PCDD/F intake doses far exceed the WHO 1998 tolerable daily intake limit" (Li et al., 2007). The study further found that "daily intake doses of children were about 2 times that of adults [...]. Thus, it is not surprising that children are the most severely affected by bad air quality in [Guiyu] and that 80% of children there suffer from respiratory diseases" (Li et al., 2007).

In more thorough recovery efforts, additional hazardous chemicals are used to process electronic equipment. In order to recover trace elements of gold and other precious metals, chips and other components are dipped in a bath of aqua regia, a mixture of nitric and hydrochloric acids. The acid is highly corrosive and harmful to any skin exposure and is also unstable and emits chlorine and nitric oxide gases of its own volition. When used to process electronics it also emits sulphur dioxide gas. Workers processing chips in Guiyu, China, are routinely exposed to the corrosive acids and toxic fumes with only the protection of rubber boots and gloves. (Finlay, 2005)

The result of all this processing can result in dramatic levels of local pollution as noted in a 2000 investigation in a processing area in southern China:

> An investigative team took one water sample, one sediment sample, three soil samples in one area along the Lianjiang River, where circuit boards had been treated with acid and fire, and then were dumped charred along the banks. The test results revealed alarming levels of heavy metals that correspond very directly with metals most commonly found in computers. The single water sample taken by a reporter in 2000, adjacent to a location where circuit boards had been processed and burned in the past, revealed lead levels that were 2,400 times higher than World Health Organization (WHO) Drinking Water Guidelines. (Finlay, 2005)

While this processing of waste can provide an income, the cost to the health of the workers and the neighboring community appears very high. Furthermore many of those involved in the work are women and children who are more susceptible to the long term health effects of these hazardous products. Schmidt (2006) criticized the exploitative nature of the work: "While the [recovery] practice does have its benefits, [...] it also exploits women and child laborers who cook circuit boards, burn cables and submerge equipment in toxic acids ...."

The result of all the processing taking place in Guiyu, China, is that the region has become widely polluted and will likely remain that way for years, "[a]lready Guiyu has become so polluted that well water is undrinkable and water has to be trucked in for the entire population ..." (Finlay, 2005).

As noted above, the level of recyclables processing in Africa has not yet reached the same intensity as in China and South Asia. Recycling efforts in Africa have so far been largely concerned with recovering copper wire and functional electronic components while the remaining material is often dumped. Some researchers have argued that the concern over dumping of electronic waste is misplaced and should, in fact, focus on the processing of the material. Dumping itself may not present a serious problem if it is managed correctly. Williams et al. (2008), for example, noted that "the risk of leaching of toxic materials in computers from well-managed sanitary landfills is very small. On the other hand, there is an increasing body of scientific evidence that the environmental impacts of informal recycling in developing countries are serious."

Arguments over the risk of dumping material in sanitary landfills is largely moot, however, since few such landfills exist in Africa outside of South Africa. In Nigeria, a case study of mobile phones found that the discarded electronic wastes

> ... are usually collected within inhabited areas and burned to reduce the waste volume before final disposal at unlined landfills. These landfills are usually burning and none of such landfill facilities are lined, or monitored, or possess leachate recovery systems of any kind. Be-

> cause landfills in Nigeria and most other developing countries are not lined and/or do not use appropriate technology, such landfill leachates will end up in surface water bodies used for domestic purposes. Even in controlled landfills, leaching of metals and other toxic or hazardous substances must be expected. (Osibanjo and Nnorom, 2008, p. 210)

As learned in more developed countries, processing and dumping can both be managed in an environmentally responsible manner, but at the cost of a significant investment in equipment and training. The dangers associated with recycling and dumping are primarily associated with the informal, ad hoc management found in developing countries today. Properly managed, recycling in developing countries should be able to provide an economic benefit with minimal environmental cost. Unfortunately, the investment needed to achieve this has not been made.

4 Benefits and Costs

There is no question that access to computers and information and communication technology (ICT) is critical for taking part in the modern global economy. It can no longer be argued—as it was in the last century—that an emphasis on ICT detracts from the achievement of other goals. Instead ICT has in many situations become an essential tool for reaching development goals. As Computer Aid International argues, computers have been instrumental in improving education, access to health care, services for disabled people, improving food security, and generally providing connectivity to improve economic viability (Computer Aid International, 2008).

It is not the intent of this paper to question this point, but instead to point out some of the environmental costs of this development and to suggest some approaches to reduce the waste impact. As noted earlier, many development efforts promote the use of secondhand and refurbished computers as a low-cost and environmentally responsible way to develop the ICT sector in developing nations.

4.1 Assessing refurbished computers

Assessing the full costs and benefits of computers—and especially secondhand and refurbished ones—is an enormous and complicated task. The variations in usage patterns, quality of original products, and environmental conditions make a systematic comparison very difficult and well beyond the scope of this research. Perhaps because of the complexity, few thorough studies have been made of the issue, but some impressive analyses can be found in reports by Open Research (2004), Bridges.org (2004), and Paterson (2007).

4.1.1 Values by price

One way to get a sense of the perceived benefits of used and refurbished computers is simply to look at the prices paid for them in for-profit market exchanges. Unfortunately the prices for refurbished computers are highly variable since they are subject to costs of shipping, taxes, duties, and labor—whether in the donor or recipient country (Open Research, 2004). Considering the variability in the types and qualities of used computers received, the differing amounts of refurbishment, and that recipients often pay for them ahead of time, sight unseen, it is not clear that the price paid is very reflective of the ultimate value of the computers.

The blurry line between secondhand computers and electronic waste means that the sector often operates in some legal grey areas and it is not surprising that accurate estimates of value are hard to come by. As noted earlier, shipping containers of what is largely waste may be labeled as new or used electronic equipment and comprise as little as 25 percent usable computers. Customs documents are unlikely to give a very good idea of the equipment's true value in this scenario. In Nigeria it is reportedly common to see used computers cleaned, painted, and resold as new so the end consumers may not have an accurate idea of the value of the machines they are buying either (Puckett, 2005).

Table 3 lists rough estimates of prices across Africa for used and new computers in 2004. The lack of detailed specificity in the data limits its usefulness, but it does give a good idea of the wide variability in pricing across the continent. By comparison, World Computer Exchange—a non-profit—provides a mix of Pentium 3 and Pentium 4 computers for US$65 plus the cost of shipping as of 2008 (World Computer Exchange, 2009). Shipping costs for a full container would add about US$12.50 to this price according to Schmidt (2006). Assuming that these are about the same specifications as the used computers on the market today, this

Country	New (US$)	Used (US$)	Notes
Cameroon*	507	-	
DRC*	1246	200	
Ethiopia*	1493	-	
Ghana*	997	-	
Kenya*	1625	249	
Malawi*	600	-	
Namibia*	871–1045	-	New is US$522–US$871 if bypassing reseller
Nigeria*	300	150	
South Africa*	828	-	
Tanzania*	350	-	
Uganda*	463	-	Brand name=US$1000
Zambia*	1719	644	
Zimbabwe*	795	-	
Denmark*	806	-	
India*	453	-	
via WCE†	-	65	
via Computer Aid‡	-	177	

* Prices estimated by African programmers attending the Africa Source workshop in Okahandja, Namibia, March, 2004. PC quality varies. Prices converted using www.xe.com currency converter, December 2004 (Open Research, 2004).

† (World Computer Exchange, 2009)

‡ (Computer Aid International, 2009)

Table 3: Comparison of new and used computer prices.

makes the non-profit rates one half to one tenth the cost of the for-profit competition while new computers run another two to five times the price of the for-profit used machines. These estimates illustrate the attractiveness of used computers for relatively poor individuals and institutions.

A problem with using price comparisons in the context of non-profit development programs is that the comparisons do not account for variations in consumer purchasing power and differences in the value of money between countries. Williams et al. (2008) note that the difference in price between new and used equipment in developing countries is relatively much larger than it is in developed countries. If, for example, the difference between the cost of a new computer and a used one is $500, that represents a much larger portion of the consumer's budget in a poor country than in a wealthy one, even when holding the price constant in absolute terms. This point strengthens the argument for using refurbished computers beyond the simple absolute price estimates. Unfortunately, this simplistic comparison still ignores the very real differences in what the consumer receives when purchasing new or used computers. The next two sections will look alternative ways of assessing used computers.

4.1.2 Estimating lifetimes

One of the key factors when estimating the value of a given computer is predicting its lifetime. If a computer is donated to a provider after three or four years of use, how much longer should the provider expect it to continue to operate?

Nearly any computer can have its life extended by continuing to replace failing components, but at some point this process will result in what is essentially a new computer at the cost of a great deal of maintenance time and expense. An appropriate definition for end of life is probably similar to the Basel Convention's definition of waste as that requiring "major reassembly." Most estimates seem to align roughly with this definition although few explicitly define when a computer should be considered at the end of its life. The range of estimates gives an average total lifespan of between seven and ten years before a computer become unusable.

If a computer has been used by its first owner for three or four years prior to donation, then by this estimate it should last another four to seven years. Computer Aid International uses the conservative end of this spectrum, estimating that a refurbished Pentium 4 or equivalent computer should provide three years, or 6,000 hours of service (Computer Aid International, 2008).

Note that these estimates are average values and that there will be significant distinctions among used computers. One distinction is how much—if any—work has been put into refurbishing the machines. If failing or weak parts are replaced during refurbishment then the computer as a whole should expect a longer lifetime. Another distinction is that between heavily-used and lightly-used computers; even computers the same age can exhibit differences in expected lifetimes and usability due to the patterns of use and environment they were subjected to. Finally there may be notable distinctions in quality between brand-name computers known to be built to internationally recognized standards and those from smaller companies or "white box" assemblers that may or may not meet the same standards (Open Research, 2004).

The usage pattern of a computer after it has been refurbished and redeployed is a key part of the expected lifetime equation. Computers that are kept clean, maintained, and protected from heat and dust will naturally last longer, but at some cost to the owners. Unfortunately, these conditions are often difficult to maintain in developing countries. Computers in developing countries may be exposed to more heat, dust, and humidity than is common in more developed nations resulting in shorter lifetimes or increased maintenance costs (Open Research, 2004).

Another key contributor to shortened computer lifetimes in many developing countries is exposure to inconsistent power—both surges and outages. Uninterruptible power supplies (UPS's) are often used to provide emergency battery power to computers to address the possibility of unexpected power outages. UPS's can help extend the life of computers and allow for their orderly shut down, but because they generally only provide about 15 minutes of power they do not help with extended power blackouts. Also the damage that might have occurred to the computer often affects the UPS instead. UPS's are less expensive to replace than computers, but their use still results in higher costs.

Running computers on solar power can make a dramatic improvement in computer lifetimes. Open Research (2004) claims to see a doubling or tripling of the expected lifetime of a computer running on solar power, but the cost of the required solar panels and batteries can be prohibitive.

Another strategy for extending the life of computers is to deploy the machines as "thin clients" that receive their operating system from a server over a local network and may push most of the processing onto the server as well. These machines will likely have a longer lifetime as they experience less wear on the hard drive—indeed the hard drive may be removed entirely—and they have less need for high power components and large amounts of memory.

Since the expected lifetime is an average across computers, when a population of machines approach their expected end of life they will not all fail at the same time. Some will fail before the expected failure date while others will continue to function well after that. Also as computers reach end of life they may experience other minor component failures before they need to be disposed of. This increasing failure rate is illustrated in the "bathtub graph" shown in Figure 2 (Open Research, 2004). This graph shows the general failure rate of a population of equipment over time. The failure rate is high at the left side of the graph reflecting fail-

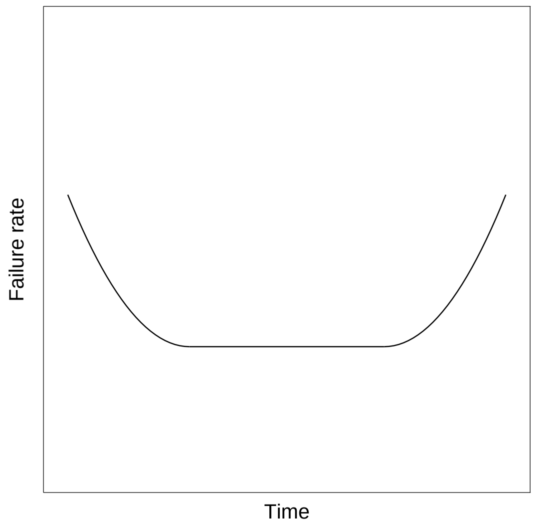

Figure 2: Bathtub graph of equipment failure over time

ures occurring shortly after manufacturing due to material defects and assembly errors, following this is a flat, low level of failure for most of the equipment's expected life before the rate increases again as parts begin to break down due to usage.

The bathtub graph demonstrates one problem with attempting to make use of computers up to the point of total failure. In the context of an individual with one computer this is unlikely to be a concern, but in a larger installation such as a computer lab in a school or community institution the increasing failure rate as the expected end of life approaches is likely to push up maintenance costs and lead to haphazard replacement in an ad hoc, unplanned manner. Trying to eke out every bit of functionality from computers may consequently result in higher costs and less productivity.

4.1.3 Estimating capacities

The bathtub graph assesses the failure rate of an entire population of computers. Another way to assess a computer is by looking at its total expected productiv-

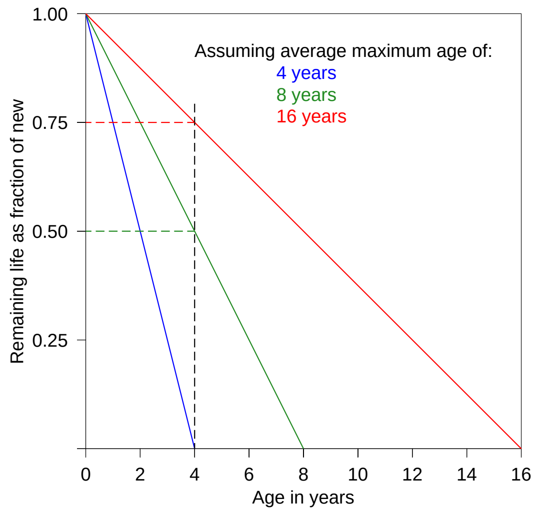

Figure 3: Relative linear depreciation by age

ity. One simple way to do this is by using linear depreciation. Here the value of a computer is based on its average lifetime less its current age. If the average computer is expected to last eight years, then a four-year-old computer still has half its life left. This depreciation is illustrated in Figure 3. The depreciation for the different estimates are all scaled to one to show the depreciation of a used computer relative to purchasing a new machine. These depreciation lines are calculated as the maximum expected lifetime minus the current age divided by the maximum expected lifetime $((max - age)/max)$. The dashed intercept lines in the figure show the remaining lifetime of a four year old computer under the different assumptions for the average maximum lifetime of computers. Casual conversations with computer donors suggest that this depreciation model may often be used by donors to assess the value of used computers. If so, they may be overestimating the computers' values, particularly when taking into consideration the value of new computers entering the market.

In addition to ignoring the equipment failure problem shown in the bathtub graph, the linear depreciation model fails to consider the enormous speed of development of new information technology. Moore's law—after Gordon Moore, an Intel engineer—famously posits that the density of transistors on affordable computer chips doubles every 18 or 24 months. While not a true "law" this remarkable trend has been roughly consistent since it was first stated in 1965. The significance of increasing density is not just to make parts smaller, denser chips also run faster, use less energy, and hold more information. As a result personal computers today run thousands of times faster than their predecessors just a few years ago and cell phones for sale on the street in Nigeria for about US $15 have more processing power than the room-sized mainframe computers of just a couple generations ago.

In order to get a better sense of the true value of used computers I have combined this exponential growth effect with the linear depreciation model to generate what could be called the relative lifetime capacity (RLC) of a used computer. While clearly not a precise calculation I think this gives a better impression of computer values. The term capacity is used as a generic stand-in for the technical capabilities of a given machine. For simplicity, assume that all advances in computer technology can be rolled into the processing speed. Then the lifetime capacity would be the total number of calculations that a computer can make during its lifetime. Following Moore's law, a computer that is 18 months old will be able to make only one half the calculations that a newly constructed computer would in a given amount of time. Therefor the total expected calculations relative to a new computer would be one half the rate of a new computer multiplied by the remaining years in its expected life. Although it is not the case that all computer development results in faster processing speed, this calculation should give a rough approximation of the exponential effect of the combination of processing speed, advances in power usage, miniaturization and increased memory size. Accordingly the relative lifetime capacity is calculated as:

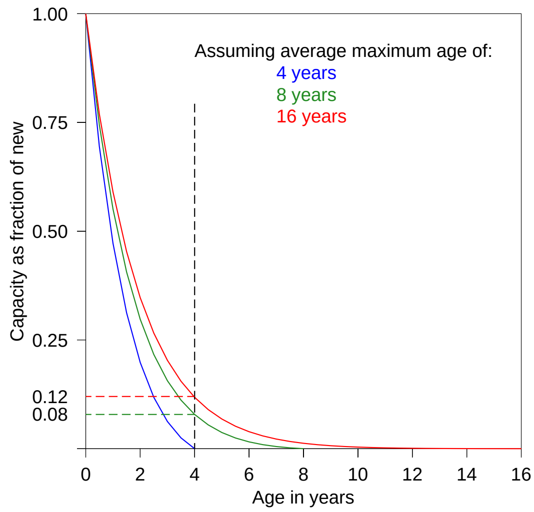

Figure 4: Relative lifetime capacity by age

$$RLC = 2^{(-age/1.5)}\left(\frac{max - age}{max}\right)$$

The RLC formula ignores differences in price since the prices of new computers have been reasonably consistent over these kinds of time frames. If anything, prices have tended to drop for machines in the same relative class.

In addition to making intuitive sense, the RLC seems to be reflected in market prices. According to a report by Open Research the estimated value of a computer at an age of five years is roughly 3 to 5 percent of the original value (Open Research, 2004). This is consistent with the relative lifetime capacity calculation when assuming an average maximum lifetime of eight years. The RLC in this case would be 3.7 percent.

The RLC curves corresponding to the previous linear depreciation curves are shown in Figure 4. This gives a dramatically different impression of the value of a used computer. Once again an assessment of four-year-old computer values is shown by the dashed lines, but results in notably lower values than result from simple depreciation. While a machine may be usable for the same total period of time, the capacity of new computers will have increased so dramatically that the value of a used computer becomes negligible well before it actually reaches its end of life. This is particularly true if we assume that the average life of a computer is sixteen years. In fact it is striking how similar the curves are for average maximum ages of eight and sixteen years. After the first few years it makes little difference how long the computers are expected to survive. The effect of exponential growth in new capacity far outweighs the effect of the computers' long lives.

The RLC graph illustrates why it has become common for computer owners to plan on upgrading every four years or so. If a computer is expected to survive for eight years, then at four years old it has only about 8 percent of the capacity of a new computer. The refurbished and second-hand computer sector can be seen in this light as harvesting that remaining 8 percent of a computer's usable capacity prior to disposal.

4.1.4 Computer donation lag time

The equipment failure rates described by the bathtub graph are largely due to equipment usage so storing computers away should put much of the effect on hold. However the relative lifetime capacity describes an effect that is primarily external to the machine itself. Whether a computer is stored or used for a year makes little difference to its capacity relative to a new machine. This points to a serious shortcoming in the timeliness of using secondhand computers for development efforts: donation lag time.

Williams et al. (2008) report that "...computers are often stored unused in closets for years before being resold or otherwise disposed of. There are important questions to answer regarding how a timely flow of quality used equipment might better contribute to mitigating the digital divide." A variety of other researchers also describe this problem. It is suspected that enormous numbers of computers are currently stored away in closets and garages in developed countries because the owners either do not know what to do with them, do not want to pay to dispose of them, or think that they may still have some value (Grossman, 2006). Unfortunately, if the RLC is any guide, every year and a half the relative capacity of these unused machines is cut in half.

This behavior seems to occur around the world and is exhibited by large institutions as well as individuals. As Finlay (2005) notes, the same effect occurs in South Africa, "Reasons for storage include difficulties in writing assets off from registers, fears relating to data security, a lack of awareness of where to dispose old technology, and psychological factors, such as the belief that old technology has some value." In fact, in South Africa, "[a]bout 70 percent of the country's e-waste is thought to be in storage—most of this held by the government."

There is a tremendous opportunity here to reduce the waste of computer resources by simply increasing the timeliness of used computer donations.

4.1.5 Maintenance and configuration costs

As most computer system administrators know and as research confirms, an installation of several uniform computers can greatly reduce the average total cost of ownership per computer (Open Research, 2004). This results from cost savings in setup and maintenance as well as the fact that having many identical computers means that some can be used as parts for others. Having a variety of refurbished computers limits access to parts within the installed pool as well as likely making it more difficult to find parts on the market. Of course, the older the computer the more difficult it will be to find parts as well.

Addressing this issue can be a challenge for providers dependent on donated computers, particularly if they accept donations from individuals. A collection of computers received this way is unlikely to have much uniformity, requiring the eventual recipients to need to maintain a wide variety of different types of machines. Perhaps the best way to increase uniformity is to encourage donations of used computers from large organizations that are likely to rotate out their computers on a regular basis and to have a uniform collection of computers to begin with.

Another way to reduce maintenance and configuration costs is by using a collection of computers as thin clients. As mentioned earlier, the thin client computers access their operating system over a local network from a server computer and then run most of their programs on the server. Not only does this reduce wear on the clients, but all the configuration and installation can be done on the server reducing the work load of the technical staff dramatically.

The thin client approach has been used very successfully in a number of development efforts, but it is not a panacea and is not appropriate in every situation (SchoolNet Africa, 2004; Bridges.org, 2004). In order to deploy thin clients, an installation must have at least one fairly high-powered computer to operate as the server for up to ten or twenty clients. This makes it more appropriate for moderate to large computer labs rather than small offices and homes. Also the technical knowledge required to setup and operate a thin client lab, while not difficult, is relatively uncommon and requires a learning curve. Finally there is the requirement to provide a fairly high level computer for the server in addition to the low level clients and the networking equipment to connect them together. But given these conditions, a thin client lab can be a very economical approach to computer lab deployment.

4.1.6 Processing as economic development

Deployment of used computers can have economic benefits outside the structures of the recipient organizations. One of the more notable possibilities is the development of a local reuse and refurbishing sector. As noted earlier, several of the non-profit providers of secondhand computers use the refurbishing process as a technical training opportunity in developed countries. An alternative to this is to move the refurbishing processes to the developing country. SchoolNet Africa in particular recommends that refurbishment be done largely by local technicians rather than in donor countries (SchoolNet Africa, 2004). Open Research also emphasizes the role of local refurbishing as an economic center. They cite the activity's importance in terms of skills development, knowledge transfer, and more broadly as social and economic development (Open Research, 2004).

Unfortunately, this makes the already murky determination of what qualifies as electronic waste even more difficult. Non-profit providers have attempted to be conscientious about avoiding the shipment of waste by ensuring that machines are refurbished and tested prior to shipping. If the refurbishing phase of the operation were moved to the recipient nation, then the proportion of waste in the shipments would inevitably increase. Presumably the computers could still be tested prior to shipping, but testing and refurbishing are often two sides of the same procedure. Splitting this process in two might increase costs and result in duplicated effort. Another way to reduce the problem of shipping untested machines could be to set requirements for the age of donated computers rather than testing the individual units. Presumably, newer computers would be more likely to be functional and so there might be less need to power-on each one to determine its usability.

The eventual disposal of the computers can also be considered in light of the economic benefit. According to a study in South Africa, "grassroots e-waste projects currently piloted demonstrate that at least a minimum wage is possible through the manual dismantling of discarded technology. The assessment suggests that more new PCs are sold into the market each year than are recycled, which illustrates the opportunity for job creation and economic development presented by e-waste" (Liechti and Finlay, 2008). The extent to which the downstream recycling sector is affected by the choice of whether to deploy used computers depends on the functional lifetime of the machines. If used computers are expected to have half the lifetime of new, then choosing to deploy them in large enough numbers could dramatically increase the rate at which computers move into the recycling and disposal stage. This can have significant environmental ramifications if the procedures are done poorly.

Not everyone agrees that secondhand computers will provide an economic benefit to the recipient countries (Puckett, 2005). Instead, some argue that the importation of used computers may undermine the production of new systems just as the importation of used clothing has damaged the clothing production sector in many areas. Shina Badaru, editor of Nigeria's *Technology Times*, says "[w]hat Africa needs as a start off, is the ability to evolve its own info tech industry . . . to support its own local system builders, to be able to evolve its own local computers, to be able to write software coded in its own local languages, to meet its own local need [. . .]. Africa does not need the used equipment coming in from the North to come in and continue to pose long-term environmental threat to our environment" (Puckett, 2005, p. 28).

However, it is not clear that the used computer market competes directly with the new production as Badaru appears to imply. Considering the stark differences in price and capacity between new and used, these products may apply to completely different portions of the market. Those interested in purchasing a used computer might simply not buy a computer at all rather than buy new if the used option were removed.

4.2 Alternatives

This paper is primarily concerned with issues around reducing the environmental impact of using used and refurbished computers for development. However a brief mention of some of the alternatives for developing the ICT sector are in order.

The standard approach for comparing computer values has been the total cost of ownership (TCO), a comprehensive estimate of the cost of a computer from purchase to disposal including maintenance and other incidentals. But Open Research notes that TCO calculation methods are adapted to first world environments and have not been used much in situations like those experienced in Africa or other developing regions (Open Research, 2004). The calculations are likely to be thrown off because installations are generally done at a smaller scale, are subject to harsher environments and inadequate infrastructure, supported by less skilled workers and have access to a smaller technology market.

4.2.1 New computers

The most obvious alternative is to deploy new computers. The advantages of doing so would be to be able to access the full lifetime capacity of the machines and to extend the useful life of an installation. New machines should be expected to last the full average lifetime rather than just the remaining portion after the initial owner's usage. Two other advantages may be the increasing energy efficiency of new computers and the lower usage of some toxic components such as lead solder. However, considering the fast turn-over for new computers, these improvements should be apparent in donated computers within a couple years if they are not already.

The clearest disincentive for using new computers is simply the financial cost.

The developing country recipients of the computers are unlikely to have the funds to afford many new computers, particularly when considering their economy's relative purchasing power. A used computer at 5 to 10 percent of the price of new becomes a very attractive option in this situation.

From a global environmental perspective, it also makes sense to choose used over new since the energy costs of computer fabrication far outweigh the energy used during a machine's lifetime. In fact, "the total energy used to manufacture a desktop computer could be as high as 4 times greater than the electricity consumed by this computer while in use ..." (Williams et al., 2008). However it would be disingenuous to argue that developing countries should use secondhand computers in order to reduce energy consumption in the countries that manufacture the machines.

4.2.2 Purpose-built computers

Another alternative to secondhand computers would be purpose-built machines specifically designed for use in developing world conditions. The most well known example of this would be the XO laptops designed by the One Laptop Per Child (OLPC) program. There are other examples as well, being manufactured on various scales from commercial computers made in India to low-cost do-it-yourself style projects. The common strategies of these designs are generally to reduce power consumption, minimize moving parts, and simplify the machines to lower manufacturing costs.

Inevitably these designs face a trade-off in power and utility versus energy consumption and cost. One of the great strengths of standard desktop computers is their general purpose design. Specialty designs tend to reduce adaptability in favor of targeting a specific problem. This can be a very powerful approach in the appropriate situation—for example low power devices running on solar panels or specialty durable thin-client designs—but the tradeoffs should be examined for each situation.

The trend toward mass-produced netbook computers may help bridge the gap between desktop and specialty designs. Netbooks tend to have many of the same features of the purpose-built machines—few moving parts, low power consumption and low cost—while enjoying the economic advantage of large scale production.

5 Conclusion

Shipping used and refurbished computers to developing countries for reuse has been argued to be an environmentally responsible way to handle the developed world's computer disposal problem while at the same time providing needed computer resources to developing countries. However, as this paper shows, the situation is not as clear as this argument would suggest.

In a global context this computer refurbishing could result in fuller use of computers and the possible reduction of the number of new computers manufactured along with corresponding reductions in energy use and waste production. However, the global perspective ignores the localized impacts of the resulting electronic waste in precisely those countries least prepared to deal with it. The quantity of waste resulting from a used computer is equal to or greater than that resulting from a new computer. And because the average used computer can expect half or less the lifetime of a new computer, the widespread use of secondhand machines could conceivably double the electronic waste load for the recipient communities. Since these communities are in poorer, less developed countries, the waste management and recycling processes are poorly regulated and largely operate on an ad hoc, informal basis further increasing the environmental costs of electronic waste.

Despite the drawbacks of computer equipment disposal, it is clear that information technology is a critical tool for taking part in the contemporary global economy. Developing countries cannot be expected to do without such an important tool for economic development and the affordability of used computer equipment makes it a logical choice for poor countries seeking to develop their IT capacity. Even if not deployed as an explicit development effort, the flow of used computers to the developing world will not slow any time soon.

Therefore it is crucial that those engaged in providing secondhand computers for development take a critical look at their efforts and seek to maximize the computing capacity provided while minimizing the environmental costs.

5.1 Recommendations

The purpose of this paper has been to investigate the environmental issues around the use of refurbished computers for development and to look at ways to frame the issues. However, it is possible to make some tentative recommendations for actions which non-profit providers and governments could take in order to minimize the environmental and health effects of these machines. Accordingly, some possible actions are listed here as recommendations for further investigation by the various stake-holders.

- Recommendations for non-profit providers
    - Ensure that provided machines are high quality, perhaps through explicit age limits on donations.
    - Control maintenance costs through seeking to provide uniform equipment.
    - Scale up computer provision through partnerships with governments and computer manufacturers and retailers.
    - Support regulated, environmentally sound recycling and refurbishment within developing countries.
    - Refurbished computers should not be the only method for providing computer resources. New machines may be more appropriate in some cases.
- Recommendations for developing country governments

  - Monitor and regulate the importation and processing of computer equipment.
  - Set a maximum age limit for imported used computers.
  - Institute an advanced recycling fee, import tariffs, or other similar mechanism to ensure that the costs of computer equipment reflect the external environmental costs.
  - Develop, regulate, and support local refurbishing and recycling capacity in order to remove the activity from the informal sector.

- Recommendations for developed country governments

  - Improve monitoring and regulation of the export of used electronics and electronic waste.
  - Provide financial and technical support for environmentally sound electronic waste recycling and disposal in developing countries.
  - Institute take-back policies to hold manufacturers responsible for the safe recycling and disposal of their products.
  - Reduce environmental and health effects by setting restrictions on the use of hazardous material in electronic equipment.

Most of these recommendations would result in higher costs for used computers in developing countries, whether acquired through non-profit refurbishers or on the open market. While this would be an unfortunate impediment to rapid development of the developing country IT sector, higher prices would more accurately reflect the total lifetime costs of these computers. Currently the environmental costs of recycling and disposal are not included in the purchase price of used computers. This exaggerates their potential benefit to the detriment of those who must ultimately deal with the health effects of their disposal.

Finally, this paper has discussed the lack of data on the transportation of electronic equipment and waste, and the locations of its eventual disposal or processing. In order to improve the management of electronic waste material and maximize the use of our computer resources it is critical that better monitoring and record-keeping be implemented, particularly by governments, but also by those engaged in the processing and transportation of electronic material.

Better data is desperately needed on the transportation, deployment, lifetime, and disposal of computer equipment in the developing world. While some data is available on the environmental and health effects of disposal and processing in China, there is little comparable analysis of practices in Africa. With better information on both benefits and costs, future research efforts might be able to reach specific quantitative conclusions about how best to maximize the utility of computer equipment in the developing world while minimizing the environmental damage.

References

African, Caribbean and Pacific Group of States. *Lomé Convention, Article 39*. African, Caribbean and Pacific Group of States, November 1995.

Ravi Agarwal. Lead and cadmium: Global impacts through e-waste. Technical report, Toxics Link, September 2008. URL https://www.who.int/ifcs/documents/forums/forum6/ppt_l&c_agarwal.pdf.

Basel Action Network. Preventing the digital dump: Ending "Re-use Abuse". Technical Report 10, Basel Action Network, June 2008. URL http://www.ban.org/Library/BP10_June_2008.pdf.

A.K. Bhuie, O.A. Ogunseitan, J.D.M. Saphores, and A.A. Shapiro. Environmental and economic trade-offs in consumer electronic products recycling: a case study of cell phones and computers. In *Electronics and the Environment, 2004. Conference Record. 2004 IEEE International Symposium on*, pages 74–79, 2004. ISBN 1095-2020. doi: {10.1109/ISEE.2004.1299691}.

Bridges.org. How to set up and operate a successful computer refurbishment centre in Africa: A planning and management guide. Technical report, Bridges.org, November 2004. URL http://www.bridges.org/files/active/0/RefurbCentre_guide_FIN_1Nov04r.pdf.

Computer Aid International. Annual report 2007/8, 2008. URL http://www.computeraid.org/pdffiles/AnnRev07-08.pdf.

Computer Aid International. Computer aid international shipment specifications, February 2009. URL http://www.computeraid.org/TechnicalSpecs.htm.

EMPA. Hazardous substances. Technical report, EMPA (Swiss Federal Laboratories for Materials Testing and Research), 2008. URL http://ewasteguide.info/hazardous_substances.

European Parliament. *Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE).* European Parliament, 2003.

Alan Finlay. E-waste challenges in developing countries: South Africa case study. Technical report, Association for Progressive Communications, November 2005. URL http://rights.apc.org/documents/e-waste_EN.pdf.

John F Gantz, Christopher Chute, Alex Manfrediz, Stephen Minton, David Reinsel, Wolfgang Schlichting, and Anna Toncheva. The diverse and exploding digital universe: An updated forecast of worldwide information growth through 2011. Technical report, IDC, March 2008. URL http://www.emc.com/collateral/analyst-reports/diverse-exploding-digital-universe.pdf.

M. Goodrich. Making electronic recycling connections. *Recycling Today*, 37(9): 64–89, 1999.

Elizabeth Grossman. *High Tech Trash: Digital Devices, Hidden Toxics, and Human Health.* Island Press, Washington, 2006.

Xia Huo, Lin Peng, Xijin Xu, Liangkai Zheng, Bo Qiu, Zongli Qi, Bao Zhang, Dai Han, and Zhongxian Piao. Elevated blood lead levels of children in Guiyu, an electronic waste recycling town in China. *Environmental Health Perspectives*, 115(7):1113–1117, 2007.

InfoDev. Knowledge map on information & communication technologies in education. Technical report, InfoDev, March 2005. URL http://www.infodev.org/files/1160_file_KnowledgeMap_ICTsEducation_costs.pdf.

International Telecommunication Union. *Measuring the Information Society: The ICT Development Index.* International Telecommunication Union, Geneva, Switzerland, 2009. ISBN 92-61-12831-9. URL http://www.itu.int/ITU-D/ict/publications/idi/2009/material/IDI2009_w5.pdf.

Ashley Keith, Kara Keesling, Kendra K. Fitzwater, John Pichtel, and Denise Houy. Assessment of Pb, Cd, Cr and Ag leaching from electronics waste using four extraction methods. *Journal of Environmental Science and Health, Part A*, 43(14):1717–1724, 2008.

Huiru Li, Liping Yu, Guoying Sheng, Jiamo Fu, and Ping'an Peng. Severe PCDD/F and PBDD/F pollution in air around an electronic waste dismantling area in China. *Environmental Science & Technology*, 41(16):5641–5646, 2007.

David Liechti and Alan Finlay. e-Waste assessment South Africa. Technical report, e-Waste Association of South Africa, November 2008.

Qian Luo, Zong Wei Cai, and Ming Hung Wong. Polybrominated diphenyl ethers in fish and sediment from river polluted by electronic waste. *Science of the Total Environment*, 383:115–127, 2007.

Alan McKenna. Computer waste: A forgotten and hidden side to the global information society. *Environmental Law Review*, 9:116–131, 2007.

Innocent Chidi Nnorom and Oladele Osibanjo. Electronic waste (e-waste): Material flows and management practices in Nigeria. *Waste Management*, 28(8): 1472–1479, 2008. ISSN 0956-053X. doi: 10.1016/j.wasman.2007.06.012.

Open Research. Paying the price? A total cost of ownership between new and refurbished PCs in the small business, NGO and school in Africa. Technical report, Open Research, December 2004. URL http://www.openresearch.co.za/TCO_Study_Open_Research.pdf.

Organization of African Unity. *Bamako Convention on the Ban of the Import Into Africa and the Control of Transboundary Movement and Management of Hazardous Wastes Within Africa.* Organization of African Unity, 1991.

O. Osibanjo, I.C. Nnorom, and K.C. Ogbonna. Modelling waste generation by the telecom sector in Nigeria: the grey side of the impressive outing. *Waste Management & Research*, 26(4):317–326, 2008.

Oladele Osibanjo and Innocent Chidi Nnorom. Material flows of mobile phones and accessories in Nigeria: Environmental implications and sound end-of-life management options. *Environmental Impact Assessment Review*, 28(2-3):198–213, 2008. ISSN 0195-9255. doi: 10.1016/j.eiar.2007.06.002.

Andrew Paterson. Costs of information and communication technology in developing country school systems: The experience of Botswana, Namibia and Seychelles. *International Journal of Education and Development using ICT*, 3(4), December 2007.

Jim Puckett, editor. *The Digital Dump: Exporting Re-use and Abuse to Africa.* The Basel Action Network, October 2005. URL http://www.ban.org/Library/TheDigitalDump.pdf.

Mathias Schluep, David Rochat, Alice Wanjira Munyua, Salah Eddine Laissaoui, Salimata Wone, Ciss Kane, and Klaus Hieronymi. Assessing the e-waste situation in Africa. *Electronics Goes Green*, 2008+, September 2008.

Charles W. Schmidt. Unfair trade: e-waste in Africa. *Environmental Health Perspectives*, 114(4):A232–A235, April 2006.

SchoolNet Africa. Treat refurbs and Africa with respect: Towards a framework on refurbished computers for African schools. Technical report, SchoolNet Africa, March 2004. URL http://schoolnetafrica.org/fileadmin/resources/Refurbished_computers_ResearchReport.pdf.

Erik Spalvins, Brajesh Dubey, and Timothy Townsend. Impact of electronic waste disposal on lead concentrations in landfill leachate. *Environmental Science & Technology*, 42(19):7452–7458, 2008.

J.B. Stephenson. *Electronic Waste: Observation on the Role of the Federal Government in Encouraging Recycling and Reuse. Testimony Before the Subcommittee on Superfund and Waste Management, Committee on Environment and Public Works, US Senate.* United States Government Accountability Office, 2005. URL http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=gao&docid=f:d05937t.pdf.

UNCTAD. WSIS follow-up report 2008. Technical report, UNCTAD, May 2008. URL http://www.unctad.org/en/docs/none20081_en.pdf.

United Nations. *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal.* United Nations, October 2005. URL http://www.basel.int/text/con-e-rev.pdf.

US Environmental Protection Agency. Electronics waste management in the United States: Approach one. Technical report, US Environmental Protection Agency, July 2008. URL http://www.epa.gov/waste/conserve/materials/ecycling/docs/app-1.pdf.

Dongli Wang, Zongwei Cai, Guibin Jiang, Anna Leung, Ming H. Wong, and Wai Kwok Wong. Determination of polybrominated diphenyl ethers in soil and sediment from an electronic waste recycling facility. *Chemosphere*, 60:810–816, 2005.

Eric Williams, Ramzy Kahhat, Braden Allenby, Edward Kavazanjian, Junbeum Kim, and Ming Xu. Environmental, social, and economic implications of global reuse and recycling of personal computers. *Environmental Science & Technology*, 42(17):6446–6454, 2008. ISSN 0013936X.

Jonathan Wolfington and Anthony R. Maranto. Policy approaches to the recycling and disposal of electronic waste. *The Pacific Journal of Science and Technology*, 9(2), November 2008.

World Computer Exchange. Annual report fiscal year 2008, 2009. URL http://www.worldcomputerexchange.org/files/Annual_Report08%5Ba%5D.doc.

Liangkai Zheng, Kusheng Wu, Yan Li, Zongli Qi, Dai Han, Bao Zhang, Chengwu Gu, Gangjian Chen, Junxiao Liu, Songjian Chen, Xijin Xu, and Xia Huo. Blood lead and cadmium levels and relevant factors among children from an e-waste recycling town in China. *Environmental Research*, 108(1):15–20, 2008.