

International Investigation of Electronic Waste Recycling Plant Design

by
Jean E. Theurer

Submitted to the Department of Mechanical Engineering
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Abstract

This thesis investigates the industry of electronic waste recycling industry in three countries: Germany, the United States, and Chile. Despite differences in the legal structure surrounding the industry, there are many similarities between plant operations and disassembly techniques. Several strategies for improving the recycling rate and improving employee safety within the plants have been identified. Appropriate clothing, included masks and gloves will improve worker safety while the recycling rate can be increased by separating the disassembly process into two tasks: disassembly and sorting. However it seems as though even with significant decreases in cost from the labor associated with recycling, the economic price of electronic waste will continue to outweigh the profits from selling recycled materials. Thus, it is important for countries to recognize the environmental and health benefits of recycling electronic waste and continue to support the electronic waste recycling industry's development.

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1. Introduction

Colloquially, electronic waste is considered ‘anything with a plug,’ including but not limited to, personal computers, laptops, refrigerators, and cell phones. Electronic waste is a relatively new waste stream; refrigerators were not mass produced until the 1950s and computers have only been affordable for the past 15 years. The spectrum of electronic waste management practices spans from open burning (a common technique in China) to automated recycling (an expensive alternative explored in Germany). This thesis will focus on the electronic waste management technique of manual recycling and delve into the details of the manual recycling process on the factory floor. Despite numerous differences in the objectives and design of electronic waste recycling across the world, there are many similarities in the implementation process, specifically the disassembly of electronic products on the factory floor.

The goal of this study is to investigate methods of decreasing the cost of electronic waste recycling and make it competitive with other management methods. In order to achieve this goal, there are several aspects of the electronic waste recycling process to analyze. For example, a study could investigate:

1. The method of collecting obsolete and damaged electronic products.
2. The organization of the facility responsible for disassembling electronic waste.
3. The method of disassembling the electronic products into raw materials.
4. The strategy for achieving the highest price at which raw materials are sold on the market.
5. The procedure for recycling raw materials (like aluminum, plastic, printed circuit boards)

Each of these aspects is associated with various costs (like transportation, labor) and revenues (like commodities pricing) and would require an on-site visit to an electronic waste recycling plant. While, unlike the automotive industry, plant managers, employees, and company owners in the electronic waste recycling industry are more welcoming and friendly towards researchers, it is critical that the purpose and scope of the project is clearly defined for an effective visit. This study is limited to investigating both the organization of the recycling facility and the method of disassembling. Data was collected from visits to electronic waste recycling plants in Germany (ElectroCycling in Goslar and Recyclingpartner in Stuttgart), the United States (ACER Com-Cycle in Melbourne, Florida) and Chile (Recycla in Santiago). In addition, phone interviews and online conversations were used to find techniques to increase the recycling rate.

This investigation into the factory floor disassembly techniques occurs against a backdrop of highly varied management practices and incentive structures worldwide. Therefore, before turning to the recycling factory level, it is worthwhile to briefly survey the range of practices and examine the incentive systems that characterize the wide variety of electronic waste management techniques across the world. Each practice has its own advantages and drawbacks (discussed in Chapter 2: Electronic Waste Management Alternatives) and every country has developed its own regulations and enforcement techniques for dealing with electronic waste (discussed in Chapter 3: The Electronic Waste Industry in Various Countries). Chapter 4: The Flow of Electronic Waste through the Plant describes the path of electronic waste through a typical electronic waste recycling plant and provides the detailed disassembly process of two common electronic waste products, desktop computers and CRT monitors. The techniques for collecting data at an electronic waste recycling plant and qualitative observations on how to improve data collection are discussed in Chapter 5: Data Collection Methods. Chapter 6: Data Collected from On-Site Visits, presents the data collected at the recycling plant in Chile and the recycling plant in the United States. From this data and qualitative observations at the plant, Chapter 7: Plant Recommendations makes suggestions for a more efficient and safe plant design and operating routine. Finally, in Chapter 8: Conclusions, the impact of these recommendations and the future of the electronic waste recycling industry is discussed.

2. Electronic Waste Management Alternatives

Open burning of electronic waste is one of the cheapest methods of electronic waste management but also the most dangerous. Burning discarded electronic products exposes employees and nearby residents to unsafe levels of PCDD/PCDFs and lead. These chemicals are linked to diseases of the nervous system (Pelclová, P, J, & al, 2006) and the immune system as well as renal (Lippmann, 2009) and cardiovascular failure. Extensive environmental and health studies have been conducted on the population of Guiyu, China, where electronic waste burning is the main industry of the town (Johnson, 2006). The concentration of PCDD/PCDFs in the soil of Guiyu is over 140 times the concentration at other electronic waste processing sites around the world. Similarly, the concentration of lead in the atmosphere is over double the rates found in, neighboring cities such as Hong Kong and Guangzhou that do not use the open burning technique (Wong, 2006). 80% of the children in Guiyu, China have unsafe levels of lead in their blood due to the burning of plastics (X., L., X., L., & Qiu B, 2007). Clearly, the nominal cost of burning electronic waste does not reflect the environmental and health damages this process inflicts on the surrounding population and area.

Incineration, land filling, and recycling are three alternative electronic waste management practices that wreak less havoc on the environment and health. In a controlled incineration of electronic waste, the United States Environmental Protection Agency (EPA) measured levels of heavy metals (including lead, cadmium and mercury) and PCDF emissions close to standard limits. The EPA study concludes that incineration does not violate safety standards imposed by the EPA (Stewart & M., 2002). Nevertheless, incineration impacts air-quality and could have an impact on health. Even though electronic waste is a small proportion (by volume) of the waste in landfills, it contributes to 70% of the heavy metals including lead, cadmium and mercury released into the environment (Global Resources Foundation, 2003). The most significant risk associated with land filling electronic waste is the leaching of hazardous and toxic materials into the soil. This contaminates not only the soil, but has the potential to affect the ground water. Air pollution is also a risk as landfills are not immune from uncontrollable fires (E-waste Guide). Like open burning, the immeasurable environmental and health costs are not generally incorporated into the economics of land filling and incineration.

Recycling also has documented health impacts. In particular, the exposure to dust during the disassembly process has been shown to irritate lungs (ewasteguide.info, 2009). However, unlike open burning, incineration, and land filling, recycling produces valuable byproducts such as glass, copper, gold, and aluminum that can be sold as recycled materials in the market. Reuse of raw materials reduces our reliance on these limited natural resources. This conservation benefit outweighs the negative health effects noted above. Overall, the electronic waste management technique of recycling is the best method. However despite the advantages of recycling over the other electronic waste management alternatives, recycling remains one of the costliest methods of electronic waste management.

2.1. Electronic Waste Recycling

It is a common misperception that with proper management, electronic waste recycling facilities can reap a large profit from the resale of recycled raw materials. While there is a value in the precious metals and copper extracted, these materials are subject to the fluctuation of commodities pricing. The small volume and expensive extraction methods preclude relying on the resale of raw materials to generate a consistent profit. Figure 2-1 shows the material composition of desktop computers by volume. Precious metals (the highest value materials) only compose 3% of the total volume. The revenue received from recycling more common components such as plastics, ferrous metals and glass (a total of 68% of the volume of desktop computers) do not make a significant economic contribution.

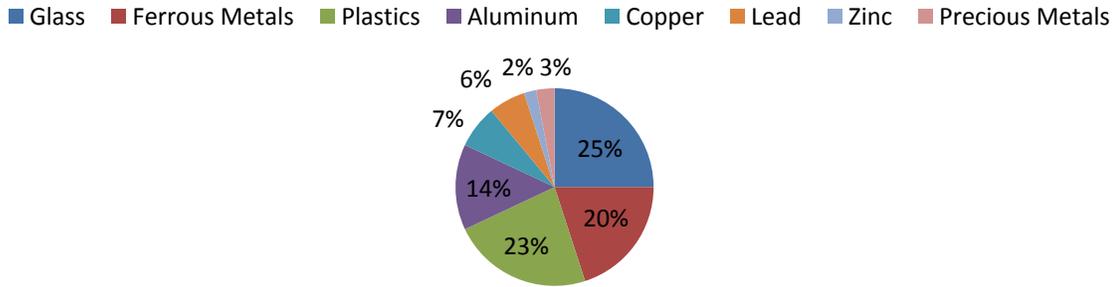


Figure 2-1: Pie chart of typical material composition of desktop computers (Pedersen, Wilson, Pitts, & Stotesbery, 1996).

In a report by the Microelectronics and Computer Technology Corporation, it is estimated that the recycled value of the components of a desktop computer amount to \$30.71 (Pedersen, Wilson, Pitts, & Stotesbery, 1996). The recycling value of electronic products does not outweigh the cost of transportation, disassembly, storage, and recycling.

The process of electronic waste recycling is illustrated in a flow chart in Figure 2-2. Discarded electronic products are collected from institutions, households and companies. The waste is disassembled in an electronic waste recycling plant and then separated into recyclable materials (for example, aluminum, plastic, CRTs) and waste products.

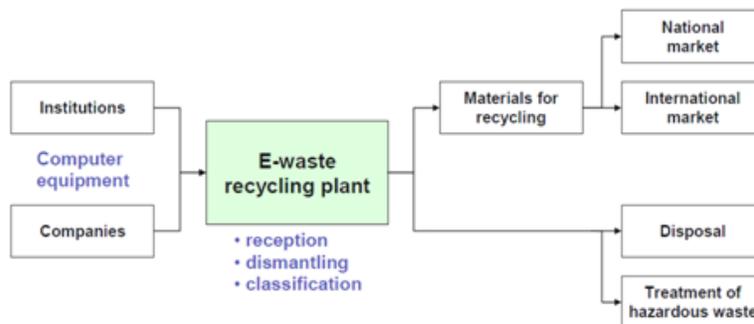


Figure 2-2: Diagram of waste flow through electronic waste recycling plant (Steubing, 2007).

At each step in this process there is the opportunity for a detailed investigation for methods to reduce cost and increase the recycling rate. For example a study could examine:

1. The collection of discarded, obsolete, damaged electronic products from consumers or companies.
2. The disassembly of electronic waste into its component raw materials and waste products
3. The process of recycling of raw materials
4. Selling valuable raw materials on the market, treating hazardous waste and disposing waste.

However, this thesis will focus on processes within the electronic waste recycling plant.

In summary, open burning, incineration and land filling of electronic waste all neglect the inherent value of the raw materials that compose an electronic product. Electronic waste recycling is the most beneficial management technique because it reduces the extraction of raw materials. However, the current economic evaluation of this technique discourages widespread adoption. In order to decrease the cost of recycling, a study could examine many different aspects of the recycling process; this study will focus on the factory floor processes.

3. The Electronic Waste Industry in Various Countries

In order to understand the magnitude of the electronic waste management problem, one must understand the size of the industry. While the generation of electronic products around the world is a good estimate for the quantity of electronic waste currently on the globe, looking at the product life-cycle identifies how the rate of electronic waste generation is changing.

While any individual product experiences a cycle of rising, peaking and then falling production, the net sum of electronic production is on the rise. German sales of desktop (in orange) and laptop (in blue) computers between 2002 and 2009 have shown trends of decreasing and increasing sales respectively, however the net total of computer sales (in purple) has shown a strong increasing trend.

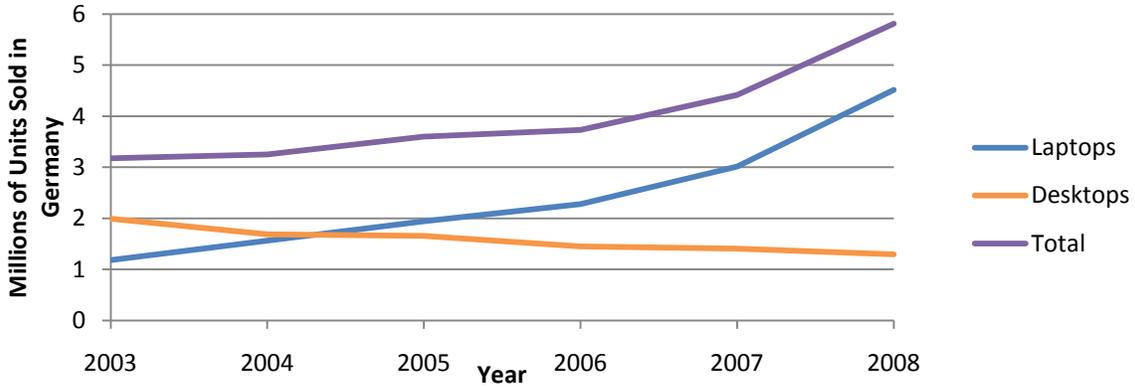


Figure 3-1: Graph of sales of electronic products in Germany between 2003 and 2008. Data collected from Consumer Electronics: Euromonitor from trade sources/national statistics (Consumer Electronics, 2010).

In the United States, Figure 3-2 shows the sales of various electronic products (laptops, flat panels, CRTs and desktops). The sales in millions of units, on the y-axis, vary with respect to time in years, on the x-axis. This data, collected from the Consumer Electronics Association Market Research, the Trade Commission and the US Census, displays trends consumers see in the market (Office of Solid Waste, U.S. EPA, 2008). The purple line, indicating the totals sales of these various products, is showing a strong upward progression. Dips correspond to the introduction of a substitute product (for example CRTs and flat panels or desktops and laptops).

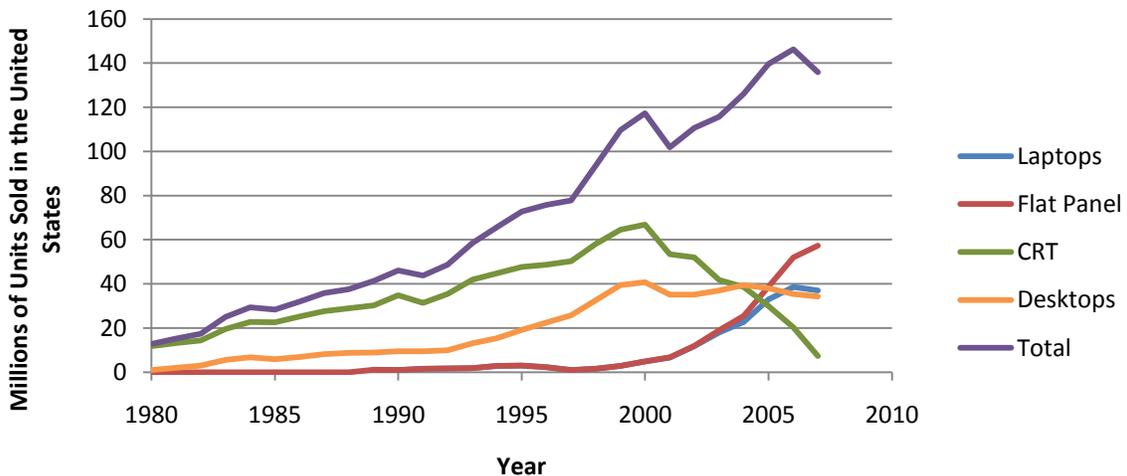


Figure 3-2: Graph of sales of electronic products in the United States between 1980 and 2007. Data for CRTs were collected by Consumer Electronics Association Market Research and ERG analysis of US Census data on shipments and Trade Commission. Data for flat panels were obtained from IDC. Data for desktops and laptops came from analysis of US Census data on shipments and Trade Commission (Office of Solid Waste, U.S. EPA, 2008).

Similarly, the sales of electronic equipment in Chile are only increasing. Figure 3-3 shows historical and predicted computer consumption (in purple) from 1996 to 2020 in Chile. The number of computer products sold in Chile (along the y-axis) is anticipated to rise above 3 million by 2020 (Steubing, 2007). As expected, the generation of electronic waste (in red) is also rising with sales.

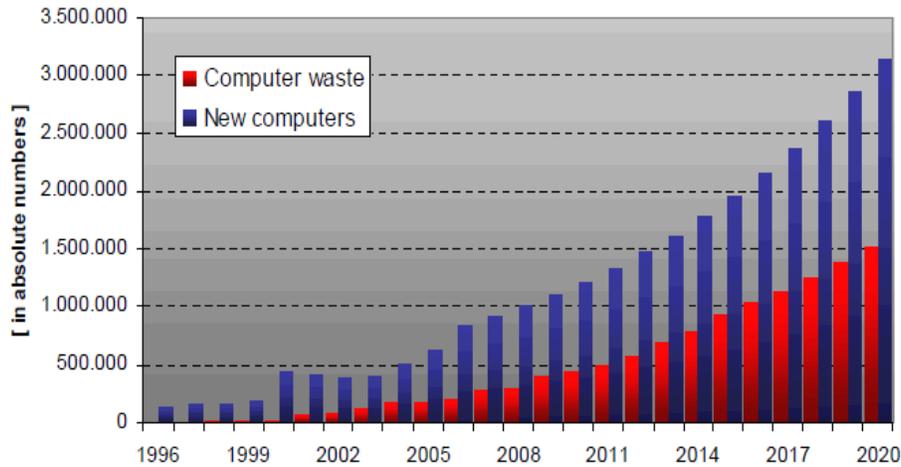


Figure 3-3: Graph of computer purchases and computer waste generation in Chile (in number or products) from 1996-2020 (Steubing, 2007).

In order to understand how the rate of electronic waste production is changing, it is important to understand the life scale of these products. For example, some products are manufactured with the intension of lasting the lifetime of the consumer (60+ years), thus, there is an upper bound on the maximum production because consumers will not need to replace the product. In contrast, many electronic products have short life spans. The life span begins at product purchase and ends when the object becomes obsolete or damaged. Flat panel and CRTs have a similar life span of 9 and 9.4 years on average. On average, desktops will last 12.3 years, while laptops are replaced every 5.9 years (Office of Solid Waste, U.S. EPA, 2008). From this data, countries can estimate how many products were trashed each year and forecast how the quantity of electronic waste will change. Figure 3-4 shows EPA estimates of the number of different types of electronic equipment that are discarded in the United States between 1999 and 2007. Millions of units sold along the y-axis shows and upward trend with respect to time on the x-axis. Again, the purple line representing the total shows a clear upward trend.

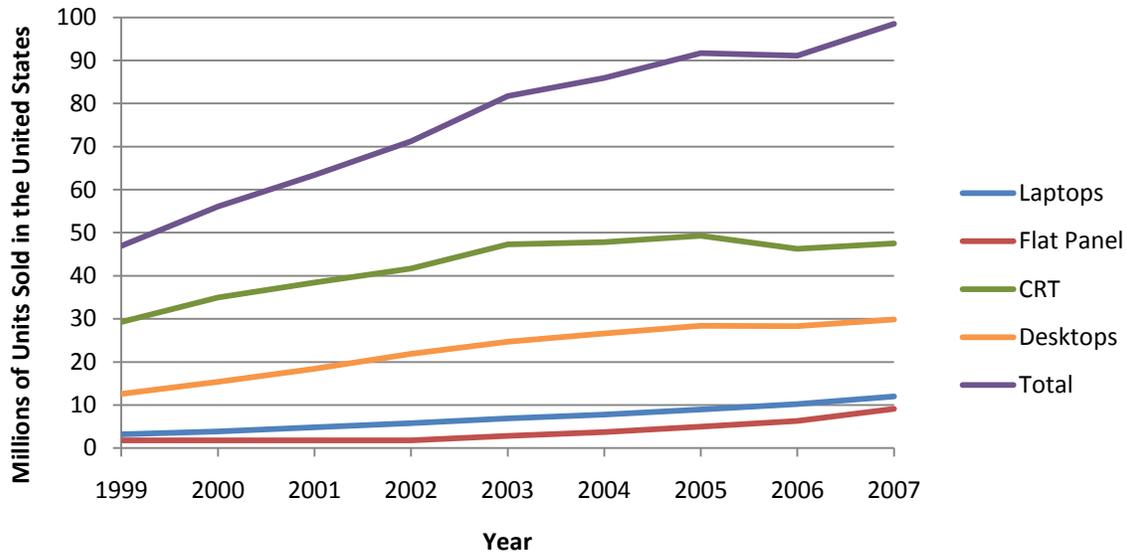


Figure 3-4: Graph of estimated obsolete electronic products in the United States between 1999 and 2007 (Office of Solid Waste, U.S. EPA, 2008).

While Figure 3-4 only shows this history of obsolete electronic waste for a few products; there is a strong indication that the electronic waste in its entirety stream will be growing over time. Electronic waste management is a serious and growing problem and every country has chosen to deal with it in a different manner. The plants studied in this report cannot be isolated from the context in which they were started. Each country: Germany, the United States and Chile, has followed a different path to the formation of an electronic waste recycling industry.

3.1. Germany

Germany has one of the most progressive electronic waste management programs in the world. In fact, the entire waste management system in Germany is the standard by which the European Union hopes to emulate. In the 1990's, Germany was one of the most densely populated countries on the globe. Aside from India and eastern China, Figure 3-5 shows many areas of Germany, circled in green, with a very high population density (Contreras, 2007).

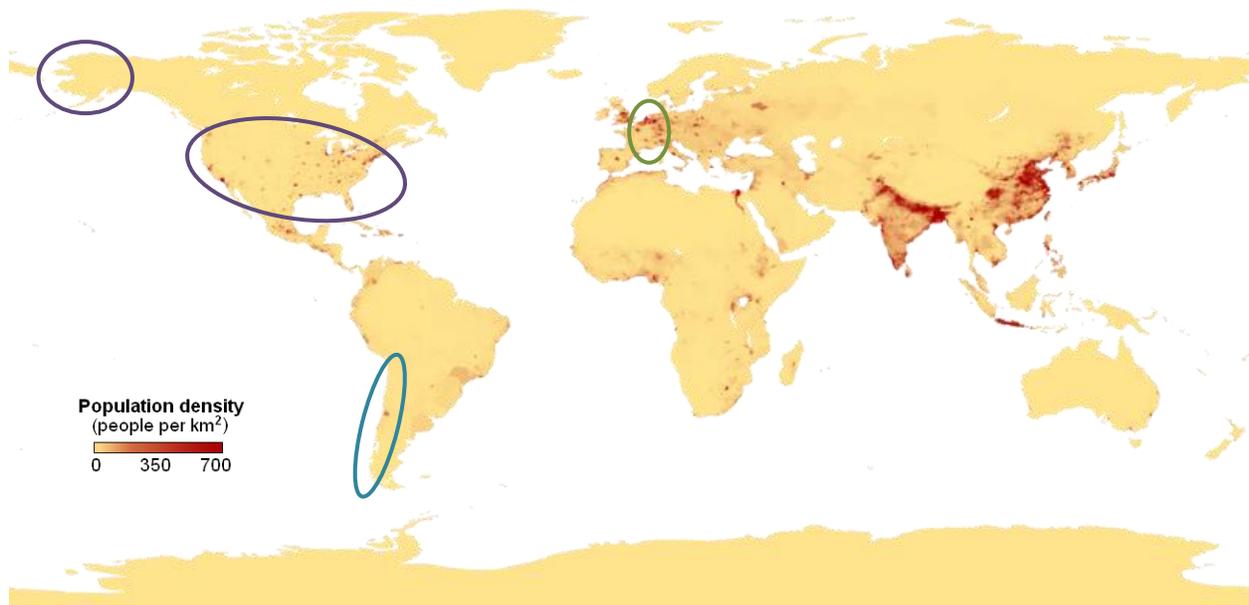


Figure 3-5: Population density of the globe in 1994 where red indicates highest and yellow indicates lowest population density. Germany, circled in green, has one of the highest population densities; the United States (in purple) shows sporadic high population density and Chile (in blue) shows Santiago as the only high population density (Contreras, 2007).

Placing waste management sites near high population centers was both a practical necessity and a political nightmare. A proposal for a waste management center in the state of Baden-Wurtemberg spawned over 100,000 complaints (Fishbein, 1994). The responsibility of waste management, a critical political issue, was placed on the back on the shoulders of producers with the passage of the German Packaging Ordinance in 1991. This law required the producers of products sold in Germany to “take-back, reuse, and/or recycle” the packaging associated with their product (Fishbein, 1994). This legislation set a precedent for the relationship between industry and government on waste management. In 2005, the Electrical and Electronic Equipment Act established the framework for electronic waste take backs by the producer (Bundesministerium fuer Umwelt, 2005). In order for a producer to sell electronic products in Germany, they must register with the Federal Environmental Agency and thus agree to financially cover the cost of transportation from municipality collection centers and appropriate disposal of the electronic equipment sold by that company (Gregory, Magalini, Kuehr, & Huisman, 2009).

The process of electronic waste recycling in Germany is illustrated in Figure 3-6. Households and companies are responsible for separating electronic waste from other types of waste and delivering

to municipal collection centers. When the municipal center reaches capacity of electronic waste, the clearinghouse is notified. The quantity of electronic waste a producer must recycle is determined by location and the market share based on the weight of the product sold in Germany (Lets Recycle, 2004). The clearinghouse notifies the producer responsible for recycling the waste. The producer contracts out the transportation and recycling services to independent companies, generally part of the European Advanced Recycling Network. This service adheres to the standards each producer must follow and delivers the electronic waste from the municipality to the electronic waste recycling facility (Kramer, 2009).

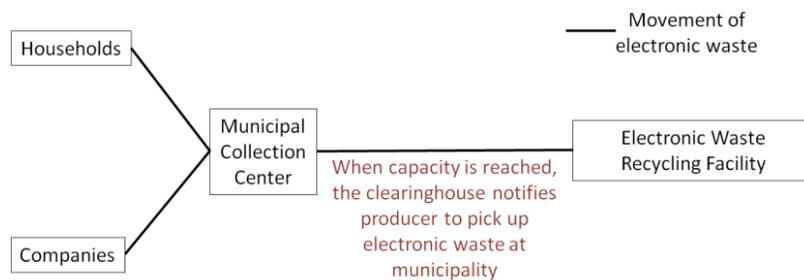


Figure 3-6: In Germany, electronic waste moves from households and companies to the municipal collection center. The clearinghouse is responsible for identifying and notifying the producer to deliver the electronic waste to the recycling facility. Diagram created by author.

In Germany, many of the electronic waste recycling facilities give work to underprivileged low-skilled workers, (mentally-handicapped, former drug abusers and unemployed youth or elderly). In exchange for this service, the government pays the wages of the employees (Fischer, 2009).

3.2. United States

The United States has sporadic location of high population density, as seen circled in purple in Figure 3-5. These hot-spots of high density do not rival the concentration of high density seen in Germany both in 1994 and in 2006 (Contreras, 2007). Thus, the recycling system in the United States has been the result of state legislation and environmental and social policies of businesses, not national regulations (Price, 2009). Unlike Germany, the United States has not yet been spurred by population density to address the waste management problem. State legislation is the most powerful force in the formation of an electronic waste recycling industry. California was the first to enact electronic waste recycling legislation with the Electronic Waste Recycling Act of 2003. Unlike the German model,

California pushes the responsibility and cost of recycling directly to the consumer, and an electronic waste recycling fee to pay for the collection and recycling of computer and television monitors (California State - Board of Equalization, 2009). Recently, Vermont passed legislation requiring electronic product producers to collect and recycling electronic products (Lyons, Hartwell, & MacDonald, 2009).

Figure 3-7 shows the status of electronic waste management laws in the states. Of the 50 states, only 21 have passed legislation requiring producers to take responsibility of the end life of electronic products, denoted in blue (Electronics TakeBack Coalition, 2010). Even with the passage of these laws in some states, the complexity and completeness of the take-back program does not rival that of Germany.

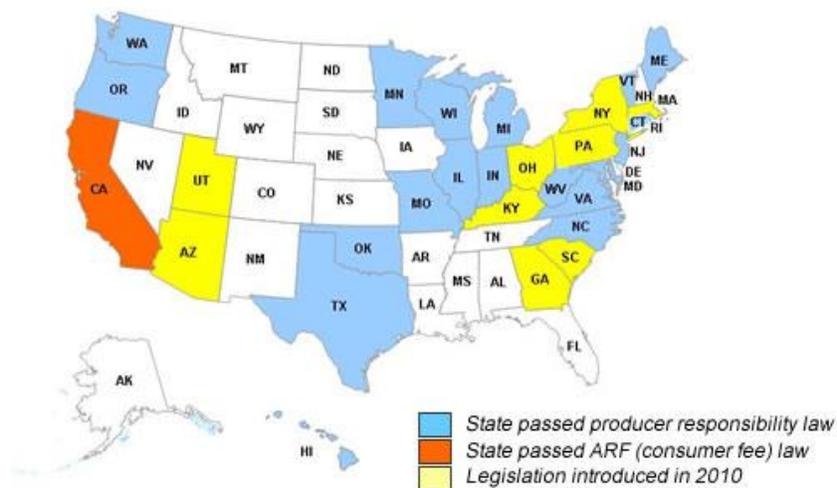


Figure 3-7: Map of electronic waste recycling legislation status in the United States (Electronics TakeBack Coalition, 2010).

For those states without strict electronic waste management laws, electronic waste is disposal largely unregulated. For example, the state of Florida, has issued grants to help initiate and support electronic waste recycling endeavors. Recipients of the grant money are issued an identification number and required to register, report insurance information, and end market information (final destination of disassembled parts). This designation gives the electronic waste recycling companies an independent validation and recognition that allows consumers to distinguish it as a recycling and not exporting company. The state of Florida checks these required reports for feasibility, however does not have the resources to perform a complete audit as is done by a third party for ISO 14.001 certification (Price, 2009).

Thus, in these states, the electronic waste recycling industry is supported solely by corporate social responsibility (CSR) policies. A crisis is often the catalyst for changes in corporate policies. For electronic producers, images of children burning toxic electronic waste or playing around electronic waste landfills ignited a wave of reforms and counter advertising. Now, almost every computer producer has a program to recycle electronic waste. Similarly, smaller businesses have followed suit by paying for the recycling of their obsolete and damaged electronics. While electronic waste recycling companies will take products from individuals, they rely on the generous policies of these companies to provide a steady source of material and a profit margin. One of the major challenges of the electronic waste recycling industry in the United States is identifying local or even national companies that will treat and then recycle contaminated raw materials in computers. In particular, finding end-markets for leaded glass (used in CRTs) is a major hurdle (Price, 2009). In the United States, only 18% of monitors and computer products were recycled in 2007 and the cell phone recycling rate was even lower at 10% (Office of Solid Waste, U.S. EPA, 2008).

Like Germany, electronic waste recycling companies in the United States seek to lower the cost of their labor supply. The employees at recycling plants in the United States tend to be low-skilled and low-wage. Electronic waste recycling facilities have not partnered with the local government to give employment to underprivileged workers (Plant Manager of Com-Cycle Florida, 2009).

3.3.Chile

Chile, recently elected the OECD community, has become a symbol of economic wealth and prosperity in Latin America (OECD, 2010). While it does not yet reach the quantities of the United States and Europe for electronic waste production, forecasts for electronic product purchasing and disposal indicate a path similar to that of Germany and the United States as shown in Figure 3-3. While there has been an initiative to increase awareness and promote the development of an electronic waste recycling industry, most of the electronic waste is exported or land filled (Silva, 2007).

The electronic waste recycling industry in Chile is dominated by one company, Recycla. Since there are no national or local government regulations on the management of electronic waste, Recycla depends solely on corporate social responsibility programs in order to turn a profit (Nilo, 2010). Major manufacturers provide Recycla with defective and overstocked products while, local companies upgrade obsolete electronic equipment and come to Recycla for electronic waste recycling services. Currently, Recycla does not offer a service for consumers to recycle their electronic waste (Steubing, 2007).

Companies bring electronic waste directly to the Recycla plant or hire Recycla to collect the electronic waste. Once the waste is disassembled, the recycling facilities in Chile are limited. Hazardous waste is handled by the Chilean government and there are local companies to recycle CRT glass, metals and plastic. However, Recycla ships components with precious metals (such as printed circuit boards, power supplies and central processing units) overseas to Europe for extraction services (Nilo, 2010). Barely 3% of the electronic waste generated in Chile gets recycled, and this figure is even less for other countries in Latin America (Steubing, 2007).

For the plant disassembly process, Recycla searches for the cheapest employees. University engineering programs in Chile require students to complete a summer factory job; Recycla hires many students to disassemble electronic waste as part of that program. In addition, Recycla has partnered with the local prisons to allow prisoners to work at Recycla during the day and sleep at the prison at night. Like Germany and the United States, Recycla seeks to minimize labor costs through the cheapest and least desirable labor sources.

Globally, the production of electronic products is growing and thus, electronic waste management strategies will be a critical need. Currently, the differences in the electronic waste recycling industry from country to country are a function of whether recycling is mandated from the national government. If the government chooses not to enforce legislation that encourages electronic waste recycling, the responsibility of proper electronic waste management falls to the private sector. In the United States and Chile, the resources the private sector can devote to public services vary drastically. In the United States many small businesses can afford to recycle their electronic waste. Whereas, in Chile most recycled electronic waste material comes from major multi-national companies.

4. The Flow of Electronic Waste through the Plant

Despite the differences in the formation of the electronic waste recycling industry in Germany, the United States and Chile, the processes of disassembling the electronic waste into its component parts shows very little variation from country to country. The movement of electronic waste through the plant is outlined in the flowchart in Figure 4-1.

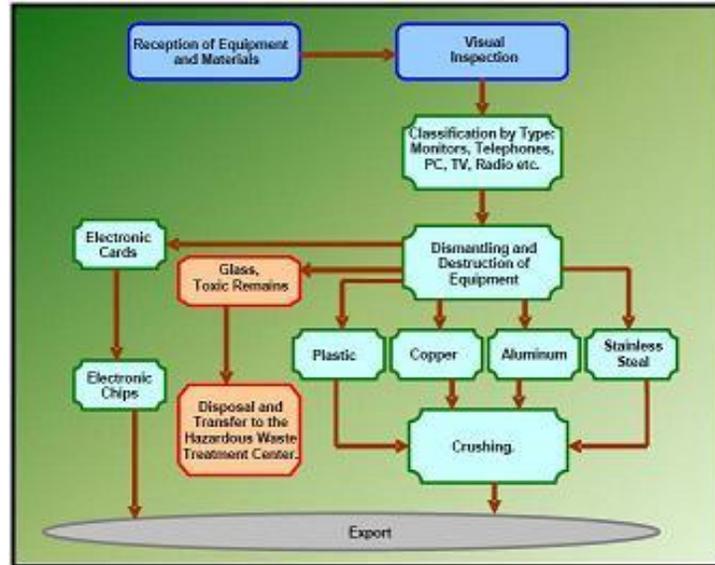


Figure 4-1: Flowchart of typical electronic waste disassembly plant operation (Nilo, 2010).

Electronic waste is delivered to the recycling plant by truck. When the electronic waste is well packed inside the truck, plants employees unload the truck placing desktops, laptops, CRTs, flat panels, etc. on pallets, 1 meter by 1 meter wide, as shown in Figure 4-2 (a). To keep the electronic waste from falling off the palette, it is stored in large cardboard boxes, large bags, or plastic wrapped. If the electronic waste is not organized in the truck, often the products will break. This makes it much more difficult to separate and balance electronic waste on pallets, thus plant employees will often stack the electronic waste in a pile as seen in Figure 4-2 (b). Recycla prefers to collect electronic waste from the individual companies using their own staff for easier removal from the truck and a guarantee of proper packing (Nilo, 2010). In contrast, the trucks arriving at electronic waste recycling plants in Germany have been packed by the municipality collection centers. Thus, material is more likely to have been ‘thrown in’ (Fischer, 2009).



Figure 4-2: (a) Printers in Recyclia plant stored on pallets after entering the facility, January 2010. (b) CRTs stored in German facility, July 2009. Photos taken by author.

The pallets are moved by forklift to be weighed. The total weight of the shipment is recorded and reported back to the customer or government. These weights are not segregated by product type unless specifically requested. The pallets are then grouped by product in different areas (both indoor and outdoor) around the facility as seen in Figure 4-3.



Figure 4-3: Electronic waste segregated in Recyclia plant storage facility. Photo was taken by author in January 2010.

Electronic waste is brought from the storage area to the disassembly area by forklift. The plant manager is in charge of deciding which products are disassembled on any given day. According to plant managers at all the facilities visited, there is no formula for deciding what should be recycled. Often it depends on which product storage area is reaching capacity or how close a particular raw material is to the critical amount for exportation (this will be explained later). Workers carry electronic waste from the pallet to their workstation. At each workstation, the worker removes components of the electronic

waste and segregates the components (power supplies, wires, PCB, CPU, plastic, etc.) into bins located around and underneath the workstation, as shown in Figure 4-4.



Figure 4-4: Wires removed from electronic waste and stored under the workstation table. Photo was taken by author at Recycla in January 2010.

Some of the items in these small bins are decomposed even more. Some recycling facilities have plastic crushers to reduce the storage space necessary for plastics. In addition, the capacitors on printed circuit boards are clipped off before they are ready to leave the plant (See Figure 4-7).

When these small bins are full, the employee empties their individual bins into a larger container located in the export area of the electronic waste recycling plant. These containers, shown in Figure 4-5, are held at the plant until a critical quantity has been reached. Business efficiency defines the critical quantities. For example, Recycla waits until they have a truck-load of CRTs before they export CRTs to local glass recycling facility. In contrast, a printed circuit boards, power supplies and central processing units are sent overseas to Germany. Thus, Recycla must hold this material until a shipping container can be filled.

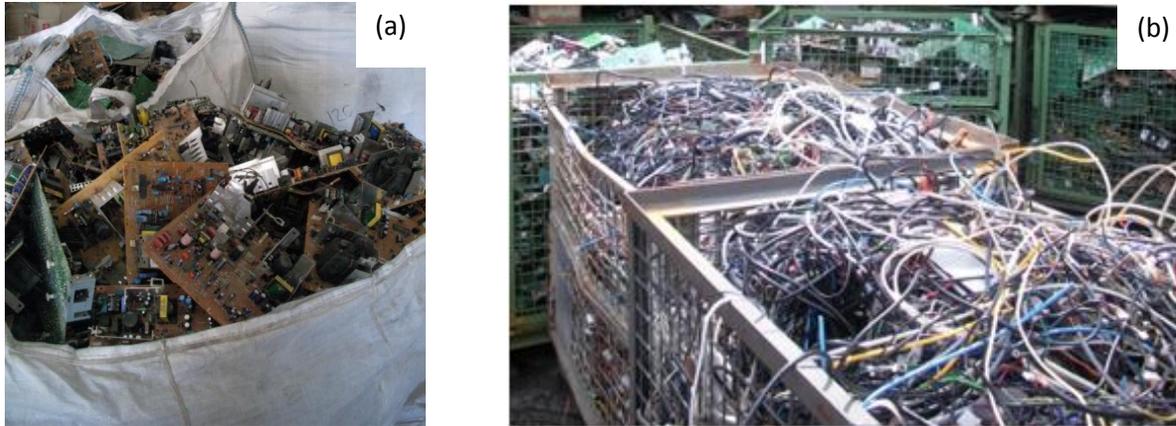


Figure 4-5: (a) Printed Circuit Boards ready for export in Recyclia facility, January 2010. (b) Wires ready for export in Germany, July 2009. Photos were taken by the author.

While the spectrum of equipment that is classified as electronic waste and ends up in the electronic waste recycling facilities is overwhelmingly large, the vast majority of electronic waste is computers, monitors, and printers (Nilo, 2010). The process of disassembling a typical desktop computer and a CRT monitor is discussed in Section 4.1 and 4.2 below. The tools and techniques used to take apart these two types of waste are representative of the typical range of tools and techniques seen at electronic waste recycling plants.

4.1. Desktop Computer Disassembly

The parts of a desktop computer vary in placement depending on the manufacturer, however all computers have the same basic parts: power supply, fan, central processing unit, memory, printed circuit boards, mother board, removable media drives (CD and diskette) and a hard drive. Figure 4-6 shows the location of these components within a desktop computer.

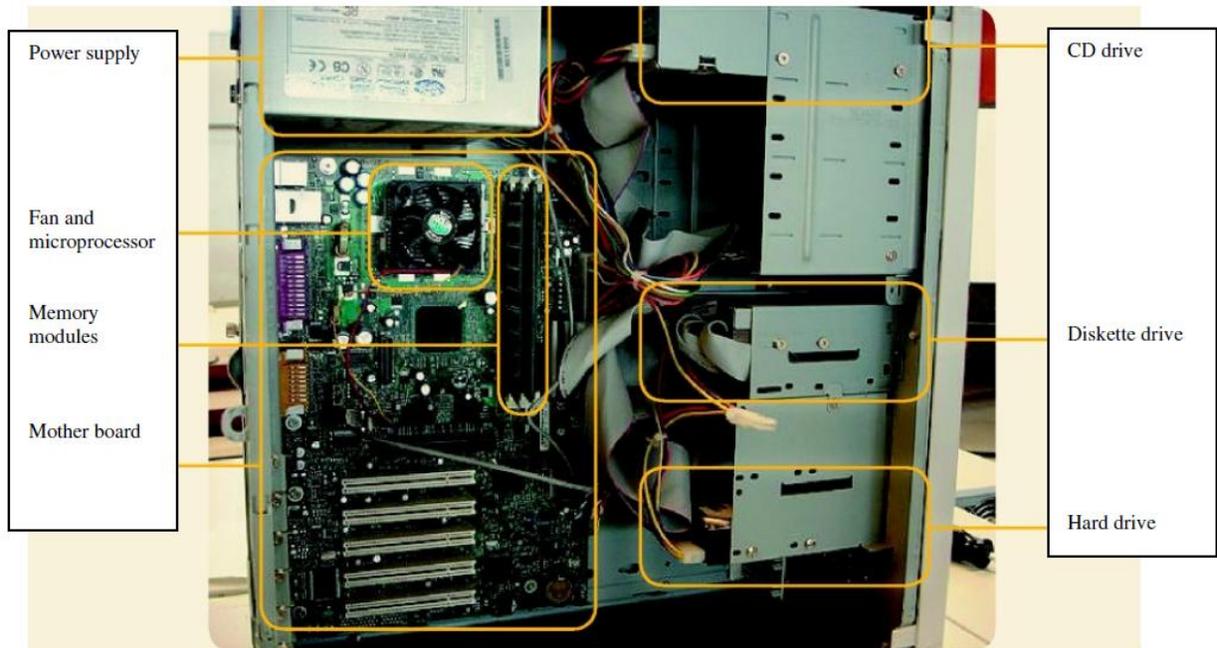
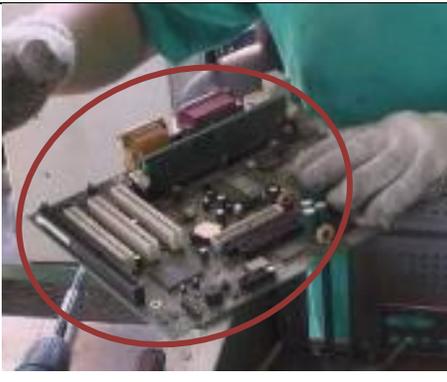


Figure 4-6: Diagram of personal computer components (Centres de Formation en Entreprise et Recupération).

The disassembly of a computer requires the removal and sorting of all of these parts. The process of disassembling a typical desktop computer is outlined in Table 1. The worker begins by removing the side panels. The order of removal of the hard drive, memory, PCB, fan, etc. depends on ease of access. Generally, the wires are removed before the removable storage drives (hard drive, diskette drive, CD drive) and the CPU and fan are removed before the PCB. The details on the outside of the box, such as the power button, extra USB slots are removed next. Finally, the plastic or metal casing is left and sorted accordingly. The first column of Table 1 is used as a reference to identify the steps of the disassembly process. In the second column, the part removed is listed and an image is shown in the third column. The removal process is characterized by the tools and value of the material removed noted in the fourth column. As discussed, it is common for a worker to interchange the removal of the PCB, CPU and fan, power supply and wires (steps 3-7) dependant on the ease of access to these parts.

Table 1: A Recycla employee disassembling a personal computer in January 2010. Photos were taken by the author.

Step	Part	Image	Tools/Actions Material
1	Side Panel		<ul style="list-style-type: none"> • Screwdriver (generally 2 screws) • Generally made of plastic or metal (limited value).
2	Side Panel		<ul style="list-style-type: none"> • Screwdriver (generally 2 screws) • Generally made of plastic or metal (limited value).
3	Fan + Heat Sink + CPU		<ul style="list-style-type: none"> • Pulling • The wire connecting the fan to the PCB is cut and valued for its copper. The heat sink is of limited value for the aluminum alloy. The CPU has the most value, containing gold and other precious metals.

Step	Part	Image	Tools/Actions Material
4	Wires		<ul style="list-style-type: none"> • Pulling • The copper in the wires are a valuable commodity.
5	PCI Cards		<ul style="list-style-type: none"> • Screwdriver (1 screw) • PCI cards have precious metals that are valuable once extracted from the PCB – this processing is generally done outside the electronic waste recycling facility. In addition, PCB's have hazardous materials (like batteries).
6	PCB		<ul style="list-style-type: none"> • Screwdriver (6 screws) • PCB's contain precious metals and hazardous materials that are extracted offsite.

Step	Part	Image	Tools/Actions Material
7	Power Supply		<ul style="list-style-type: none"> • Pulling and Clippers • Power supplies contain both hazardous materials and precious metals.
8	Floppy Drive		<ul style="list-style-type: none"> • Screwdriver (4 screws) • Removable media drives contain both precious metals and hazardous waste.
9	Power Controls		<ul style="list-style-type: none"> • Pulling • Power controls are usually composed of plastic and wiring.
10	Hard Drive		<ul style="list-style-type: none"> • Screwdriver (4 screws) • Hard drives are valuable for their aluminum and magnets
11	USB adaptors on the casing		<ul style="list-style-type: none"> • Screwdriver (2 screws) • Metal and wires are valuable materials.

Step	Part	Image	Tools/Actions Material
12	Casing		<ul style="list-style-type: none"> Plastic is crushed and recycled offsite.

Steps 6 and 7 require further processing of the printed circuit board before they leave the electronic waste recycling facility. The three-dimensional components of printed circuit boards, like large capacitors and MOSFETs shown in Figure 4-7, are removed from the circuit board before they are shipped to the appropriate recycler for extraction of the precious metals.



Figure 4-7: MOSFETs, capacitors, and resistors on an older printed circuit board that must be removed by the electronic waste recycling facility before being shipped to a printed circuit board recycling facility. A PCB with such a high density of three-dimensional components is of less value than the newer, flatter PCB (Plant Manager of Com-Cycle Florida, 2009). Photo was taken by author in January 2010.

4.2. CRT Monitor Disassembly

The typical monitor consists of a printed circuit board, yoke, electron gun, a plastic outer casing and a cathode ray tube. From experience disassembling, workers at the Recycla plant have found that CRT monitors are more similar in design across manufactures than personal computers. The typical parts found in a CRT are displayed in Figure 4-8.

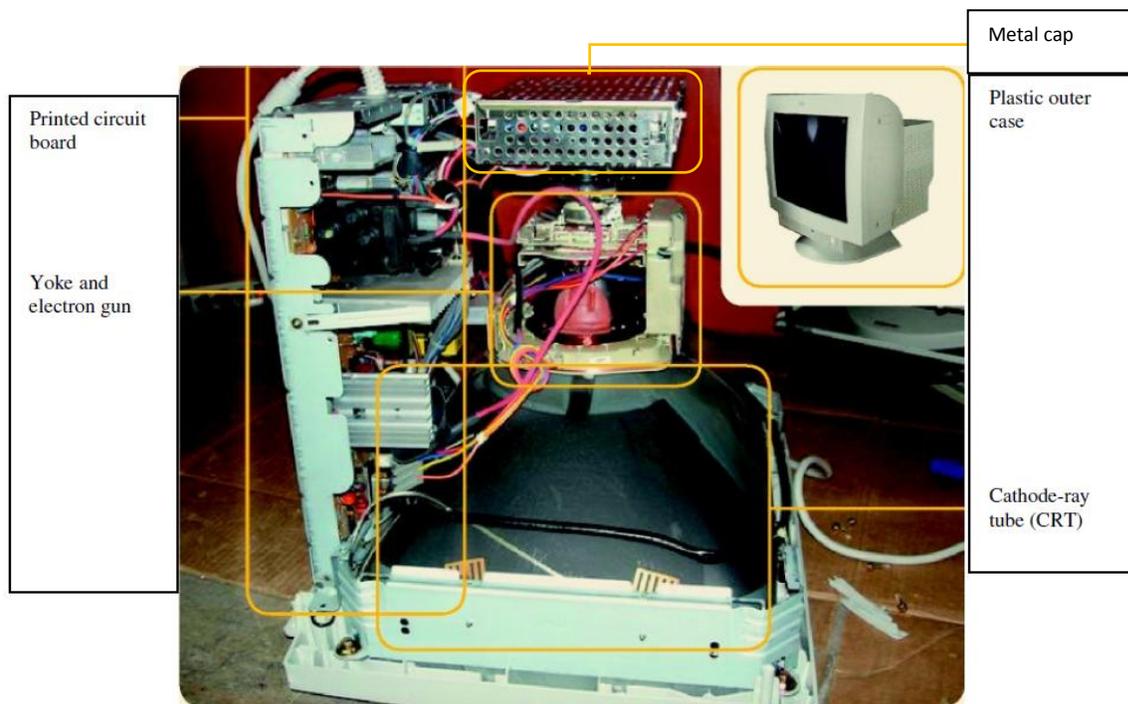
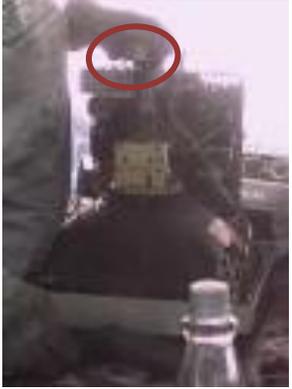
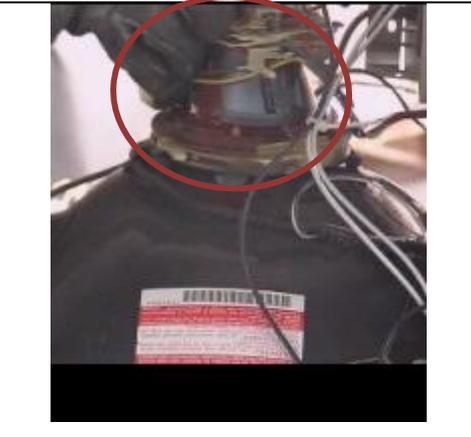


Figure 4-8: Diagram of the components of a CRT monitor (Centres de Formation en Entreprise et Recuperation).

The process of disassembling a monitor is outlined in Table 2. The worker must first remove the power cord and plastic casing of the CRT. Next most workers begin to remove the yoke off the electron gun. The yoke is one of the most valuable components of the CRT (Nilo, 2010). This requires cutting wires, removing the metal cap by pulling and twisting and then unscrewing the two metal clasps. The removal of the metal cap is one of the more dangerous activities in the recycling of a CRT. If the metal cap is twisted too much, the glass at the top of the electron gun snaps off and exposes the employee to the chemicals inside the CRT (including lead). The safety impacts of this are discussed in further detail in Chapter 7.2: Safety. Once the yoke has been removed, the CRT can be unscrewed from the plastic casing. The PCB generally slides out of the plastic casing and the employee must remove the three-dimensional components (including resistors, capacitors and MOSFETS) of the PCB, see in Figure 4-7. Table 2 is structured in a similar format as Table 1; the first column of Table 2 is used as a reference to identify the steps of the disassembly process. In the second column, the part removed is listed and an image is shown in the third column. The removal process is characterized by the tools and value of the material removed noted in the fourth column.

Table 2: Disassembly of CRT monitor by employee at Recycla in January 2010. These images were taken by the author.

Step	Part	Image	Tools/Actions Material
1	Power Cord		<ul style="list-style-type: none"> • Clippers • Generally valuable for the copper in the wire.
2	Casing		<ul style="list-style-type: none"> • Screwdriver (4 to 6 screws) and pulling • Plastic is the most valuable component of the casing.
3	Metal cap		<ul style="list-style-type: none"> • Pulling and twisting • The cap on the end of the is made of metal

Step	Part	Image	Tools/Actions Material
4	Wires		<ul style="list-style-type: none"> • Clippers • The metal cap is attached to the CRT with wires which are valuable for their copper.
5	Clasp		<ul style="list-style-type: none"> • Screwdriver (1 screw) • The clasp is recycled for the metal it is made of.
6	Clasp		<ul style="list-style-type: none"> • Screwdriver (1 screw); this image also shows improper use of tools. The screwdriver is used to pry open the clasp. • The clasp is recycled for the metal.
7	Yoke		<ul style="list-style-type: none"> • Screwdriver and clippers for prying, cutting, pulling • The copper in the yoke is a very valuable commodity.

Step	Part	Image	Tools/Actions Material
8	Casing		<ul style="list-style-type: none"> • Screwdriver (4 screws) • The casing is composed of plastic
9	Cable		<ul style="list-style-type: none"> • Clippers • The copper in this cable is valuable.
10	CRT		<ul style="list-style-type: none"> • Clippers • The glass in the CRT is contaminated with lead
11	Wires		<ul style="list-style-type: none"> • Clippers • Wires cut from the PCB are recycled for their copper content

Step	Part	Image	Tools/Actions Material
12	PCB		<ul style="list-style-type: none"> • Screwdriver (8 screws) • PCB's contain precious metals and hazardous materials that are extracted offsite
13	Power Supply		<ul style="list-style-type: none"> • Screwdriver (5 screws) • The power supply is removed for aluminum and precious metals.

One of the challenges of an electronic waste recycling plant is standardizing the process of disassembly. Currently the volume of the electronic waste stream (only 4% of solid waste) is not large enough to afford a more detailed segregation of discarded electronic products. Thus, plants must deal with a varied material input from refrigerators to televisions to radios. Within each of these product categories, each manufacturing has their own design and parts. Workers must be adept, flexible, and creative to accommodate a range of electronic waste and use various techniques to disassemble them.

The plants interviewed in this study do not mandate a specific procedure for the disassembly of electronic parts. Instead, the individual workers are expected to develop their own system for disassembling. Thus, the process of disassembly for any given product, from plant to plant, is almost identical.

5. Data Collection Methods

To compare plants and identify procedures that will reduce costs and improve safety, it is necessary to identify the dimension and layout of each facility. Photographs are very helpful for reconstructing the plant layout and dimensions; however they offer little if any information about the electronic waste disassembly process. In addition to photographs, a quick notebook sketch of the plant layout is invaluable when trying to stitch together images.

To look specifically at the disassembly process in an electronic waste recycling plant, a researcher has many methods of observation at his or her disposal. For the most information about the processes of disassembly, *known observation* is the best method. In this circumstance, the employee is constantly aware that you are observing his/her actions. In an ideal case, there would be two data collectors. One person is in charge of videotaping and zooming in and out to record the fine details of the employee's movements. In general, the employee will be standing or sitting with their disassembly work on a table. The employee is surrounded by small containers for the pieces of e-waste. As the employee disassembles, the material is distributed into the appropriate bin. The cameraman should be sure not to interfere with employee's recycling process. The second person, armed with a stopwatch and clipboard is responsible for making observation and recording the time of those observations for future reference and ease of data analysis. After the data collection session, the employee, camera man and the second data collection person could review the tape together. Any questions about the process or an action by the employee could be clarified on the spot. In this study, data collection was done by one individual without the opportunity to interview the employee about his/her actions. This method, known observation, has drawbacks as well. Observed employees are likely to recycle equipment at a faster rate (6.3 minutes for desktop computers) than if they are not observed (7.2 minutes for desktop computers). These results will be discussed in further detail in Chapter 6: Data Collected from On-Site Visits. In addition, the observed employee is likely to take fewer and shorter breaks and not converse with colleagues while being watched.

To obtain an estimate of time for required to complete disassemble an electronic product there are two methods. For a coarse estimate of the time, *self-reported observation* is most efficient. Employees can be responsible for recording the type of equipment dismantled, start times, and end times. It is important to clearly define the start and end of dismantling (does it include travel time required to bring the electronic product from palette to workstation?). In thus study, the time required to bring the electronic waste product from the palette to the workstation was not included. In addition,

it is important to clarify that accurate time measurements are valued, thus if an employee forgets to record the start time, he/she should make note of this, and not estimate the start time. From the experiences of this study, there was no significant difference between the times recorded by employees and the times identified from video observation. To double check this, it is recommended that the camera be left unattended but on and pointed towards employee while the employee is responsible for filling out time sheets. Reviewing the video tape provides a second check on the data.

For a detailed, fine-grain estimate of the time required to complete certain tasks in the disassembly process, *hidden observation* is the best method of collecting data. The physical person holding the camera and watching the actions of the employee real time produces a behavioral change in the employee. When observed by camera alone, employees seemed to revert back to their usual routines of longer breaks and conversation with other employees. This data is not as detailed as known observation as the camera does not follow the movements of the employee; however it provides a more accurate description of the employee's work process. Thus, hidden observation is the most valuable method of data collection.

It is important to remember that data collection is limited by physical constraints of battery power or hard drive space. Low resolution (640 x 480) is adequate to observe the actions of the employee. Critical equipment parameters include battery life and data storage. Access to a power outlet and large hard drive space or real time compression software is extremely valuable. This will enable continuous filming and a more accurate picture of electronic waste recycling.

In the process of collecting data from electronic waste recycling plants, researchers must pay attention to how they are disrupting the typical environment of the plant. Just observing will change the quality and quantity of data that can be collected. To reduce this effect, it is important to remove the traces of observation. Thus, without the physical presence of a camera man, the employees are much more likely to behave as they normally would. For accurate results, unknown observation is best.

6. Data Collected from On-Site Visits

Each of the plants visited in Germany, the United States, and Chile has a different factory floor design. However despite the physical differences in physical size of the plants, each floor layout consisted of three main subcomponents: the disassembly area, the incoming material area and the

outgoing material area. In addition, data on the disassembly time for desktop computers and CRT monitors was collected for the United States and Germany. In the German plant, employees were mentally handicapped and thus, their recycling rates were significantly slower than the employees at the United States and Chilean plants.

6.1. Plant Layout

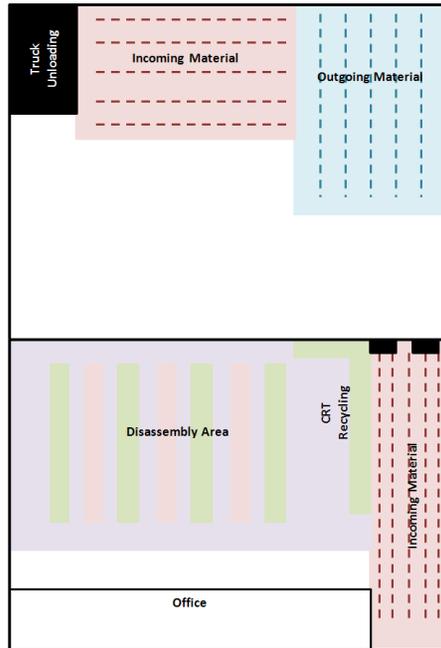
The plant layout for the electronic waste recycling facilities in Germany, the United States and Chile are sketched in the respective column of Table 3. These diagrams are created from sketches, videos, and pictures taken from site visits. Each of these facilities has the same basic units: Incoming Material Storage, Disassembly Area, and Outgoing Material Storage. The size of these units (with respect to plant) does not differ significantly across plants, however the details of how each unit is set-up is of interest and will be discussed further in Chapter 7: Plant Recommendations.

The plants in Germany, the United States and Chile all share similar methods of electronic waste recycling techniques as discussed in Chapter 4.1: Desktop Computer Disassembly and 4.2: CRT Monitor Disassembly. However the layout of the disassembly area shows some significant differences. The German plant, in the first column of Table 3, has tables in the Disassembly Area separated by export material. Employees turn from their desk and walk behind them to get more material to disassemble. In contrast, the plant in the United States does not bring electronic waste close to the disassembly workers. Employees at the far side of the Disassembly Area must walk to the pallets located in the Incoming Material section. Finally, the Chilean plant is compromise; pallets are brought from the Incoming Material area to the disassembly workers.

Table 3: Diagram of plant layout for facilities in Germany, the United State and Chile estimated from on-site sketches, videos, and pictures. Dimensions are approximate.

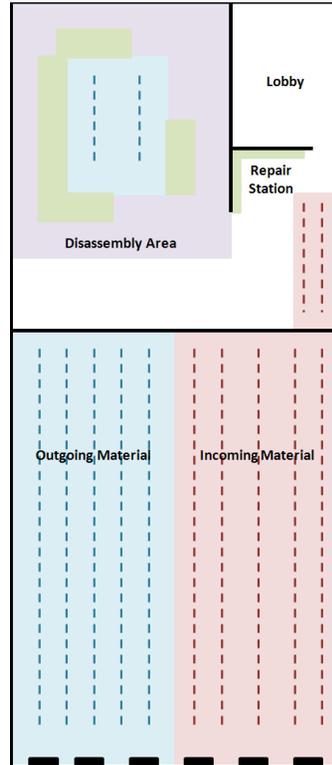
31

Recyclingpartner (Germany)



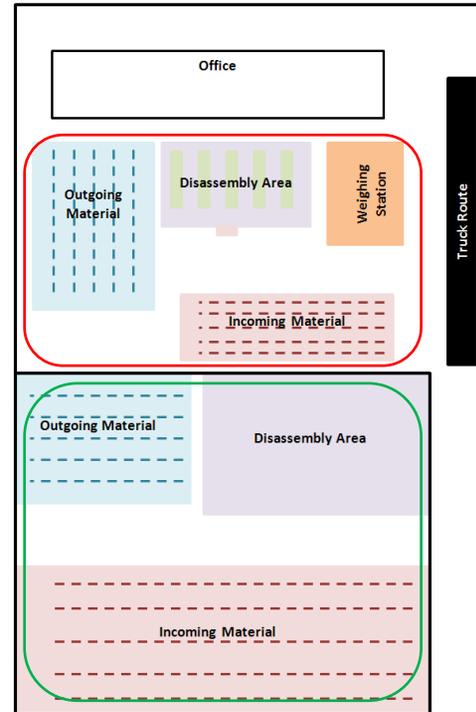
Dimensions: 90ft by 150ft = 13,500 ft²

Com-Cycle (United States)



Dimensions: 70ft by 175ft =
12,250 ft²

Recycla (Chile)



Dimensions: 150ft by 110ft = 16,500 ft²



Note: The diagram of the Chilean plant shows almost two replica plants; one outdoor facility outlined in red and an indoor facility outlined in green. When data was collected in January of 2010, the plant was in the process of expansion. The outdoor facility, near the office, was actively used while the indoor facility, enclosed in a black box, was being constructed. When the plant is completed (expected in the summer of 2010), there will be duplicate Disassembly Areas and space for overflow storage, as suggested in the diagram. Diagram created by author.

The differences between the Incoming Material and Outgoing Material storage areas are easily distinguished through pictures. Table 4 shows images from three electronic recycling plants. Each column identifies pictures from Germany, the United States and Chile. The rows correspond to different areas of the recycling facility: Incoming Material, Disassembly Area, and Outgoing Area. For reference, the square footage per employee is also listed in the last row.

Table 4: Comparison of electronic waste facilities in Germany, the United States and Chile. Images from Germany are at the Electrocyling plant in Goslar. Images from the United States are from the Com-Cycle plant in Melbourne, Florida. Images from Chile are from Recycla in Santiago. All photos are taken by the author.

	Recyclingpartner (Germany)	Com-Cycle (United States)	Recycla (Chile)
Incoming Material			
Disassembly Area			
Outgoing Material			
Area (ft ²) Workers	1350	2,041	1,269

As discussed in Chapter 4: The Flow of Electronic Waste through the Plant, German plants receive electronic waste from municipality collection centers. When the electronic waste arrives at the

plant it is often broken and difficult to balance on pallets. In contrast, the Outgoing Material Area for all three plants shows the usage of large containers (metal, cardboard and plastic) for the storage of wires, plastics, printed circuit boards, and other materials ready to leave the plant.

It is interesting to note that the plant in the United States has the highest ratio of square feet to disassembly employees. Tons of electronic waste processed from the plants is proprietary information, otherwise, it would be interesting to see which plant makes the most efficient use of space (Smith, 2010). However, using estimates found for the recycling rate of different electronic waste components, it is possible to estimate the quantity of electronic waste each plant processes.

6.2. Recycling Rate

Since this study has so few data points, it is important to be suspect of the results and conclusions drawn, however the qualitative observations should be given weight as the net sum of on-site visitation for all four plants exceeds 69 hours. In particular, the observations about the electronic waste recycling plant in Chile received the most attention (a total of 3 weeks were spent working with the electronic waste recycling plant).

From the video data of plant employees disassembling desktop computers and CRT monitors, the steps and techniques for disassembly were determined and discussed in Chapter 4: The Flow of Electronic Waste through the Plant. In this section, the video was used to measure the time each task takes. Because many of the employees at the German recycling facility suffered from mental illnesses and physical handicaps, the German recycling data is not presented in this study. Instead, only the plants in the United States and Chile are compared.

According to the CEO at Synergy Recycling in West Virginia, USA, “a general rule in hand disassembling of computers or monitors is approximately 8 - 12 per person per hour” (Clayton, 2010). This corresponds to between 5 and 7.5 minutes per computer or monitor for disassembly. At Com-Cycle in Melbourne, FL, USA, two employees were recorded recycling a desktop computer. Their recycling times fell within the range suggested at 5:23 and 6:01 minutes.

The data collected at the Chilean plant was much more descriptive. Figure 6-1 and Figure 6-2 show the self-reported recycling time required to disassemble CRT monitors and desktop computers at Recycla respectively. Along the x-axis, disassembly times range from 5 to 30 minutes and quantity of product (CRT monitors and desktop computers) spread from 0 to 60 along the y-axis. In Figure 6-1 ,

monitor disassembly, 7 employees disassembled 93 monitors. In Figure 6-2, desktop computer disassembly, 5 employees disassembled 107 desktop computers. When the disassembly time is calculated, the time required to transport the electronic waste product from the palette to the workstation is not included.

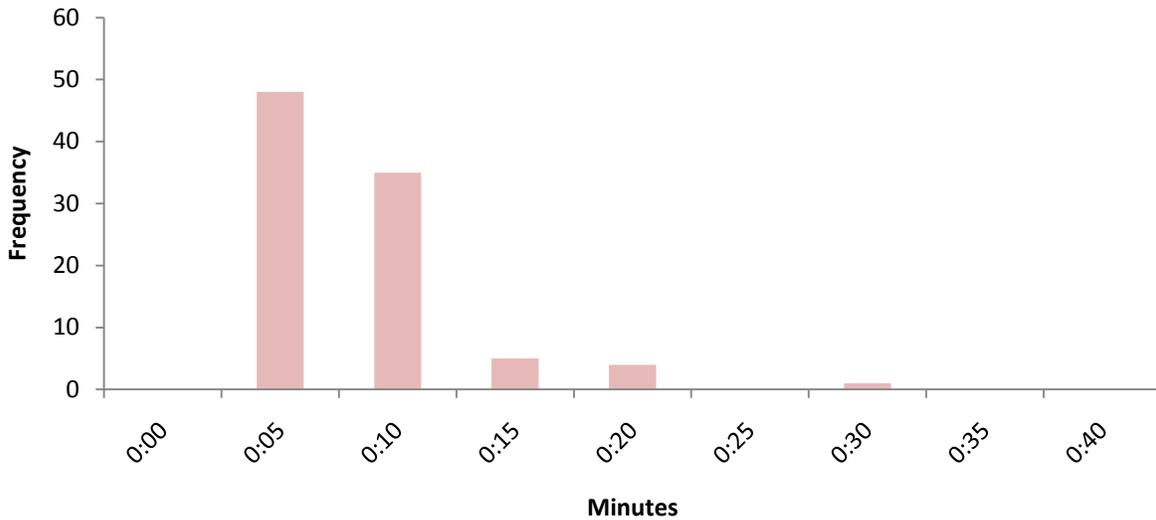


Figure 6-1: Graph of CRT monitor disassembly time shows the self-reported monitor disassembly by 7 employees at the Recyclia plant. A total of 93 monitors were disassembled.

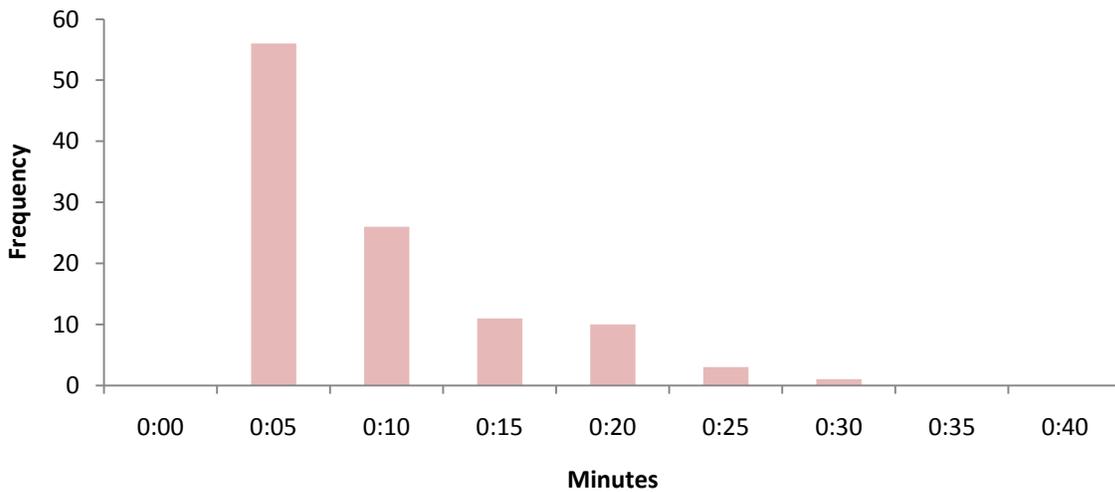


Figure 6-2: Graph of desktop computer disassembly time shows the self-reported desktop computer disassembly by 5 employees at the Recyclia plant. A total of 107 monitors were disassembled.

The distributions in Figure 6-1 and Figure 6-2 show a significant range in disassembly time for both CRT monitors and desktop computers. This range can be explained by the differences in employees. At the disassembly plant, there are temporary workers who consist of engineering students satisfying their program internship requirements and temporary employees who are hired when there is an over flow of material in the plant. These temporary workers rarely work at the plant for more than three months and therefore have little loyalty or investment in the company. These employees have an average disassembly time of 16.4 minutes for CRT monitors and 20.1 minutes for desktop computers. In comparison the permanent employees have been employed by Recycla from 1.5 to 4 years. Their average recycling time for monitors is 6.2 minutes and 6.8 minutes for desktop computers.

The recycling time of desktop computers in Chile can be directly compared to the recycling time of desktop computers in the United States. There seems to be a substantial difference between the observed recycling time of employees in the United States and in Chile. However it is important to note that employee's recycling times during known observation (the employee can see the cameraman filming while he/she is working) speeds the recycling speed. In addition, the number of data points collected (only two individuals in the United States and five employees in Chile) is too low to make any conclusions about significance. However, it is quite clear that the average recycling time of 7 inexperienced Chilean employees is much higher than the employees in the United States and Chile.

Table 5: Comparison of average desktop computer recycling times (in minutes) by employees in the United States and Chile. This data was collected using known observation. The cameraman was visible to the employee.

United States (minutes)	Chile (experienced)	Chile (inexperienced)
5:42	6.48	20.06

Using these time estimates and the number of employees at each plant, the quantity of electronic waste recycled at each plant can be approximated. Assuming that each electronic waste recycling plant only recycles desktop computers for an entire year, how many tons of electronic waste will be recycled and what percent of the market in each country will the plant capture? Several assumptions must be made. Since data on the time to process electronic waste in Germany was not collected, it is assumed that employees process at the same rate as inexperienced employees in Chile. In addition, the number of working days is adjusted for the typical number of holidays and vacation days in each country.

These estimates are displayed in Table 6 where the number of employees in each plant and the average time to recycle a desktop computer is taken from the data collected in this study. Each country had different labor laws and national holidays, but assuming a work day of 8 hours and the appropriate number of work days in each country, the raw number of desktop computers recycled annually is calculated. For comparison, the raw number of desktop computers recycled annually is compared to the number of desktop computers sold in each country in 2008. The final, bolded row, presents the percent of the number of desktop computers sold in each in 2008 that could be recycled by the respective plant if that plant were to dedicate its resources *solely to recycling desktop computers*.

Table 6: Assuming each plant only recycled desktop computers, this table presents the quantity (tons) of desktop computers that could be recycled annually. In addition, the quantity of desktop computers is compared to the number of computers sold annually in each country (Consumer Electronics, 2010)

<i>Assuming the plant only recycles desktop computers</i>	Germany	United States	Chile	
			Experienced Employees	Inexperienced Employees
Number of Employees	13	6	7	6
Time to Recycle a Desktop Computer (seconds)	1206	342	408	1206
Number of Computers recycled per day by all employees at the plant	310	505	637	
Number of Working Days	222	240	234	
Raw Number of Desktop Computers Recycled Annually	68919	121263	149152	
Number of Computers Sold 2008 (in millions) ¹	1.30	11.97	0.33	
Percent of Market	5.32%	1.01%	45.47%	

This exercise allows a comparison to be made between the quantity of electronic waste produced and the capacity an electronic waste recycling plant can handle. These estimates of the quantity of desktop computers recycled are an upper bound on the quantity a plant could recycle. If these estimates are accurate, the United States would need about 100 electronic waste recycling plants (of the same size) in order to take care of the number of desktop computers sold in 2008. Desktop

¹ Data collected from Consumer Electronics: Euromonitor from trade sources/national statistics.

computers are only one of the hundreds of products disassembled by electronic waste recycling facilities.

A further breakdown of CRT monitor processing at Recycla is shown in Table 7. The data was collected by reviewing hidden observation video data. Wasted time corresponds to time spent sorting the components of electronic waste (such as the printed circuit boards, plastic, aluminum, etc).and time spent not using tools (socializing or taking breaks). On average about a minute is wasted. This wasted time (about 15%) includes time to socialize with co-workers and time sorting the components of the electronic waste product (bending over and placing electronic waste components into bins located under the workstation or walking to bins not near the workstation). The average time to disassemble a CRT monitor was 7:03 minutes within the range suggested by the CEO of Synergy Recycling.

Table 7: Average monitor disassembly time of employees at Recycla in seconds

Average Disassembly Time (seconds)	
Total Time	443
Removal of Plastic Casing	96
Removal of Cap	24
Removal of Yoke	51.3
Removal of CRT	114
Removal of Plastic Front from PCB	79.7
Removal of Wires from PCB	76.5
Wasted Time	67

At the Recycla, a small scale experiment was conducted where an employee recycled three desktop computers in a row twice. In the first round, the employee sorting the components while disassembling the computer (as is normally done). However, she did not have travel back and forth to the palette to retrieve a new product. In the second round, the employee waited until the end (the disassembly of all three computers) to sort the material components of the desktop computers. When waiting until the end to sort electronic waste components, 40 seconds are saved per computer as shown

in Table 8. In addition, time to recycle each computer decreases by over a minute when the employee does not have switch tasks from disassembling to sorting.

Table 8: Disassembly of a desktop computer by employee at Recycla. In the first round (column 2), the employee sorted the waste while disassembling. In the second round (column 3), the employee sorted the waste of all three computers at the same time.

Time (seconds)	Sorting while Disassembling	Sorting after Disassembling
To recycle per computer	356	291
To sort per computer	63	22.3
Total per computer	419	313.3

In summary, across the electronic waste recycling plants examined, the similarities outweighed the differences. Every plant is composed of discrete units for incoming material storage, disassembling and outgoing material storage. In addition, the differences between disassembly rates for employees in the United States and experienced workers in Chile do not show significant differences for both the disassembly of desktop computers and CRT monitors.

7. Plant Recommendations

The data collected from the plants in Germany, the United States and Chile can be used to inform facility plant design. This section will use both the qualitative impressions and data collected from the plant visits to discuss how electronic waste recycling can be improved and optimized.

7.1. Design for Disassembly

To improve the recycling rate it is pertinent to address the source of the problem: electronic product manufacturers. The principles of manufacturing often directly conflict with features that are easy to disassemble. Joining processes like gluing and snap fits are potentially more economical when assembling. However, when disassembling, it becomes more difficult to separate and identify different materials. Prying and pulling require much more physical effort from disassembly employees. In addition, there is always the risk that materials do not completely separate and become contaminants in the end recycled product. Electronic equipment designers and manufactures should consider the costs associated with disassembling products when creating new models. Germany has successfully

implemented the beginning stages of a legal framework that filters the cost of disassembling back to the electronics producers. The United States and Chile should learn from the program implemented in Germany to inform their own decisions about electronic waste recycling.

There needs to be a feedback loop where the producers of electronic products have an incentive to reduce the environmental impact of that product at the end of its life cycle. Whether the impact is reduced through faster recycling times or the elimination in hazardous materials may depend on the technologies available and the consumer market. However, incorporating the end-of-life cost of each product into the design and market price will be critical to maintaining a healthy public image.

7.2.Safety

Employee and environmental safety is an enormous concern from a legal and personal stand point. While countries around the world have different standards for employee protection, some basic standards of physical safety must be met.

Chemical Hazards

According to an ODEC document, the primary sources of hazard from handling e-waste include barium oxide and phosphors (from dismantling CRT monitors) and lead (from dismantling CRTs and printed circuit boards). Short term exposure to barium oxide can result in “[irritation] to the eyes, the skin and the respiratory tract” and may result in death. (International Programme on Chemical Safety and the Commission of the European Communities, 1999). Exposure can be mitigated through the use of proper safety equipment such as gloves and protective outerwear.

While many e-waste recycling facility managers deny it, broken CRTs are common phenomena when recycling electronic waste. Removing the metal cap off the CRT requires an experienced finesse. Inexperience and fatigue contribute significantly to the breaking CRT tubes. From experiences at the electronic waste recycling plant in Chile, this study has found that even experienced employees (defined as working at the plant for one year or more) tend to break the CRT glass 15% of the time. During the winter, employees that work in outdoor facilities estimate that this rate increases (Mauricio, 2010). Exposed to the cold weather, employee’s fingers become numb from the cold or bulky from gloves, impeding their ability to appropriately remove the metal cap. When disassembling a monitor, the portion of the glass at highest risk for fracture is the neck, circled in red in Figure 7-1 and Figure 7-2.



Figure 7-1: Cathode Ray Tube Neck. The Red circle marks the location of the CRT neck. Photo taken by author.

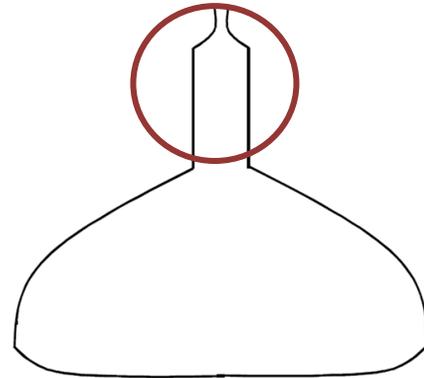


Figure 7-2: Cathode Ray Tube Diagram. The Red circle marks the location of the CRT neck (Townsend, Musson, Jang, & Chung, 1999).

According to a study at the by Timothy Townsend at the University of Florida, 36 monitors and televisions from various manufactures (including Panasonic, Acer, Gateway, IBM, HP) were tested for leachable lead concentration according to the United States EPA toxicity characteristic leaching procedure. The maximum concentration found in the neck of 36 CRTs was 22.4mg/L with an average of 8.67mg/L. The histogram in Figure 7-3 shows the distribution of leachable lead concentrations from the report.

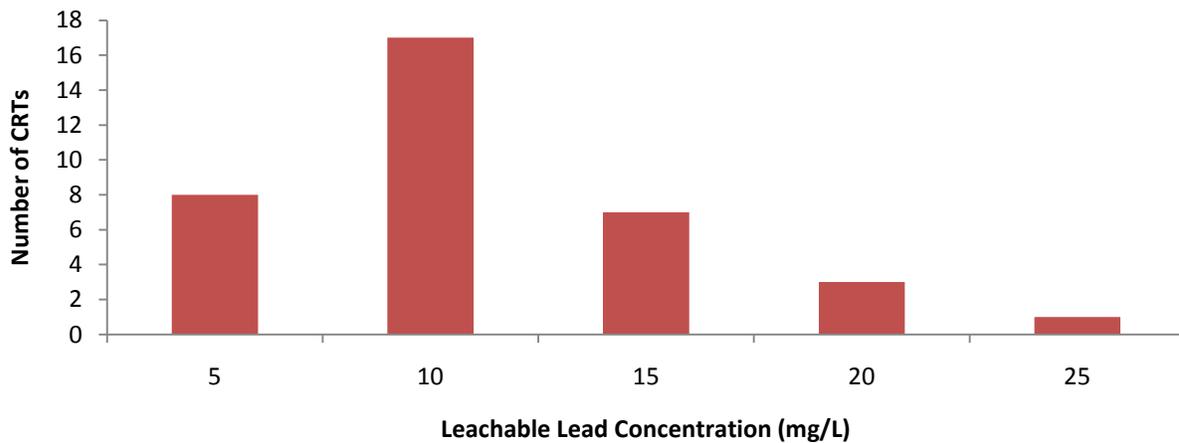


Figure 7-3: Histogram of leachable lead concentration in the neck of 36 CRTs used as computer monitors and televisions (Townsend, Musson, Jang, & Chung, 1999).

In the United States, the regulatory limit of 5.0 mg/L is exceeded by more than half of the monitors examined (Townsend, Musson, Jang, & Chung, 1999). In addition to lead, airborne beryllium dust or vapor has been linked to chronic lung disease at concentrations as low as 0.01 $\mu\text{g}/\text{m}^3$. At Noranda, Inc, several employees have been diagnosed with chronic beryllium disease (Global Resources Foundation, 2003). It is critical to protect workers inhalation of airborne lead particles.

While the chemical hazards for high temperature processing of many electronic waste components are well documented, it is important to note that in many circumstances, e-waste is left in an unprotected, outdoor facility where it is exposed to a range of temperatures and weather conditions. A comprehensive study of the damage caused by this exposure to natural elements has not yet been conducted.

Physical Hazards

Aside from chemical hazardous, there are many physical hazards when working in an e-waste disassembly facility. The manual methods of separating materials often require hammering and prying, thus shards of metal and plastic fly off the equipment and pose a hazard. When using both power and manual tools, safety glasses should be worn at all times. In Figure 7-5, an employee is disassembling a CRT by pulling a screwdriver towards her body. Employees should be instructed in safe use of tools. Pulling sharp or blunt objects towards one's body is dangerous. In addition, prying off the CRT plastic casing has cause a plastic shard (circled in red) to fly near her face, a glaring warning that safety glasses should be standard equipment for employees.

By the end of the day, there is a thick layer of clutter (for example, plastic and metal shards and loose screws). It is common practice in all four electronic waste recycling plants studied to sweep the facility clean at the end of the day. However, the quantity of clutter on the floor makes it difficult for employees to move back and forth between their workstation and the pallets of equipment (reducing the recycling rate) and the clutter increases the risk and damage if one of the employees trips and falls in the plant. From both an efficiency and safety perspective, plant managers must enforce more frequent clean-up practices.

Facility Rules

To eliminate employee risk to hazards, several safety precautions must be enacted. Each disassembly facility should have a poster of workplace rules that can be read from all areas of the facility (OECD, 2003). These rules should include, but are not limited to:

1. No eating, drinking, or smoking at the workbench.



Figure 7-4: Employee drinking at workstation, particulates at the workstation could easily be ingested by the employee through the water. Photo taken by author in July 2010 in Santiago, Chile.

2. Wear a dust mask and safety glasses at all times while in the disassembly facility.



Figure 7-5: Photo of employee without safety glasses; a piece of plastic, pried up from the monitor has flown as high as the employee's face. Photo taken by author in July 2010 in Santiago, Chile..

3. Employees may only wear company designated work clothing while in the disassembly facility.
4. Before exiting the facility, employees must wash their hands.
5. The floor space in the facility must be clear at all times.
6. Earplugs must be worn when operating heavy machinery.
7. No smoking in disassembly facility



Figure 7-6: Photo of employee smoking in disassembly facility. Photo was taken by author in July 2010 in Santiago, Chile.

A standard safety protocol for each facility must be developed and adhered to, for the protection of the employees. These rules should be taken seriously by the employees and plant managers. Disobedience or forgetfulness should not be excused, but instead, serious action should be taken.

7.3. Workstation Design

Examining the workstation for disassembly employees across plants, there is a common theme of clutter and disorganization. Employee's tool boxes consist of duplicate tools which makes searching for the correct tool laborious. From the observations of the disassembly process for various electronic waste products, this study suggests that the toolboxes of employees be narrowed down to only the essential tools required for disassembling. In the plants in China and the United States, to avoid wasting time by searching for the correct tool in a toolbox, many employees would identify the critical tools and leave them on the table for easy access. The toolbox would remain on the table, as shown in Figure 7-7, limiting the space available for disassembly.



Figure 7-7: Employee at Recycla accessing toolbox for screwdriver. Photo was taken by author at Recycla plant in January 2010.

After reviewing the videos collected at the Recycla and Com-cycle plants, the following tools are used most often in electronic waste disassembly:

1. 1 Screwdriver with the following bits
 - a. 2 Flat head bits
 - b. 2 Phillips head bits
 - c. 2 star bits
 - d. 2 hex bits
2. 1 Wedge
3. 1 Electrical wire clipper
4. 1 hammer
5. 2 vise clamps

In Germany, instead of toolboxes, tools were kept in small drawers under the disassembly table. From observation, this study recommends this method of storing tools. Drawers under the table do not limit the floor space under the table and also do not clutter the top of the table. It is recommended that tools are stored in drawers under the table and not toolboxes onto of the table.



Figure 7-8: German disassembly worker keeps tools in drawer circled in red. Photo was taken by author.

While these tools will not be most efficient to tackle every piece of electronic waste seen at plants, however they will be capable of disassembling common products such as printers, laptops, CRTs, flat screens, cell phones, desktops, etc. Electronic waste recycling facilities also receive a variety of other electronic products but in much smaller quantities. For less common products such as refrigerators, plants should devote specific workstations for unique products or hand out specialized equipment only when necessary.

7.4. Disassembly Line

Manual electronic waste disassembly facilities are set up in a similar manner. Each employee is assigned to a workstation and is responsible for moving electronic products from storage pallets to their workstation for dismantling. The components of the dismantling process (plastic, metals, copper, PCB, etc.) are then collected at the individual workstation into a larger storage container. In addition, the employees at electronic waste recycling plants seem to fall into two categories. The experienced employees who are adept at disassembling and the temporary employees who do not have the skill set.

In response to this dichotomy, it seems the skill sets of both types of employees can be maximized through a separation of tasks. Figure 7-9 shows a schematic of the disassembly line proposed. Disassembly workers line up along the sides of a conveyor belt. The disassembly workers bring the electronic waste products from the pallets (in dark blue) to their workstations. At the workstations, they disassemble the product and place all by products on the conveyor belt (in black). This conveyor belt shuttles material onto a larger table where sorting employees (temporary workers) are responsible for segregating the material into bins (in purple).

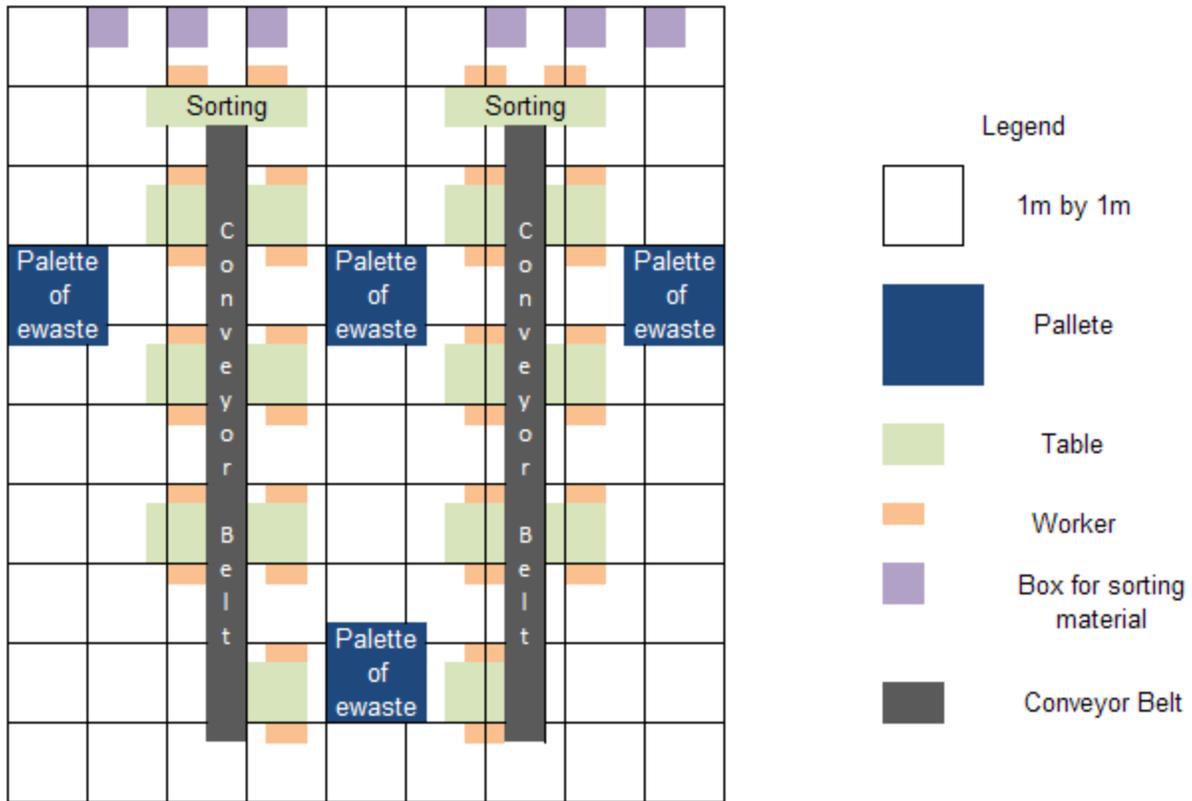


Figure 7-9: Diagram of disassembly line separating the process of disassembly from sorting. Diagram created by author.

The ratio of disassembly to sorting employees will vary from plant to plant and require individual adjustment. According to the information from the Recycla plant, on average permanent employees take 6.2 minutes for monitors and 6.8 minutes for desktop computer disassembly. Therefore, Recycla should start this disassembly line with a ratio of 7 disassembly employees to 1 sorting employee. The disassembly line proposed in Figure 7-9 is not a technical drawing, but merely a suggestion of how electronic waste recycling plant disassembly areas can be designed for better recycling efficiency. The ratio of disassembly employees to sorting employees shown in Figure 7-9 is recommended for the Recycla plant.

In summary, to decrease the cost of electronic waste recycling, many aspects of the plant design should be adjusted. First of all, the electronic products themselves can be design for easy disassembly.

Safety and cleanliness inside the plant should be a high priority for both cost saving benefits and employee protection. In addition, the tools used by employees to disassemble electronic products should be standardized and not interfere with the disassembling process. Finally, experimentation with the disassembly line itself may yield a higher recycling rate.

8. Conclusions

The electronic waste recycling industry has many similarities and differences across countries. For nations as developed and industrialized as Germany, the United States and Chile, the wide range of legal frameworks that characteristics and support the industry is surprising. However, given these differences in government, business and social support, the factory floor operations of electronic waste recycling facilities in each country are surprisingly similar.

The similarities in the set-up of the plant in electronic waste recycling facilities can be attributed to the limited number of available methods to design a factory and the limited number of ways to manually disassemble electronic waste. Considering the precarious economic foundations upon which this industry rests, it is not surprising that plant managers do not take the initiative to experiment with different methods of recycling. A significant reduction in the recycling rate could potentially risk the profitability of the business.

The goal of this study was to identify procedures that would increase the recycling rate and thus decrease the cost of recycling. Because of the similarities between plant set-ups and recycling techniques, recommendations for recycling rate improvement can be made as a whole instead of country specific recommendations. While several ideas are developed in Chapter 7: Plant Recommendations, there is little evidence that the reduction in cost will make a dramatic impact on the price of recycling electronic waste. Even if the recycling rate were to double, and the cost for recycling each desktop computer were miraculously halved to under 15 dollars, this lower price would not compete with the cost of land filling or incineration.

With trends towards minimization and the removal of hazardous waste in electronic products, perhaps the electronic waste recycling industry will become obsolete. With smaller electronics, the pure quantity of natural resources to collect and recycle may not outweigh the potential for energy generation through incineration or gas production in landfills. However, more likely, with the decreasing cost and wide-spread availability of electronic products, recycling the raw materials will be a

critical part of the continued production and improvement of electronic products. Will the government of every nation realize the benefit in subsidizing this industry? Will the quantity of electronic waste recycled ever justify the creation of automated disassembly machines? Only the future will tell.

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