ECONOMIC MODEL FOR END OF LIFE MANAGEMENT
OF PRINTED CIRCUIT BOARDS

by

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ABSTRACT

The objective of this research is to develop an economic model for the recycling of printed circuit boards. The process of extraction of copper using traditional recycling methodology is considered. Both cost and energy models are develop for this process. The various factors affecting the costs are identified and the assumption of linearity between the individual costs and the total cost is validated using test of hypothesis. The costing methodology used is activity based costing. All the activities and cost centers are defined and the total cost is arrived at.

The energy calculations are performed by analyzing the energy inputs that go into each process step. The energy computation is then made based on these energy inputs and the total energy is arrived at.

The cost and energy models are validated by making use of a case study. Also, the energy estimate for new process of recycling like super critical fluids is computed based on the energy model developed. The economic model provides a framework where both cost and energy calculations can be performed and the process can be evaluated and improved upon.

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CHAPTER I

INTRODUCTION AND PROBLEM STATEMENT

1.1 Introduction

In this changing technological scenario with humongous industrial advancement going on human development has come a long way. A great achievement, but the dark side to this brilliant facet is the environmental degradation as a product of all the progress. With the rapid increasing advancements in electronic technology, electronic products that were formerly thought of as cutting edge are becoming obsolete at a very high rate. By becoming obsolete these products are unwanted and subject to disposal. The disposal process is usually through the use of landfills, thus becoming electronic scrap. Electronic scrap is waste generated by used manufactured electronic products such as obsolete computers, televisions and telephones. Landfills are now increasingly reaching their capacity largely due to this electronic scrap. Also, the disposal of electronic components and products in landfills are just a temporary measure and since these wastes do not degrade they remain poisonous forever.

Many European countries have come up with legislations which ban the use of landfills for electronic components and non-degradable substances. Japan already has a national law on recycling home appliances. The European Union is working with its member states on a broad directive that includes product take back and specific recycling goals for all types of electronic products. With legislations in place, land filling will no longer be an option. End of life management of these products in a safe and environmentally manner is the only alternative that we all can arrive at.

End of life management deals with the process of managing and trying to dispose, reuse, recycle or remanufacture products that are becoming obsolete or have reached the end of their useful life. End of life Management can be considered as a reactive approach. The main concern with the end of life management is to reduce the environmental impact of these old and obsolete products and to dispose them in a safe and friendly manner. The concept of the end of life management started parallel with life cycle analysis and for all practical purposes can be considered as a part of it.

Unlike the traditional product life cycle, end of life management consists of a closed loop. The original equipment manufacturer also has to take care of the disposal of the product. Collection of the product after its useful life is undertaken and classified. It is then taken for the appropriate disposal method and the product is recycled, reused or remanufactured.

End of life Management can be implemented, planned for and can be incorporated by various techniques. Some of these techniques are general in nature and incorporate end of life management during the planning and design stage itself. These methods can be considered proactive in nature and the others reactive. Some of the main techniques are listed below:

1. Life cycle Analysis and Environmental Life Cycle Analysis,
2. Modularity Analysis,
3. Design for Environment,
4. Recycling, Reuse and Remanufacture.

In this thesis, I have addressed the issue of recycling, reuse and remanufacture of printed circuit boards. Printed circuit boards are used in all kinds of electronic circuits, from simple one transistor amplifiers to the largest super computers. Today, printed circuit boards come in all shapes and sizes, small to large. Some boards contain integrated circuits and some bare (unpopulated), which all may be recycled in some capacity. With a recovery and recycling process these electronic scrap materials could produce potential environmental benefits and economical profits.

Recycling companies have tried to cope, using a combination of manual and automated processes to take apart these machines and recover valuable materials, such as metals and pure glass. But recycling companies still being in its nascent stage do not have the adequate technology, processes, techniques and models to counter this huge volume of electronic scrap. Recycling companies in conjunction with upstream manufacturers are working on end of life management of these electronic components.

In this thesis “Economic Model for End of Life Management of Printed Circuit Boards,” the end of life management of printed circuit boards is chosen and the extraction of copper from the waste stream is considered. The entire process of recycling is studied in depth and an economic model is developed. The economic model is classified into two main sections, the cost model and the energy model. Quantitative measures and metrics are evaluated and developed for each model. With an economic model developed, there is a basis for evaluating the money making and losing centers. Also, new processes for recycling can be evaluated based on this economic model. This model provides a

framework for modeling the cost and energy details involved in the process of recycling printed circuit boards.

This thesis has been structured into 6 chapters. Chapter I deals with the introduction, problem definition and the research objectives. Chapter II will deal with the literature review. Chapter III explains the process of recycling printed circuit boards and the extraction of copper. Chapter IV is divided into 2 sections, one explaining the proposed cost model and the other one dealing with energy. Quantitative calculations and metrics developed are illustrated in this section. Chapter V deals with the validation of the model by making use of a case study as an illustration. Chapter VI deals with conclusions and research contributions.

1.2 Problem Definition

Electronic waste is a growing environmental problem. Electronic waste is land filled, incinerated or recovered without any pretreatment, meaning that a considerable quantity of valuable material is both wasted and has the potential to leach into the earth around landfills or be released to the skies from smelters.

The problem of waste electrical and electronic equipment (WEEE) will be dealt with a new directive from the European parliament, which comes into effect between now and 2006. The legislation will place increasing environmental responsibility on producers and retailers of electronic goods. Measures will include the separate collection of WEEE from general municipal rubbish, better treatment of WEEE and recovery of materials, and better design of products to allow easy recycling. The aim is improved recycling and re-use of generic features of electronic waste such as printed circuit boards,

cathode tubes, cables, liquid crystal displays, batteries and components such as semiconductors, capacitors and resistors.

Responding to environmental concerns such as increasing landfill stress, the WEEE directive will extend recycling of base metals beyond what is currently economically feasible.

Base metals are, on the whole, fairly innocent by standers in offences against the environment. The most environmentally problematic substances are arsenic, chloro fluoro carbons, poly vinyl chloride and the flame retardants used in plastic covers and cables. Only lead makes it to the European commissions hit list along with other heavy metals such as mercury, chromium, and cadmium. But as major components in electronic goods, base metals recovery still plays an important economic role. The thesis addresses this issue, by considering the extraction of copper from printed circuit boards and developing the cost and energy models for the same.

This thesis addresses the problem of recycling printed circuit boards by building an economic model to compute and evaluate options in the recycling process. Since recycling technologies are still in their infancy and are mostly still driven by manual labor, there is no accurate cost data or models to deal with this problem.

Also, many researchers all over the world are focusing their energies to develop novel procedures in recycling printed circuit boards and extracting as much value as possible from it. But to do this efficiently, an analysis is required of the cost and energy consumptions involved in the process. This economic model for the traditional recycling process will serve as a guideline to build better technologies for recycling these boards.

1.3 Research Objectives

The main objectives of the economic model are as follows:

1. To establish the linearity relationship between the total cost and the individual costs and validate it using tests of hypothesis.
2. To build a model which will give an account of the costs involved in the activities defined in the process or system.
3. To provide a basis for cost and energy calculations of the process in the same model.
4. To validate the activity based cost model using a case study.
5. To implement or calculate the energy estimates for innovative processes such as super critical fluid based technology.

CHAPTER II

LITERATURE REVIEW

The literature review is divided into 3 sections namely, the various life cycle cost analysis models, literature review on activity based costing and the recycling of copper. Many papers were reviewed pertaining to the topic of cost and energy models during end of life cycle analysis approach. It was found that not much work has been done in this area and much is yet to be done. The literature survey addresses the costing procedures during the design and manufacturing stages of the life cycle, but does not deal in detail during the end of life stage. Also, the advantage of using activity based costing procedure is detailed in the literature review section.

2.1 Life Cycle Cost Analysis Models

In their paper, “Environmental life cycle cost analysis of products”, Kumaran et.al (2001) incorporate eco costs into the total cost of the products. The authors mention the cost savings of reuse and recycling strategies but do not address the details of end of life costing. The model proposed by them attempts to prescribe a life cycle cost model to estimate as well as correlate the effects of these costs in all the life cycle stages of the product. The conceptual model developed by these authors includes the following costs:

1. Cost of effluent control,
2. Cost of effluent and waste treatment,
3. Cost of waste disposal,

4. Cost of implementation of EMS,
5. Costs of eco –taxes,
6. Costs of rehabilitation,
7. Costs of energy,
8. Costs of recycling and reuse strategies.

The model developed is a conceptual model and does not give a detailed, procedure-oriented process to calculate these costs. Also, the model concentrates on the environmental costs and does not deal with the logistics, processing and disassembly cost of end of life products.

Dincer et al. (2001) in their paper, “Economic Analysis of End of Life Computer Systems in Educational Institutions,” have proposed and provided an economic analysis of different options such as disposal, disassembly, recycling, reuse and resale of these systems. They use the method of mathematical programming formulation to maximize the total profit from collection and processing end of life computers in educational institutions.

The objective function consists of maximizing the total profit, which is the difference between the total revenue and the total cost and can be written as follows:

$$\text{Maximize } Z = TP = TR - TC.$$

The mathematical programming method illustrated in their paper makes use of linear programming procedure to solve the problem. The disadvantage with this approach is it places too much emphasis on mathematical programming and cannot identify the

individual cost making centers. Also the mathematical programming model does not handle uncertainty issues involved in costing.

Aseidu and Gu (1998) in their paper “Product life cycle cost analysis: state of the art review,” have mentioned various life cycle cost analysis models. In this review, the cost break down structure of Fabrycky and Blanchard has been provided. They have come up with a life cycle costing model from the designer or producer’s point of view. They suggest that the actual cost that accrues during design phase is 10-20%. While at this phase, an organization commits up to 70 to 80% of the total life cycle cost of the system. Given the financial consideration at the production and operation phases of the system’s life cycle, they advocate the greatest potential area for cost saving and prevention is the design stage. This is because the changes in the system design (packaging, characteristics, size, useful life, maintenance support activity, disposal methods, etc.) at the production and operation phases are much more costly relatively to the changes during design activities. Cost competitiveness for new system can take place when no such cost (opportunity, warranty, production and construction and design costs) incurs.

Alting (1993) has illustrated the life cycle costs of products. In his model, the life cycle costs are shared among the manufacturer, user and society. The cost break down structure is also provided wherein emphasis is laid on the end of life management of products. The environmental costs are also considered in all stages of the product life cycle. This model gives us a broad overview or the strategic importance of considering the life cycle costs of products in our analysis.

Most current LCA techniques are modifications of the approach developed by the Society for Environmental Toxicology and Chemistry (SETAC). Practical use of the SETAC approach involves drawing a boundary that limits consideration to a few producers of interest in the chain from raw materials to consumers. Researchers at Carnegie Mellon have found that limiting the analysis in this way may lead to consideration of only a fraction of the total environmental discharges associated with the product or process. They have developed an approach based on models of industrial activity (input-output tables) and pollution discharge data (Cobas et al., 1996). The resulting software tool, called Economic Input-Output LCA or EIO LCA allows for economy-wide LCAs at a fairly coarse scale. The input-output analysis technique that forms the basis of the model was developed by Wassily Leontief, for which he received a Nobel Prize in 1973. Leontief assumed that the complicated interactions within an economy can be approximated by proportionality relationships. Leontief (1987) explains the basic working of input- output analysis by choosing 5 sectors of the economy.

To use the EIO LCA model, the user must first determine which life cycle stage is under consideration and how best to determine the dollar value of the resources required for the product, process or service in the life cycle stage of question. For example, if the user is interested in the manufacturing stage, they would need to know the approximate dollar value for each of the materials (steel, oil, electricity, etc.) required for manufacturing. If the user was interested in looking at the environmental implications of product use, they would need to determine the dollar values of the inputs required for lifetime use (for example, fuel requirements, electricity requirements, paper requirements

etc.). The resulting environmental discharge and resource use results would then need to be summed to arrive at a “manufacturing and use” LCA.

These are some of the various life cycle cost analysis models which have been reviewed from the vast number that is available. The various life cycle cost analysis models deal with the various stages in the life cycle of the product and none of the models give a detailed framework for the calculation of costs and energy for the end of life management of electronic products and in particular printed circuit boards. The costing methodology or framework employed in this thesis is that of activity based costing, based on the activity based life cycle costing analysis developed by Jan Emblemsvag. The literature review regarding activity based costing and its advantages are illustrated in the next section.

2.2 Activity-Based Costing

Another costing methodology which has been widely used and is used as the basis for the economic model is the activity based life cycle costing developed by Jan Emblemsvag. Activity based LCA is a life cycle assessment/analysis method with similar scope as the well known ISO 14000 LCA but with several advantages over the ISO 14000. According to Emblemsvag (2001), the following are the advantages of activity based LCA.

“1. Activity-based LCA utilizes an environmental impact indicator that always yields comparable results whereas the ISO 14000 LCA cannot produce comparable results and hence inhibit rank prioritization.

2. Activity-based LCA is based on the highly effective ABC method which, in conjunction with total quality management (TQM), becomes even more effective, and can therefore directly harvest all the advantages of the so called ABC-TQM continuum. ISO 14000 LCA, in contrast, only draws upon TQM and misses the vital link to over 200 years of cost management experience.
3. Activity-based LCA is an integrated framework where cost and environmental issues are equally attended. ISO 14000 LCA, in contrast, ignores costs almost completely.
4. Activity-based LCA performs assessments of all products and the entire organization in the same model at the same time whereas in ISO 14000 LCA tends to focus on product by product.
5. Activity-based LCA is the only LCA method that can credibly handle overhead resources, i.e., according to modern cost management principles. This is also a logic extension of Point 4.”

Since ABC is crucial to activity-based LCA, some explanation of ABC is pertinent. ABC is a full-absorption costing method that gains more and more ground on conventional methods, due to both more correct cost assessments and superb tracing of the costs. Conventional costing systems, on the other hand, cannot trace overhead costs. The tracing capability is enhanced by the usage of uncertainty and sensitivity analysis in activity-based LCA. Compared to the conventional costing systems, ABC differs in two major points according to Cooper (1990).

1. In an ABC system it is assumed that cost objects (products, services and so forth) consume activities, while a conventional system assumes that cost objects consume resources. There are several implications of this difference, but the most important is that ABC acknowledges that one cannot manage costs, one can only manage what is being done, i.e., activities.
2. An ABC system utilizes drivers on several levels (unit-, batch-, product- and factory level), while a conventional system uses only unit-level characterizations called allocation bases, which roughly speaking is an arbitrary, unit-level driver. Hence, ABC is much more accurate.

Further, Copper (1990) in his article illustrates the steps to design the activity based costing approach for any system. In this article, the author details the steps involved and the quantities that need to be measured in making ABC a successful costing methodology. The 5 design steps are as follows:

1. Aggregate actions into activities.
2. Report the cost of activities.
3. Identify activity centers.
4. Select first stage cost drivers.
5. Select second stage cost drivers.

Jiao and Tseng (1999) in their paper develop an approach called pragmatic product costing approach. This approach is based on the activity based costing approach itself, but calculates the resource consumption in a different manner. In the activity based costing approach, the resource consumption is determined in terms of the number of cost

drivers for each activity and the unit cost per cost driver for the activities. This approach is time consuming and is laborious in identifying all the cost drivers. The pragmatic product costing approach determines resource consumption according to the estimated processing time for each activity timed by the unit price of standard time. This intermediate measurement provides a common, consistent methodology to approximate various cost functions for different activities and cost drivers.

Gunasekaran (1999) in his paper illustrates the disadvantages of the traditional costing system, where in cost information is not reported by activity, and the cost information is typically reported too late to supplement improvement efforts. The author also mentions that the nature of business has changed and the overhead costs (such as administrative costs, staff function costs, etc.) have become predominant. Hence, the need for a better and accurate costing system which takes into account all these factors.

The literature on activity-based costing and its advantages are vast in number. Only a selected few have been taken into account in this literature review. The emphasis in this literature review has been on the activity-based costing life cycle analysis approach. The economic model makes use of this framework in developing the costs. The next section deals with the literature review of the process of recycling copper and energy consumption.

2.3 Recycling Process of Copper and Energy Consumption

Goosey and Kellner (2003) in their paper report the results of a scoping study carried out to identify the technologies and process that can be used to recycle materials from end of life printed circuit boards. The various mechanical approaches like pulverization, heat treatment using pyrolysis technology and hydrometallurgical approaches are illustrated.

Yokoyama and Iji (1997) in their paper, “Recycling of Printed Wiring Boards with Mounted Electronic parts,” have illustrated the removal of integrated circuits from the board by making use of mechanical forces. The paper explains in detail how surface mounted devices (SMD) and through hole devices (THD) are removed from the board. The process of pulverization and separation of metallic and non metallic components is also illustrated.

Low and Williams (1997) in their paper present improved models of the economics of the options that can be taken at the end of the first life of the product. The various options considered are recycling, resale, remanufacture and scrap. Mixed strategies are developed for these various options to arrive at the appropriate strategy.

Ikuta et al. (1996) in their research have described a pyrolysis-based technology for the recovery of useful materials such as silica from the resin wastes. These resins are used in integrated circuits. The problem of recycling these thermosetting plastics has been considered in this paper. However in this thesis, the emphasis is on the recovery of metallic components from the printed circuit boards.

Lueckefett et al. (1997) in their paper have reviewed the product legislations in various European countries. The various products and materials on which the directives have been issued are illustrated in the form of a table.

Worhach and Sheng (1997) have developed a methodology to relate process parameters and component design features to energy consumption and waste streams. For each product, the total energy, total mass flow and the total processing time can be determined with respect to the process chosen. Thermal energy is calculated using mass, specific gravity and the temperature of the individual components.

Sandborn and McFall (1996) have modeled the energy required by process steps by assigning a rate to each activity (machine) in the process flow.

The quantity of energy used by a process step is:

$$\text{Quantity of Energy} = (F) \sum_{i=1}^n (\text{Rate}_i)(\text{Time}_i)$$

where the Rate_i is the rate at which the process step (machine) uses energy (measured in watts for example) and Time_i is the time over which Rate_i is in effect.

Mattis et al. (1996) have created a framework for computing the energy expended in the forming process in injection molding dies. The process model that is presented describes the modes of energy utilization in injection molding processes. The energy based process model accounts for the different energy and mass flows in the process. The total energy used in the process is the sum of the energy used in the individual processes.

The literature review described above contains papers from the topics of life cycle cost analysis, activity based costing and the process of recycling copper and energy computation. The popular LCA models have been reviewed and presented here. In

summary, we can conclude that though there are many models on LCA, there is none dealing with the problem of end of life management issues and in particular with printed circuit boards. The models presented above are very useful in their specific area of need and cannot be generalized to other scenarios. Also, most of the models concentrate upon the design stage and not the end of life and useful life of the product. These lacunae were taken into account when developing the economic model for the end of life management of printed circuit boards.

CHAPTER III

RECYCLING PROCESS FOR PRINTED CIRCUIT BOARDS

3.1 Introduction

A printed circuit board may be roughly divided into its electronic parts and resin board portions, and useful materials are unevenly distributed between the two. For example, gold and silver are contained in the electronic parts, while copper, glass fiber and resin are contained in and on the resin board.

The composition of a printed circuit board varies greatly depending on the application where it is used. The following table illustrates a typical composition of a printed circuit board (Table 3.1).

Table 3.1 Composition of Printed Circuit Board

Material	Percentage
Non- Metal	>70%
Copper	~16%
Solder	~4%
Iron and Other Metals	~10%

Source: (Goosey and Kellner, 2003).

The recycling of printed circuit boards waste has been a problem, however because of the glass fiber and metals contained in printed circuit boards make them difficult to pulverize. Also, the presence of cured thermo setting resins, in the resin-

boards and electronic parts is another obstacle to the recycling of printed circuit boards. As a result, most of the waste has been disposed of in landfill sites. One recycling technology for printed circuit board waste consists of pulverizing it as a whole and physically separating out useful materials like copper. Another recycling technology is used to refine useful metals (i.e., gold, silver and copper) from those printed circuit boards that contain these metals in high ratios.

3.1.1 Metal content in printed circuit board

Obtaining printed circuit boards/printed wiring boards should be of great interest for recycler considering the potential profit. Printed circuit boards contain a variety of metals in widely varying concentrations. Table 3.2 shows the sample metal content of computer PWB scrap as shown below. The concentrations quoted here vary greatly due to the huge differences in the composition of different electronic components. There is no such thing as a typical composition.

Table 3.2: Metal Content in Printed Circuit Boards

Metal Name	Content (ppm)	Main use in PCB
Cu	143000	PCB tracks
Fe	45000	Screws and Leads
Al	28000	Lead Frames, Heat sinks
Pb	22000	Solder
Sn	20000	Solder
Ni	11000	Mechanical Parts and Leads
Sb	4500	Flame retardant
Zn	4000	Zinc plated mechanical part
Ag	639	Conductive adhesives
Au	566	Bond wires, contacts
Cd	395	NiCd batteries
Ta	192	Tantalum capacitors

Source: (SUM.E.Y.L, 1991)

The metals found in printed wiring boards can be divided into two groups: base metals and precious metals. Base metals such as copper, iron, nickel, tin, lead, aluminum and zinc are found in electronic components of the printed circuit boards. The electrical connections on printed circuit boards are usually made from copper, which have a considerable amount of value. The most common type of metals found, is an alloy of tin

and lead. Other metals may be obtained which are concentrated in certain components, e.g., tantalum in high-performance capacitors.

The main economic driving force for recycling of electronic scrap is the recovery of precious metals. Many types of PCB scrap have sufficient concentrations of precious metals such as gold, silver, platinum and palladium. Precious metals, obtained justify the use of highly sophisticated metallurgic processes to recover these metals. The recovery rates of in percentages are listed in Table 3.3.

Table 3.3: Metal Recovery Rate

Metals	Au	Ag	Pd	Pt	Cu	Ni	Pb	Sn	Zn
% Recovery	98	90	90	90	99	85	85	80	85

Source: (Legarth et al., 1995)

There are 3 main scenarios for metal refining: copper, lead and tin (Gao et al. 2002). The copper recycling scenario is the most popular as the revenue generated from copper is higher than that of lead and tin. If the environmental aspects are taken into consideration then the copper scenario is inferior to that of lead and tin primary production scenarios. The important aspect to note from both the lead and the tin scenario is that, copper refining takes place in the side streams generated from the above two processes. The main process sequence in the lead scenario is that of Kaldor furnace

smelting, pyrometallurgical refining and finally the casting of refined lead ingots. Tin recycling scenario is mainly used to recycle the combined tin alloy and PCB fees mixture. In this thesis, the area of concentration is copper scenario as more value can be generated from the amount of metal extracted.

The process of extraction of copper by the traditional recycling method is illustrated in the following sections.

3.2 Recycling Process of Printed Circuit Board and Extraction of Copper

The process of recycling printed circuit board begins with the removal of mounted parts on the board. The parts are removed by using a combination of mechanical energy and heat energy and the integrated circuits and other parts are removed which can be reused and resold in the market. The next step in the process is that of solder removal. After the solder is removed, the boards are pulverized and reduced in size. The process of separating takes place where the metals are separated from the non metals. The copper rich powder is then taken to secondary recyclers and using pyro technology process, the copper is extracted. Gold and silver become by products in this process and they in turn are sent to secondary refiners for precious metal recovery.

The process described above gives us a broad overview of the recycling process of printed circuit boards. The following flow chart will provide a broad picture of the recycling process before proceeding on to the details and the intricate details of the process (Figure 3.1).

Figure 3.1: Flow Chart of Printed Circuit Board Recycling and Copper Recovery

Figure 3.1. Continued

Figure 3.1. Continued

Figure 3.1. Continued

3.2.1 Scrap pretreatment

At least three steps can be identified in the processing of printed circuit boards:

1. Hand sorting and / or Mechanical sorting,
2. Calcination / Combustion,
3. Shredding.

Hand sorting is usually accomplished with the use of a slow moving conveyor belt. Hand sorting requires both skill and judgment, since the operator must visually identify the scrap material having significant precious metals. With computer scraps other valuable electronic components that remain intact (such as, memory chips, tantalum capacitors, and integrated chips) may exceed the value of precious metals content. These items may be sold for reuse.

Mechanical sorting involves unit operations of sorting printed circuit boards. These include unit operations include crushing in a hammer mill, magnetic separator, rolls crusher and eddy-current separation.

Calcination is a precursor to shredding and sampling. This involves heating sorted electronic scrap components at an extremely high temperature ($\sim 420^{\circ}\text{C}$) to cause the plastic components to become brittle, thereby allowing shredding or grinding. Combustion takes place in a concurrently fired rotary kiln. Its purpose is to remove the carbon present in the scrap, which interferes with the pyro metallurgical process.

Shredding or pulverization is more of a size reduction. Size reduction may be accomplished with the use of milling. Milling printed circuit boards that have been made brittle prior to the high elevate temperature.

3.2.2 Component removal

Some recyclers specialize in removing high-value components from printed wiring boards for resale to manufacturers or for use as spares. This is known as 'pulling', since ICs sometimes have sockets from which they can literally be pulled, but more often pulling actually means desoldering components (Yokoyama and Iji, 1997).

Technologies used to mount components to printed circuit boards are as follows:

- a. Through-hole technology,
- b. Surface Mount technology.

These two technologies are currently used to attach components to printed wiring boards: Through-hole technology (THT) and Surface Mount Technology (SMT). Sometimes the two technologies are combined, with THT components on one side of the board and SMT components on the other. Since SMDs are only attached to the resin board by soldering, they can be removed by heating them above the solder melting temperature. However, because THDs are attached with pins through the board as well as solder, and chip components are attached with adhesive and solder, effective disassembly of these components proved difficult.

Solder joints can be melted using special desoldering irons, IR radiation, forced hot air, or by immersing the joints in a bath of molten solder. The predominant solder material is a eutectic alloy of 63% tin and 37% lead by weight, which melts at 183 °C (Yokoyama and Iji, 1997). Concern over the toxicity of lead has led to the investigation of alternative alloys, mostly based on tin with additions of other metals such as antimony,

bismuth, copper, indium, silver or zinc. It seems unlikely that any of these materials will replace tin-lead solder in the near future. This is due to high material prices, poor mechanical properties, and most importantly, melting points that differ significantly from that of lead-tin solder, requiring a redesign of the complete system. A more promising replacement is conductive adhesives, consisting of a thermosetting polymer matrix filled with conducting particles, usually silver. These materials also offer the advantage of lower processing temperatures in production. From a recycler's point of view, alternative solder materials are desirable only if they contain high concentrations of valuable metals which make PWB scrap more valuable. Otherwise they only complicate disassembly and repair, as different solder alloys will require different desoldering temperatures, and conductive adhesive joints will not melt and therefore require large forces or chemical solvents to disassemble.

Printed wiring boards can be disassembled selectively or simultaneously. In a selective disassembly operation, only components identified as valuable or containing dangerous substances are removed. Simultaneous disassembly, by contrast, means desoldering all components indiscriminately and then sorting them. The two approaches have been described as “look and pick” and “evacuate and sort.” Melting all the solder on the board and shaking components off can achieve evacuation. Specially designed machines can develop sufficiently large accelerations to remove even THT components with bent pins.

In removal process for electronic components, the solder on the printed circuit board is removed as solder particles and various forms adhering to the components. The

solder on the board surface is recovered using the surface abrasion method, and the solder inside the through-holes using the heating-impacting method. The solder recovered as particles and powders can be used as a valuable solder resource.

3.2.3 Pulverization and separation of resin boards

The pulverizing process is highly effective and abrasion resistant for the resin board through the combination of the crushing step using cutting and shearing forces, and the fine pulverizing step using compressive and shear forces. The resulting powder is separated into copper-rich powder and a glass fiber-resin powder using a separating process involving gravimetric and electrostatic separating methods. Copper is pulverized more coarsely than the glass fiber and the resin because of their brittleness. The effective recovery of copper from the board powder with this particle size is mainly due to the difference in sizes of these materials, in addition to the differences in the specific gravity of the materials (copper: 8.9, glass: 2.5, resin: 1.2). The copper rich powder separated by gravimetric method is further purified by electrostatic separation. This can be used as a high-level copper resource for refining. The glass fiber-resin powder consists of glass fiber cured epoxy resin, and small quantities of copper and solder. This powder has the possibility of being reused because it contains small amounts of solder involving lead. The pulverizing and separation process is illustrated by Figure 3.2 below.

Figure 3.2: Pulverizing and Separation Process

Source: (Yokoyama and Iji, 1997).

3.2.4 Metallurgic refining techniques used for printed circuit boards

Hydro metallurgic. This process involves leaching with an acid, alkaline or other solution selectively dissolves certain metals and leaves others unaffected.

Pyro metallurgic. This category includes many different techniques such as smelting, roasting, and sweating. The common point is that the metal is heated to high temperatures, and impurities are removed in some way. They may be volatilized by a

chemical reaction or by heat, or may be converted to slag's which rise to the surface of molten metal, or sludge's which sink to the bottom.

Electro metallurgic. This technique is based on electrolysis. Metal anodes and cathodes are placed in an electrolyte solution and a current is applied. Positively charged metal ions are transported from the anode to the cathode, where they form a very pure piece of metal.

Biological. Metals or metal compounds are ingested by aquatic micro-organisms which accumulate them in their bodies. The metal is then concentrated by removing all the microorganisms from the solution. Biological refining techniques are not extensively used at present but may become important in the future.

3.2.5 Pyrometallurgical techniques

These are mainly done in five separate operations:

1. Scrap pretreatment,
2. Roasting,
3. Smelting,
4. Converting,
5. Copper refining and anode casting.

3.2.5.1 Scrap pretreatment

Scrap pretreatment may be achieved through manual, mechanical, pyrometallurgical, or hydrometallurgical methods. Manual and mechanical methods

include sorting, stripping, shredding, and magnetic separation. The scrap may then be compressed into briquettes in a hydraulic press. Pyrometallurgical pretreatment may include sweating (the separation of different metals by slowly staging furnace air temperatures to liquefy each metal separately), burning insulation from copper wire, and drying in rotary kilns to volatilize oil and other organic compounds. Hydrometallurgical pretreatment methods include flotation and leaching to recover copper from slag. Flotation is typically used when slag contains greater than 10 percent copper. The slag is slowly cooled such that large, relatively pure crystals are formed and recovered. The remaining slag is cooled, ground, and combined with water and chemicals that facilitate flotation. Compressed air and the flotation chemicals separate the ground slag into various fractions of minerals. Additives cause the copper to float in foam of air bubbles for subsequent removal, dewatering, and concentration.

3.2.5.2 Roasting

Roasting is performed in copper smelters prior to charging reverberatory furnaces. Roasting is performed to remove arsenic and parts of sulphur. In roasting, charge material of copper concentrate mixed with a siliceous flux (often a low-grade copper ore) is heated in air eliminating 20 to 50 percent of the sulfur as sulfur dioxide. Portions of impurities such as antimony, arsenic, and lead are driven off, and some iron is converted to iron oxide. Roasters are either multiple hearth or fluidized bed; multiple hearth roasters accept moist concentrate, whereas fluidized bed roasters are fed finely ground material. Both

roaster types have self-generating energy by the exothermic oxidation of hydrogen sulfide, shown in the reaction below.

3.2.5.3 Smelting

In the smelting process, the objective is to remove the oxides of iron which is present from the previous process by combining it with silica. This forms a compound which is capable of being melted and being separated from the impurities. The required heat comes from partial oxidation of the sulfide charge and from burning external fuel. Most of the iron and some of the impurities in the charge oxidize with the fluxes to form a slag on top of the molten bath, which is periodically removed and discarded. Copper matte remains in the furnace until tapped. Matte ranges from 35 to 65 percent copper, with 45 percent the most common. The copper content percentage is referred to as the matte grade.

3.2.5.4 Copper converting

The main raw material for converting is the molten Cu-Fe-S matte from smelting. The other raw materials are silica flux, coke and oxygen enriched air. Copper scrap can also be fed to the converter. Converting is done in a Pierce-Smith converter as a batch process. Once the molten matte is poured into the converter, air is blown into the matte through nozzles called tuyeres. Air is blown so that the iron present in the matte oxidizes into iron oxide and sulphur di oxide. Silica is then added into the converter and iron

reacts with silica to form silicate slag, which is removed from the converter. This leaves molten copper sulfide or white metal. The remaining sulphur in the white metal is then oxidized to sulphur dioxide leaving blister copper.

3.2.5.5 Copper refining and anode casting

Blister copper is refined in the anode furnace in order to remove the remaining sulphur and oxygen. In the first step sulfur is removed by blowing air into the furnace. In the second step the extra oxygen is removed as gaseous carbon monoxide and water by injecting liquid propane gas to the molten copper. The refined blister copper is then cast into anodes. The spent anodes returned from electro refining are conveyed to the converter where they are fed to the second stage of copper converting.

The final refining of the anode copper is carried out in electrolytic cells in a tank house. Application of an electrical potential between the copper anode and a metal cathode in a $\text{CuSO}_4\text{-H}_2\text{SO}_4\text{-H}_2\text{O}$ electrolyte causes the dissolution of copper from the impure anode and its deposition on the cathode. Some impurities are precipitated in the anode slime on the bottom of the electrolysis cells due to their insolubility in the electrolyte used. The dissolved impurities are taken in the bleed to solution purification. The initial cathodes used are thin, pure-copper starting sheets, which are produced in the refinery itself. Fully grown cathodes are removed from the cells, washed with water and packed. They are sold for melting, casting and fabrication of copper semi products.

The pyro metallurgical treatment of copper sulfide concentrates commonly includes two types of operations, smelting and converting. In the smelting phase, part of

the sulfur and iron in the concentrate feed is oxidized with oxygen-enriched air and a molten sulfide phase (matte) rich in copper is produced. Copper converting consists of air oxidation of the molten matte from smelting. Converting removes the iron and sulfur from the matte and produces crude molten metallic blister copper. The slag formed is discarded after a purification step. Blister copper is fire-refined and cast into anodes. The anodes are electro refined to pure copper cathodes. The remaining anode slime is further treated to recover the remaining metals.

CHAPTER IV

RESEARCH METHODOLOGY AND MODEL DEVELOPMENT

4.1 Research Framework

The methodology used to develop the economic model was based on the activity based approach developed by Jan Emblemsvag. The approach consists of 5 main steps, namely: create an activity hierarchy and hierarchy network, identify the resources, identify and order the resource drivers and activity drivers and find their intensities, compute the cost and energy consumption and waste generation of the consumption of activities. Using this framework, the methodology for the end of life management of printed circuit boards has been constructed. Two additional steps have been added to this methodology where in the identification of all the players in the process, both upstream and down stream is considered and also selection of the waste stream for recycling(in this particular case it is copper recycling). Also the various costs which have been identified in the process are based upon the Fabrycky and Blanchard model which broadly gives the cost break down structure, the LCA model developed by Alting and analytical models for logistics and acquisition developed by Govil (1984). The other cost centers were identified by studying the process and having brain storming sessions with the research group. Once the various costs were identified, the factors affecting these costs were used as input into the cost models. The methodology for constructing the economic model is as follows:

1. Identify the Major players in the process.
2. Study the activities of the Major players.
3. Identify the resources.
4. Develop the activity hierarchy and the resources used.
5. Select the waste stream under consideration.
6. Compute the cost, energy consumption and waste generation.
7. Check for Model Accuracy.

Figure 4.1: Framework Used to Develop Economic Model

4.1.1 Identify the major players in the process

In the end of life management of any product, there are generally three main players or stake holders. For example, in the printed circuit board's case which we have considered, the main players are the original equipment manufacturer, who is responsible for the disposal of the electronic components in a safe and environmentally friendly manner. The next stakeholder in the process is the primary refiner or the disassembler and the final stakeholder is the secondary refiner. The primary refiner, generally removes out all the integrated circuits and other items which can be reused or remanufactured and tests them, repairs them and finally sells these circuits and components in the secondary market. Sometimes, big recyclers act as the primary as well as the secondary refiners, if not the separated waste streams for further extraction goes to the secondary refiner. The secondary refiner is generally used for the extraction of metals and other materials such as plastic etc. The metal refiners extract, precious metals or base metals depending on the content of the printed circuit board and their area of expertise. Copper refiners can extract copper to the extent of 99.9% purity. These metals are then sold in the secondary market. The relationship between the major players in the process is illustrated in Figure 4.2 below.

Figure 4.2: Relationship between the Major Players in the End of Life Management Stage.

4.1.2 Study the activities of major players

The original equipment manufacturer generally has the responsibility of disposing the product in a safe manner. The original equipment manufacturer has the responsibility of collection and consolidation of waste materials and then sending it to the primary refiner.

The primary refiner collects all the materials and checks them for reusable products. The products are stored in inventory and then sold in the secondary market. The primary refiner pays the original equipment manufacturer for the waste that has been sold. It is the responsibility of the primary refiner to dispose all these products in a safe manner. The various waste streams are initially generated in this stage. In the printed recycling boards, all the boards are stripped of their IC's and they are tested and resold in the market. The board is now bare, i.e., devoid of all components. The solder is removed and is sold as filler material for products. The boards are then subjected to pulverization and the metallic and non metallic streams are generated. At this stage, the primary refiner transports the waste streams to the secondary refiner. The secondary refiner, based upon his area of expertise, extracts the various metals and sells them in the market.

4.1.3 Identify the resources

At this stage in the model development, the various resources used by the major players are identified. These resources act as the activity drivers. There are many resources used in the recycling of printed circuit boards and the list is extensive. Some of the main resource drivers are listed below.

- Direct Labor,
- Number of components (PCB),
- Machinery,
- Running hours of the machinery,
- Fuel and other inputs for the activities.

4.1.4 Develop activity hierarchy and resources used

In this stage of the model development, the activity hierarchy or the precedence relationship is established and the resources used or consumed at each stage are noted. The activity hierarchy can be process plan or the disassembly sequence and the routing used. The disassembly of printed circuit boards and their activity hierarchy is shown in Chapter III. The activity hierarchy shown in Chapter III is just for the process of recycling the boards. Activities such as transportation from original equipment manufacturer to the refiner and the refiner to the market are not shown. The resource consumed at each stage of the activity hierarchy is depicted in the energy calculation stage.

4.1.5 Select the waste stream

There are various waste streams generated during the end of life management of printed circuit boards. The waste stream which needs to be costed and energy calculations made is selected. The extraction of copper from the metallic waste stream is selected in

this particular process. There are other waste streams also generated such as the precious metals and plastic recycling streams.

4.2 Introduction to Economic Model

The economic model is divided into two sections, namely the cost model and the energy model. Both the models are used in conjunction to evaluate different alternatives in a process or make a comparison between two processes. The energy model is computed on the basis of the inputs to the process and identifying the kind of energy consumed at each stage. The various kinds of energies at each stage are then computed using mathematical formulae and the total is arrived at for that particular process. In this thesis, the energy consumption of pyro metallurgy is illustrated in the case study.

Before the actual costing of all the activities in the process is done, the linearity relationship of the individual costs to the total cost is established using tests of hypothesis and regression technique. The individual cost centers themselves cannot be taken for the test of hypothesis as they are not independent in nature. The factors affecting the costs are taken as the variables for the tests of hypothesis. Hypothetical values are allocated to each of these individual values and the test is conducted and linearity is established.

The model developed in this thesis is the activity based cost model which identifies the activities and cost centers in the process. The various cost centers are take back cost, logistics cost, etc. The activities defined in the process are costed and the total cost is arrived at. Similarly, the revenues generated from this process are also computed. The total profit/loss is then arrived at based on the revenues and the cost incurred. The

case study of Gannon and Scott refineries is used to compute the total cost using this methodology. The energy consumption is also computed for the case study.

Further, a comparison of the pyro metallurgy technique and supercritical fluids is made based on the energy consumption of the process. The conclusions of the model are then arrived at by making use of the case study and the literature review.

4.3 Multiple Regression

The mathematical model aims to define the relationship between the total cost of recycling and the various process costs concerned with the recycling process of the waste stream selected and to determine quantitative expressions between the above said costs. The main purpose of multiple regression is to establish the linear relationship between the total cost and the individual activity costs and validate them using tests of hypothesis.

Model assumptions are:

1. There are two types of variables, independent variable which are the process costs and the dependent variable which is the total cost.
2. Determination of the regression equation is based on the least squares methodology.
3. Linearity of relationship is considered and validated only for the hypothetical range assumed.
4. The values chosen for the independent variables are hypothetical values.

4.3.1 Identification of independent variables

After studying the process, we can identify the independent variables which affect the total cost of the system. An independent variable is identified for each cost center. The cost themselves cannot be taken as independent variables. The following quantities were identified as individual variables for this system.

1. Weight (W) corresponding to the take back cost of the system: Weight is the primary independent variable. The weight of the printed circuit board obtained for each batch will not be the same. The take back cost of C_1 will depend on the weight obtained and on the content of the board.
2. The next variable identified with logistics cost is the distance traveled from the source to the point of destination. This variable (m = distance traveled), affects the logistics cost of the process. The logistics cost is also affected by weight, but since we have accounted for weight already in the variables, we do not account for it again
3. The third variable is the disassembly time, T_d which affects the disassembly cost. This variable keeps changing with the complexity of the circuitry on the boards.
4. The fourth variable is the testing time, T_t . This variable is similar to the disassembly time, but the process is testing of the integrated circuits and their upkeep.
5. The fifth variable which affects the total cost is the processing time in the furnace. This variable is associated with the processing cost or the furnace cost. This time can be considered as the total time the material spends in the furnace. This time is

the cumulative time of the roasting process, smelting, converting, fire refining and electrolysis. This time can be represented as T_{furnace} .

6. The sixth variable identified for the reverse logistics cost is the distance of the market from the recycling plant. If the distance is more, then the reverse logistics cost is more, if the distance is less then the reverse logistics cost will be less. The reverse logistics cost also depends on the weight obtained after recycling. The weight obtained after recycling, reuse and remanufacture differs from batch to batch.
7. The last independent variable which affects the total cost is the weight of the wastes. The waste disposal cost is dependent on the weight of the wastes generated.

The regression model, analyses the relationship between these various independent variables which affect the individual costs and the total cost which is the dependent variable.

$$T_C = a + b_1 W + b_2 m + b_3 T_d + b_4 T_t + b_5 T_{\text{Furnace}} + b_6 W_F + b_7 W_w, \quad (4.1)$$

and the normal equations are

$$\sum T_C = na + b_1 \sum W + b_2 \sum m + \dots + b_7 \sum W_w. \quad (4.2)$$

$$\sum W T_C = a \sum W + b_1 \sum W^2 + b_2 \sum W m + \dots + b_7 \sum W W_w. \quad (4.3)$$

$$\sum m T_C = a \sum m + b_1 \sum W m + b_2 \sum m^2 + \dots + b_7 \sum m W_w. \quad (4.4)$$

$$\dots \quad \dots$$

$$\dots \quad \dots$$

$$\sum W_w T_C = a \sum W_w + b_1 \sum W W_w + \dots + b_7 \sum W_w^2. \quad (4.7)$$

The constants $a, b_1, b_2, \dots, b_m$ in the above equation are computed from normal equations.

T_c = Total cost of recycling

W = Total weight of Printed Circuit boards before recycling

m = distance in miles between the source and the recycling destination.

T_d = Time of disassembly / batch

T_t = Testing time for the components / batch

T_{furnace} = Total processing time in the furnace / batch.

W_F = Total weight obtained after recycling.

W_w = Weight of the wastes obtained after recycling.

Regression is the study of relationships among variables. One purpose of regression may be to predict, or estimate, the value of one variable from known or assumed values of other variables related to it. In our mathematical model we have used multiple regression as there are more than two variables. There are seven independent variables (cost centers) and one dependent variable. The dependent variable is the total cost, whose value depends on the individual variables. All the variables selected in the model are treated as significant parameters. This assumption is made and a significance test for the parameters is not done as there are less number of variables.

4.3.2 Conditions under which multiple regression can be used

Multiple regression is made use of as there are more than one variable or cost center which affects the total cost of the system. Multiple regression is used to establish linearity relationship between the total cost and the individual costs centers. Hypothetical values are assumed for each of the independent variables and test of hypothesis is conducted. The linearity is validated only for the range considered in the hypothetical values assumed. The range of values assumed for each independent variable is shown in Table 4.1. Multiple regression and tests of hypothesis is made use of to validate the linearity of the independent costs with respect to the total cost which is the dependent variable. In practice or reality if we need to use estimates provided by multiple regression then we need to have the following types of data:

1. Historical Data for the independent variables,
2. Data from an analogous process or similar system.

In this thesis we do not have accurate and sufficient historical data or analogous data to provide estimates of the total cost involved in the process. The data could not be obtained due to the sensitive nature of the cost data and proprietary problems. Hence, only test of hypothesis for linearity is conducted using hypothetical data.

4.3.3 Why choose a linear model?

In the economic model considered above, the total cost is the summation of the individual costs and energy consumptions at the various process stages. If the number of processes increases then the total cost increases. Also, there exists a linear relationship,

between the individual costs and their sub components. The total cost is the summation of the individual activity costs. The other models such as the polynomial model and the exponential model were considered, but they cannot be applied in this situation as variables cannot be raised to any power and there is no exponential pattern observed in the case.

Total cost = $\sum$ costs for all activities.

The linear multiple regression model was chosen because there are 7 independent variables. By choosing the regression model we can establish the relationship between the total cost and the independent costs. Also, using tests of hypothesis the linearity is validated for the range under consideration.

4.3.4 Hypothesis

We want to test

$H_0 : b_i = 0$ for all $b_i, i = 1, 2, \dots, k$

$H_1 : b_i$ not equal to zero.

The null hypothesis $H_0 : b_1 = b_2 = \dots = b_7 = 0$ assumes that there is no linear relationship between total cost, T_c and the independent variables.

The alternative hypothesis H_1 assumes that at least one b_i is not equal to 0. There is a relationship between T_c and at least one of the independent variables.

4.3.5 The test

The test is conducted using the F distribution with k and $n-k$ degrees of freedom. In the economic model there are seven independent variables, therefore $k=7$ and n is the number of observations over which the cost values are arrived at. From the above degrees of freedom we can infer that the minimum number of observations to take is nine for our model.

When $n = 9$, we have $9-(k+1)$ degrees of freedom, but since we are not accounting for the error and the 'a' value is known, the number of parameters estimated will be equal to 7. i.e., $9-(7) = 2$ degrees of freedom.

The test was conducted to determine, the relationship between the independent and the dependent variables. To conduct the test, nine observations, which is the minimum number required for F-test is considered. The values chosen for the various variables and the total costs are positive values. Arbitrary sample values are chosen, since the independent costs can take any positive value, depending on the system.

The following table shows the various values of the variables, assumed to prove the model under consideration.

Table 4.1: Table Showing the Various Cost Figures Chosen

TC 100's of \$	W tonne's	m 100's of miles	T _d min	T _t min	T _{furnace} hrs	W _f 10's pounds	W _w 10's pounds
25	15	8	35	9	25	23	18
35	18	5	40	8	30	29	16
45	36	2	55	7	15	15	14
55	50	10	60	6	18	10	13
65	28	9	32	3	19	17	20
15	19	7	38	2	30	24	19
5	12	6	39	1	20	28	25
75	10	5	23	5	16	30	20
60	20	12	27	3	18	25	19
Total=380	208	64	349	44	191	201	164

The next step in the process was to form the normal equations and solve them to obtain values of $a, b_1, b_2, \dots, b_7$.

The normal equations so formed are as follows:

$$380 = 9a + 208b_1 + 64b_2 + 349b_3 + 44b_4 + 191b_5 + 201b_6 + 164b_7.$$

$$9490 = 208a + 6134b_1 + 1529b_2 + 9081b_3 + 1075b_4 + 4217b_5 + 3975b_6 + 3513b_7.$$

$$2830 = 64a + 1529b_1 + 528b_2 + 2417b_3 + 294b_4 + 1357b_5 + 1398b_6 + 1173b_7.$$

$$14240 = 349a + 9081b_1 + 2417b_2 + 14607b_3 + 1787b_4 + 7362b_5 + 7303b_6 + 6130b_7.$$

$$1935 = 44a + 1075b_1 + 294b_2 + 1787b_3 + 278b_4 + 949b_5 + 956b_6 + 746b_7.$$

$$7405 = 191a + 4217b_1 + 1357b_2 + 7362b_3 + 949b_4 + 4315b_5 + 4383b_6 + 3486b_7.$$

$$8170 = 201a + 3975b_1 + 1398b_2 + 7303b_3 + 956b_4 + 4383b_5 + 4869b_6 + 3789b_7.$$

$$6705 = 164a + 3513b_1 + 1173b_2 + 6130b_3 + 746b_4 + 3486b_5 + 3789b_6 + 3092b_7.$$

The above equations are then solved for values of a , b_1 , b_2 , ... b_7 . The equations are then converted into matrix notation and solved using matlab (software tool). After solving these equations, we obtain the values of the constants (Table 4.2).

Table 4.2: Values of Coefficients

a	15.3096
b1	4.6576
b2	-2.5803
b3	-3.4542
b4	2.8552
b5	-1.1295
b6	2.9782
b7	0.8266

Substituting these values into equation 4.1 we get,

$$T_C = 15.3096 + 4.6576W + -2.5803m + -3.4542 T_d + 2.8552T_i + -1.1295T_{total} + 2.9782W_F + 0.8266W_w.$$

The values we obtain from the above equation are estimates of the total cost. The next step in the procedure is to obtain the sample values of the Total cost, i.e., $T_{ceestimate}$.

$$= 15.3096 + 4.6576(15) + -2.5803(8) + -3.4542(35) + 2.8552(9) + -1.1295(25) + 2.9782(23) + 0.8266(18) = 24.4709$$

Similarly, the $T_{ceestimate}$ for all the 9 observations are computed as shown in the table below.

Table 4.3: Table Showing Values of Total Cost and Total Estimate Cost

$T_c = \text{Total Cost}$	$T_{\text{estimate}} = \text{Total cost Estimate}$	$T_c - T_{\text{estimate}}$	$(T_c - T_{\text{estimate}})^2$
25	24.4709	0.5291	0.279947
35	36.6269	-1.6269	2.646804
45	47.1309	-2.1309	4.540735
55	52.4626	2.5374	6.438399
65	66.2318	-1.2318	1.517331
15	13.4899	1.5101	2.280402
5	5.325	-0.325	0.105625
75	71.6195	3.3805	11.42778
60	62.6296	-2.6296	6.914796
	Total	0.0129	36.15128

The standard error of estimate is then calculated based on the values obtained in the table above. The standard error of estimate is a measure of the variability of the actual values around the average predicted by the regression equation. The error of estimate or variance is given by:

$$S^2_{T_c, C} = \sum (T_c - T_{\text{estimate}})^2 / (n-k) = \sum SS(E) / (n-k). \quad (4.8)$$

Taking square roots we get the standard error of estimate.

$$S_{T_c, C} = \sqrt{36.15128 / (9-7)}$$

$$= 4.2515 = MS(E) = \text{mean squares of error}$$

The next step in the test is to determine the multiple coefficient of determination.

Multiple coefficient of determination is the ratio of variation in the total cost explained by the individual, independent costs to the total variation in total cost.

$$R^2_{Tc, Ci} = \frac{\text{Variation in } Tc \text{ explained by variation in } W, m, \dots Ww.}{\text{Total variation in } Tc} \quad (4.9)$$

$$R^2_{Tc, Ci} = 1 - SS(E)/SS(T).$$

Where SS(E) = sum of squares error

$$SS(T) = \text{Total sum of squares} = SS(R) + SS(E)$$

Where SS(R)= sum of squares of regression.

To calculate $R^2_{Tc, Ci}$ we need to find out the value of SS(T). The value of SS(T) is obtained from the following table (Table 4.4).

Table 4.4: Table Showing the Values of T_{coverage}

$T_c = \text{Total Cost}$	$T_{\text{coverage}} = \text{Total cost average}$	$T_c - T_{\text{coverage}}$	$(T_c - T_{\text{coverage}})^2$
25	42.2222	-17.2222	296.6048
35	42.2222	-7.2222	52.1604
45	42.2222	2.7777	7.7160
55	42.2222	12.7777	163.2716
65	42.2222	22.7777	518.8272
15	42.2222	-27.2222	741.0492
05	42.2222	-37.2222	1385.4936
75	42.2222	32.7777	1074.3828
60	42.2222	17.7777	316.0494
	Total	0.00002	4555.5555

Therefore,

$$\begin{aligned}
 R^2_{T_c, C_i} &= 1 - SS(E)/SS(T) \\
 &= 1 - 36.1512/4555.5555 \\
 &= 0.992064
 \end{aligned}$$

This implies that the variation in the individual variables, $W, m, \dots W_w$ explain 99.2% of the variation in the total cost T_c . The remaining 0.8% of the variation is due to error.

The final test for testing the hypothesis is done using the F distribution:

$$F = \frac{\frac{\text{Explained Variation}}{k}}{\frac{\text{Unexplained Variation}}{n-k}} \quad (4.10)$$

where n= number of observations. In this case n= 9.

And k = number of independent variables, in this case = 7.

Therefore,

$$F = \frac{\frac{4555.55 - 36.1512}{7}}{\frac{36.1512}{2}}$$

$$= 35.86(\text{obtained value})$$

From the tables, (Younger, 1979) using the F tables,

Confidence limit = 95%.

V1= number of parameters= 7.

V2= n-p= number of observations- number of parameters needed

$$= 9-7 = 2.$$

From the tables, we get a value of 19.35.

Since the value estimated of F from sample data (35.86) is > 19.35 the null hypothesis is rejected; i.e., H_0 is not true.

There is a linear relationship between the total cost and the independent variables as the null hypothesis has been rejected.

4.3.6 Interpretation of regression and the coefficients obtained

As noted earlier, the regression equation is just used to establish the relationship between the individual costs and the total costs. Since we have 7 independent variables, the graphical representation will have 7 different dimensions. It is hard for one to imagine and analyze the relationship between each of these 7 individual costs and the total cost. A direct relationship exists between the individual variable and the total cost. The physical representation of 'a' and the other constants is explained in the following paragraphs.

4.3.6.1 The regression constant

For the regression constant a , to have a physical meaning, two conditions must be satisfied and must hold good for all predictors.

1. It must be physically possible for X_i , $i=1$ to 7, i.e., $W, m, T_d, T_t, T_{total}, W_F$ and $W_w = 0$. This means that all the costs must be equal to zero.
2. One must have data around $W = m = \dots = W_w = 0$ (Younger, 1979)

What this means is, when all the costs are equal to zero, there is only a fixed cost of a present. This fixed cost a , is nothing but the cost incurred, even when there are no orders with the company. The fixed cost 'a' can be considered as the cost of overheads or other

expenses. The cost of overheads can include many things like, cost of maintenance of machines, cost of salaries to staff workers, cost of electricity, cost of maintenance of building and so on and so forth. This cost is the fixed cost. This cost is incurred by the company irrespective of whether there are any orders.

4.3.6.2 Net regression coefficients

The constants $b_1, b_2, \dots, b_7$ are called net regression coefficients. For instance, b_1 measures the effect of weight(take back cost) on total cost by “netting out” or controlling for, the effect of other individual variables on total cost .

For example, when $b_1 = 4.6576$ means that if there are two batches of printed circuit boards which need to be recycled and the weight of batch 1 is greater than that of batch 2 by 2 tonnes, then the total cost of batch 1 exceeds that of batch 2 by $2(4.6576)$, i.e., \$93.152, provided the variables of all the other processes are constant.

Similarly when $b_2 = -2.5803$ means that if there are two batches of printed circuit boards which need to be recycled and the logistics cost of batch 1 is lesser than that of batch 2 by \$100, then the total cost of batch 1 is lesser than that of batch 2 by $100(2.5803)$ i.e \$258.03, provided the costs of all the other processes are constant.

4.4 Activity-Based Cost Model

4.4.1 Assumptions used

1. The process under consideration is a theoretical process from which the model is built upon. In practice, there might be a few changes in the process and the resource drivers might be different.
2. The capacity of the machines is assumed to be finite value, the value of which varies from case to case basis.

The economic model developed for printed circuit board recycling makes use of activity based costing considering the advantages of ABC costing. The following steps were followed in the process of developing a cost model.

1. Flowchart of the traditional process.
2. Identification of various cost centers.
3. Computation of various costs.

4.4.2 Identification of various cost centers

The following main cost centers were identified in the recycling process:

1. Take Back Cost: This cost is the cost of consolidation and classification of the product.
2. Logistics Cost: This cost as the name implies is the transportation cost of the consolidated unit to the recycling unit.
3. Disassembly Cost: This cost is the cost of disassembly of the printed circuit board. This cost is the cost incurred in removing all the components present on

the printed circuit board. The cost involved in making the board naked of all components.

4. Testing Cost: This is the cost incurred in testing the integrated circuits, packaging them and making them ready for resale.
5. Processing Cost: This cost is the cost of separating the naked board(various steps) into metallic and non metallic streams. This process cost also is the cost in obtaining the refined secondary metals after going through various processes.
6. Reverse logistics Cost: This cost is the cost incurred in transporting the recycled, remanufactured or reusable products to the Market place.
7. Waste Disposal Cost: This cost is the cost incurred in disposing the waste generated during the recycling procedure.

4.4.3 Revenues generated

1. Recycle Revenue: This is the revenue generated by the company by selling recycled products.
2. Resale Revenue: This is the revenue generated by the company by selling products such as integrated circuit chips, or other components which can be resold.
3. Remanufacture Revenue: This is the revenue generated by the company by selling products that can be remanufactured such as printed circuit boards used for games and toys.

4.4.4 Definition of terms: recycle, remanufacture and reuse

Recycle: The product is disassembled to recover the materials and perhaps components (Low et al., 1997).

Remanufacture: Product is recovered and restored to its original condition (both function and cosmetics). This includes the reuse of components and materials (Low et al., 1997).

Reuse/ Resale: The existing product is recovered and sold with minimum intervention, to another customer requiring similar product function (Low et al., 1997).

Before we get into the actual cost figures there are some indices that need to be defined. These indices are nothing but recycle index, remanufacture index and reuse index. These indices are important, as the entire lot that comes into the company for end of life management does not get recycled. Some portion of it is recycled, some portion of the product is resold and some other portion remanufactured and the rest is the waste stream that is generated.

$$\alpha = \text{Alpha} = \text{Resale Coefficient} = \frac{\text{Weight resold}}{\text{Total weight of the printed circuit boards}} \quad (4.11)$$

This is the ratio of the weight of material which is resold to the total weight of the printed circuit board.

$$\beta = \text{Beta} = \text{Recycling Coefficient} = \frac{\text{Weight Recycled}}{\text{Total Weight of the printed circuit boards}} \quad (4.12)$$

This is the ratio of the weight of the material which is recycled to the total weight of the printed circuit board.

$$\lambda = \text{Lambda} = \text{Remanufacturing Coefficient} = \frac{\text{Weight Remanufactured}}{\text{Total Weight of the printed circuit boards}} \quad (4.13)$$

This is the ratio of the weight of the material which is remanufactured to the total weight of the printed circuit board.

4.4.5 Notations used

T_c = Total cost.

C_1 = Take back Cost.

C_2 = Logistics Cost.

C_3 = Disassembly Cost

C_4 = Testing Cost.

C_5 = Processing Cost.

C_6 = Reverse Logistics Cost.

C_7 = Waste Disposal Cost.

W = Total weight of the printed circuit boards obtained.

C_{1w} = Cost/ unit weight of the printed circuit board.

C_{2w} = Cost/ unit weight/distance travelled.

m = Distance Travelled.

n_1 = Number of components/board.

T_d = Disassembly time/component

C_L = Labor Cost/unit time.

C_M = Machine Cost/unit weight/unit time.

T_t = Testing time/component.

T_p = Pulverizing time/batch

n_{1p} = Number of times the batch is pulverized.

W_b = Weight of the batch.

n = Number of batches.

C_F = Running Cost of furnace/unit weight/unit time.

T_r = Roasting time/batch.

T_s = Smelting time/batch.

T_c = Converting time/batch.

T_F = Fire refining time/batch.

T_E = Electrolytic refining time/batch.

W_F = Total weight obtained after recycling.

W_w = Weight of the wastes obtained after recycling.

C_d = Disposal cost/unit weight.

4.4.6 Calculations

The calculations for the various cost centers are as follows:

Take Back Cost = C_1

$$C_1 = (W * C_{1w}). \quad (4.14)$$

Logistics Cost = C_2

$$C_2 = W * C_{2w} * m. \quad (4.15)$$

Disassembly Cost = C_3

$$C_3 = (n_1 * T_d * C_L \text{ or } C_M). \quad (4.16)$$

Testing Cost = C_4

$$C_4 = (n_1 * T_t * C_L). \quad (4.17)$$

Processing Cost = C_5

$$C_5 = C_{51} + C_{52} + C_{53} + C_{54} + C_{55} + C_{56}. \quad (4.18)$$

Where C_{51} = Pulverizing and separation Cost.

C_{52} = Roasting Cost.

C_{53} = Smelting Cost.

C_{54} = Converting Cost.

C_{55} = Fire refining Cost.

C_{56} = Electrolytic refining Cost.

Pulverizing and Separation Cost = C_{51}

$$C_{51} = n * (n_{1P} * W_b * C_M * T_p). \quad (4.18.1)$$

Roasting cost = C_{52}

$$C_{52} = W_b * C_F * T_r * n. \quad (4.18.2)$$

Smelting cost = C_{53}

$$C_{53} = W_b * C_F * T_s * n. \quad (4.18.3)$$

Converting Cost = C_{54}

$$C_{54} = W_b * C_F * T_c * n. \quad (4.18.4)$$

Fire refining Cost = C_{55}

$$C_{55} = W_b * C_F * T_F * n. \quad (4.18.5)$$

Electrolytic refining Cost:= C_{56}

$$C_{56} = W_b * C_M * T_E * n. \quad (4.18.6)$$

Reverse Logistics Cost= C_6

$$C_6 = W_F * C_{2w} * m. \quad (4.19)$$

W_F = weight of the final products after recycling.

C_3 = Cost/unit weight/distance travelled

m = distance traveled

Waste Disposal Cost= C_7

$$C_7 = W_w * C_d. \quad (4.20)$$

Therefore, the Total cost T_c will be equal to,

$$T_c = a + C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7. \quad (4.21)$$

$$\begin{aligned} &= a + W * C_{1w} + W * C_{2w} * m + n * n_l * T_d * C_L + n * n_l * T_t * C_L + n * (n_{lp} * W_b * C_M * T_p) + \\ &W_b * C_F * T_r * n + W_b * C_F * T_s * n + W_b * C_F * T_c * n + W_b * C_F * T_F * n + W_b * C_M * T_E * n \\ &+ W_F * C_{2w} * m + W_w * C_d. \end{aligned}$$

where 'a' represents the fixed cost.

4.4.6.1 Revenues calculations

Recycle Revenue = RCR

$$RCR = \beta * W * P_1 \quad (4.22)$$

β = fraction of a particular recycle component

W = Weight of the entire recycling batch

P_1 = Market price/ recycle component or product

Resale Revenue = RR

$$RR = \alpha * W * P_2 \quad (4.23)$$

α = fraction of a particular resale component.

W = Weight of the entire recycling batch.

P_2 = Market price/ resale component or product.

Remanufacture Revenue = RMR

$$RMR = \lambda * W * P_3 \quad (4.24)$$

λ = fraction of a particular remanufacture component

W = Weight of the entire recycling batch

P_3 = Price/ weight of remanufacture lot

$$TP = \text{Total Revenues} - \text{Total cost} \quad (4.25)$$

$$= (\beta * W * P_1 + \alpha * W * P_2 + \lambda * W * P_3) - (a + W * C_{1w} + W * C_{2w} * m + n_1 * T_d * C_L + n_1 * T_t * C_L + n * (n_{1P} * W_b * C_M * T_p) + W_b * C_F * T_r * n + W_b * C_F * T_s * n + W_b * C_F * T_c * n + W_b * C_F * T_F * n + W_b * C_M * T_E * n + W_F * C_{2w} * m + W_w * C_d.)$$

From the following equation we can see that, if we have to maximize our profits we have to reduce the number of processes and recover the metals at an earlier stage in the process and also we need to reduce the amount of time required in recovering these metals. Also, the new process should be designed in such a manner that the recovery rate is high as compared to the traditional process.

4.5 Energy Model

The energy calculation for the printed circuit board recycling is done by identifying the various resources that go into the process. The following flowchart describes the various kinds of energies used at the process (Figure 4.3).

Figure 4.3: Process Flow of Recycling with Energy Inputs

Figure 4.3: Continued

Figure 4.3: Continued

Figure 4.3: Continued

Figure 4.3:Continued

From the flow chart we can clearly see that there are mainly three types of energy that is made use of in the process. They are as follows:

1. Heat energy,
2. Electrical Energy,
3. External fuel energy.

The energy calculations are done by studying the process in detail first and then identifying the process parameters at each stage in the process. After identifying the process parameters, the kinds of energies used at that stage of the process is identified. Then the process of computation of energies is done. If the model or the parameters are unsatisfactory then the process is repeated and the process is followed again. This methodology of energy calculation is simple and very effective. If the process changes, then the model also needs to be automatically updated as the energy calculations are done based on the process parameters, which have been identified in the previous step.

The first step in the printed circuit board process is the removal of all integrated circuits and components mounted on the board and making the board bare. The components are mounted on the board through the use of through hole technology or surface mount technology. Both these processes make use of solder, which has lead content in it to fasten it on to the board. To remove the components, the solder needs to be melted. This consumes heat energy. The calculation for consumption of heat energy is as follows:

Heat energy = $T_{H1} = \text{mass} * \text{specific heat} * (\text{Final temperature} - \text{Initial temperature})$

$$T_{H1} = M_b * C_L * (T_{F1} - T_{I1}). \quad (4.26)$$

Where M_b = mass of the boards,

C_L = Specific heat of Lead,

T_{F1} = Final temperature,

T_{I1} = Initial temperature.

After the board is made bare of all the components and the solder is removed, the next step in the process, as highlighted in the flowchart is the pulverization process. In this pulverization process, the boards are fed into a hopper and then into a shredder where in the board is reduced to particulate matter. This shredder consumes electricity and we can compute the energy at this process by knowing the power rating of the motor which drives the shredder. The electrical energy consumed by this process is given by:

$$\text{Electrical Energy} = T_{E1} = n * T_1 * P_{M1}. \quad (4.27)$$

Where n = number of batches over which the entire lot is shredded.

T_1 = time the shredding machine runs/ batch

P_{M1} = power rating of the motor which drives the shredder.

The next process is the separation of the metallic and non metallic components of the board. This process is done by means of gravity separation followed by electrostatic separation. Since the metallic particles are heavy and they are attracted to a charge, they separate out leaving the plastics and other non metallic components. This process also uses electrical energy as a rotor with high voltage is applied for electrostatic separation.

$$\begin{aligned}\text{Gravitational Energy} = T_{G1} &= \frac{1}{2} * \text{mass} * \text{velocity of air vortex} * \text{number of batches} \\ &= \frac{1}{2} * M_b * V_a * n\end{aligned}\quad (4.28)$$

Where M_b = Mass of the boards,

V_a = Velocity of the air input,

n = number of batches.

$$\text{Electrical Energy} = T_{E2} = T_2 * P_{M2} * n \quad (4.29)$$

Where T_2 = amount of time the electrostatic separator runs/batch,

n = number of batches,

P_{M2} = power rating of the motor which drives the electrostatic separator.

After the separation of the metallic and the non metallic elements take place, the metallic elements are then taken to the furnace for the extraction of the metallic components. The energy that is used in furnaces is heat energy which is generated by the exothermic reaction of oxygen and the constituent materials. The number of process steps, such as roasting, smelting, converting depends on the type of furnace used. Sometimes, the furnaces combine all these processes into a single process and sometimes it is not. The heat energy therefore can be computed by using the following formula

Heat energy = T_{H2} = mass * specific heat * (final temperature – Initial temperature)

$$T_{H2} = \sum M_b * C_p * (T_{F2} - T_{I1}) \text{ for } i = 1 \text{ to } 4 \quad (4.30)$$

Where M_b = mass of the boards,

C_p = Specific heat of copper,

T_{F2} = Final temperature,

T_{I2} = Initial temperature.

The last and the final process in the traditional recycling of printed circuit boards involves the refining of copper by electrolysis. In this process an electric potential is applied between the anode and the cathode and the pure copper gets deposited on the cathode. The energy consumed by this process is given by:

$$\text{Electrical Energy} = T_{E3} = T_3 * P_{M3} * n \quad (4.31)$$

Where T_3 = amount of time the electrolysis runs/batch,

n = number of batches ,

P_{M2} = power rating of the source (AC or DC) which drives the electrolysis machine.

The final and the total energy consumption by the process will be the summation of all the energies consumed at the individual process stages.

Total energy = $T_E = \sum$ Individual energies at each process stage.

$$= T_{H1} + T_{E1} + T_{G1} + T_{E2} + T_{H2} + T_{E3}$$

$$= M_b * C_L * (T_{F1} - T_{I1}) + n * T_1 * P_{M1}^{1/2} * M_b * V_a * n + T_2 * P_{M2} * n$$

$$+ \sum M_b * C_p * (T_{F2} - T_{I1}) + T_3 * P_{M3} * n.$$

CHAPTER V

VALIDATION OF THE MODEL BY INDUSTRIAL CASE STUDY

5.1 Introduction of Company

The name of the company has not been disclosed for purposes of maintaining confidentiality. The company deals with the extraction and assaying of precious metals and copper. They make use of shredders, electric induction furnaces, electrolytic refining techniques and processing capabilities for precious stones.

The following flowchart illustrates the process of extraction of copper at the company's refineries (Figure 5.1).

Figure 5.1: Company Process Flow

Fig 5.1: Continued.

The printed circuit boards are first acquired by the company and then they are transported to the refining facility. The boards are completely recycled and there is no resale of component parts such as integrated circuits and there is no re manufacture also. The boards are shredded using a 200 Hp-hour motor and they are reduced in size to half inch pieces. Then a representative sample of 10% is taken from these shredded pieces and sent to incineration and made into ash. This 10% sample is then further reduced in size using a shredder or granulator. The sample is then sifted and the metallic and non

metallic components are separated using a 40 mesh. The greater than 40 mesh particles contain copper and less than 40 mesh particles contain noble metals such as gold, silver and palladium. These particles are then subjected to testing and their composition is found out. If the composition of the boards is favorable and it has appreciable amounts of copper and noble metals only then it is processed and recycled. If the particles do not contain appreciable amounts of metals in it, then the report is sent back to the original equipment manufacturer or the client and the destruction and incineration charges are specified. The destruction of these materials is done in a safe and environmentally friendly manner.

The sample which contains appreciable amount of metals is taken for processing. The less than 40 mesh particles and the greater than 40 mesh particles are both sent to an overseas precious metals refinery and the amount of metals (precious and copper) extracted are sold at the metal exchange values. The greater than 40 mesh particles, only 10 % (sample) are mixed with one is to one ratio of copper and copper is extracted from the furnace. The copper that is obtained is sold in the market based on the grade and the purity of copper. The rate at which it is sold is based on the London metal exchange values.

5.2 Data Obtained

The data obtained from the company are as follows:

1. Take Back Cost – \$ 0.80/ lb
2. Logistics Cost - \$ 0.02 - \$0.06/ lb
3. Disassembly Cost – Not Applicable
4. Testing Cost – Not Applicable
5. Processing Cost - \$ 0.60/ lb
6. Reverse logistics Cost - \$0.02 \$0.06/lb(logistics cost and reverse logistics cost assumed to be same)
7. Waste Disposal Cost – Not Applicable.

Labor Cost at Gannon and Scott - \$25/hour

Minimum weight accepted for each batch – 2000 lbs

Precious metals recovered from < 40 mesh powders (approximate content found in desk top related circuit boards).

Gold ---- 6~ 7 ounces /ton

Silver ---- 19~ 20 ounces/ ton

Palladium ----- 1.5 ~ 2 ounces / ton.

The data that is obtained above is only one time data provided by the company and is based on the expert opinion of the regional manager of the refining company. The energy computation for the separation process of metallic and non metallic streams using pyro metallurgy technique being used by the company is computed using the data. The energy consumption in the furnace process for purification of copper is not considered as

data is not available. Then the activity costs based on actual data provided by the expert is computed. The conclusions and the results are based on the data provided by the company and cannot be generalized to the whole industry. It is specific to the problem under consideration and the data obtained. The word document and the table in which the results were provided are attached in the appendix section of the document.

5.3 Cost Computation using Activity-Based Method

As per the activity model when applied to the case study, there are only 4 main cost centers. They are Take back Cost, Logistics Cost, Furnace Cost and Reverse logistics Cost. The total cost for the entire process is therefore composed of these 4 components and can be computed as:

Cost Calculations (as per cost data given by company)= \$ 0.80 * 2000 + \$0.06 * 2000+ NA + NA + \$ 0.60* 750+ \$0.06 * 750 = \$ 2215

Where 0.80 = cost of acquiring the boards = Take back Cost;

0.06 = cost of transportation of the boards = Logistics Cost,

0.60 = cost of furnace operations = Furnace operating Cost,

0.06 = Reverse Logistics Cost.

The figures of 2000 lb and 750 lb correspond to the initial weight of the printed circuit boards and the weight of copper obtained after processing. The values of 2000 lb and 750 lb are taken into account based on proportionality relationship and the data provided by the company. Therefore, the cost incurred to the company per pound is $2215/2000 = 1.1075\$/\text{pound}$.

The revenues generated by the company are through the metals obtained from recycling such as copper, silver, gold and palladium. All the revenue that is generated is through recycling only. The revenues that are generated are computed as follows:

$$\begin{aligned} &750*1.5 + 370*6(\text{ounces}) + 19*4.92(\text{ounces}) + 194*1.5(\text{ounces}) \\ &= \$1125 \text{ (just from Copper)} + 2220(\text{from Gold}) + 93.48(\text{from silver}) + 291 \text{ (from} \\ &\text{palladium)} = \$3729.48 \end{aligned}$$

(Value of Gold, silver, palladium and copper are average prices on 17th October 2003 at 11.00 am, from New York Market and the London metal exchange).

We can see from the calculation of the revenues that the revenue obtained from copper is not sufficient to cover all the costs and the company makes a profit from the noble metals that are present in the electronic scrap. Also, we can infer that in order to reduce the costs, we need to develop processes that lower the total cost of the process. Processes which consume low energy and have lesser overheads will be more effective in the recovery of these base metals and noble metals.

5.4 Energy Computation for Traditional Process

As we can observe from the process, there are two steps where in the boards are pulverized and then the boards are granulated. The printed circuit board powders are incinerated in a furnace which consumes heat energy. There fore the total energy consumption of the process is as follows.

Energy is used to reduce the boards to half inch size. In this process a 200 Hp-hour motor is made use of. The energy type consumed is electrical energy. The electrical energy can be computed by knowing the power rating of the motor and the time duration for which the motor runs. Since the capacity of the shredder is 3000 pounds/ hour and we are using just one ton, the electrical consumption will be as follows.

From the data given by the company, we have 3000 lb of copper shredded in one hour. Therefore, the amount of time required for shredding 2000 lb is 0.67 hrs or 40 min. The energy calculations are based on the formulae discussed in Chapter IV.

$$\begin{aligned}\text{Electrical Energy} &= TE1 = n * T1 * PM1. \text{ for shredding} \\ &= 1 * 0.67 * 200 \text{ hp- hour} \\ &= 134 * 2.6845 \text{ MJ} \\ &= 359.723 \text{ MJ}\end{aligned}$$

Where n = number of batches,

T1 = the amount of time required/batch for shredding,

PM1 = power rating of the motor used.

The next step in the process is that of incineration or furnace processes for making it into ash. This makes use of heat energy. Heat energy is calculated using the following formula,

Heat energy = TH1 = mass * specific heat * (final temperature – Initial temperature) +
Amount of heat energy required to maintain the final temperature due to heat losses

TH1 = Mb * Cp * (TF2 – TI1) + % of total heat energy * Time required for the furnace process.

where Mb = mass of the boards

Cp = Specific heat of copper

TF2 = Final temperature in the furnace.

TI1 = Initial temperature in the furnace.

$$= 2000 * 453.59 / 9.8 * 0.09 \text{ cal/g} * (499.95^\circ\text{C} - 40^\circ\text{C}) * 1 + 0.2 * 16.04 * 2$$

$$= 16.04364 \text{ MJ} + 0.2 * 16.04 * 2 \text{ MJ}$$

$$= 16.04 + 6.416$$

$$= 22.45 \text{ MJ}$$

The second additional factor is used, because once we increase the temperature to the final temperature, there must be a constant input of heat energy to maintain it at that temperature to counter the heat loss that takes place. The actual formula for calculating heat loss is based on the application of Newton's law of cooling to the surface losses.

This equation is given by (Sun, 2002)

$$W = (h * S * (T - T_a)) / V \quad (5.1)$$

where W = Heat Lost,

h = convection coefficient,

S = Surface area of reacting system,

V = Volume of the reacting system,

T = Temperature inside the reacting system,

T_a = Temperature outside the reacting system.

These equations are a part of Semenov's model or theory and in practice can be calculated by the above formula. However, in this thesis, due to the lack of data, we have assumed that 20% of the total heat energy is utilized to counter this heat loss and the temperature is kept constant.

The next step in the process is that of fine shredding or granulation. The same shredder is made use of for this purpose and electrical energy remains the same. After the boards are made into ash, the ash is further milled for screening. But at this stage, all the 2000 lbs is not present and only 1500 lbs is obtained (as per data given by the company). Therefore, the amount of time required for granulation is 30 min or 0.5 hours.

Electrical Energy = $TE_2 = n * T_1 * PM_1$. for granulation.

$$= 1 * 0.5 * 200 \text{ hp-hour}$$

$$= 100 * 2.6845 \text{ MJ}$$

$$= 268.45 \text{ MJ}$$

where n = number of batches,

T_1 = the amount of time required/batch for shredding,

PM_1 = power rating of the motor used.

Therefore, the total energy that is required is given by:

Electrical energy for shredding + Heat energy consumption in furnace+ Amount of heat energy required to maintain the final temperature+ Electrical energy for granulation

$$= TE1 + TH1 + TE2$$

$$= n * T1 * PM1 + Mb * Cp * (TF2 - TH1) + 0.2 * TH1 * T2 + n * T1 * PM2$$

$$= 359.72 \text{ MJ} + 16.04364 \text{ MJ} + 0.2 * 16.04 * 2 \text{ MJ} + 268.45 \text{ MJ}$$

$$= 650.62 \text{ MJ} / 2000 \text{ pounds}$$

$$= 0.3253 \text{ MJ} / \text{pound.} \quad (2000 * 0.3253 * 947.817)$$

$$= 0.61 \text{ million btu/ton.}$$

This is the amount of total energy that is required for processing and extracting one ton of copper from this process. The amount of energy required for shredding and granulation accounts for nearly 80 % of the total energy consumption. The process needs to be made more energy efficient by reducing the amount of shredding or granulation.

5.5 Innovative Process Energy Computation-Super Critical Fluids

Many new technologies are being developed for the recycling of printed circuit boards and among them is a super critical fluid technology. These fluids possess low and tunable densities that can be varied between those of a gas and a liquid. These fluids are being used at low temperatures and high pressures to recycle printed circuit boards. The following flowchart illustrates the process of super critical fluids on printed Circuit boards.

Figure 5.2: Super Critical Fluid Process

System preparation: With predetermined amount of PCB and co-solvent fed into the reactor, the system is pre-pressurized with CO₂ or other SCF to 1/10 of the target pressure, and then the reactor is heated to the target temperature with the pressure maintained constant.

Reaction process: The reactor is pressurized with CO₂ directly to the target pressure with its temperature maintained constant. Then the gas booster is stopped while

the pressure is maintained by the check valve. The constant pressure and temperature exert steady SCF treatment on the PCB delaminating and the process will be kept for a predetermined time period.

Pressure drop: at the end of a predetermined time period, a rapid depressurization, usually several seconds, is conducted with the intent to induce foaming in the reaction process. Then the reactor is pressurized to the target pressure again. This action is repeated for investigation of cyclic depressurization effects on PCB delaminating in the SCF treatment.

Test conclusion: At the end of the process, the pressure is released rapidly and the system cooled to room temperature. All experimental data are collected, and the PCBs are removed from the vessel to be examined for degradation and delamination.

We can see from the process that there are 2 times energy is utilized. One for the pressurization of the reactor and the other to heat the reactor and maintain it at that critical temperature. Therefore the energies used are Pressure energy and Heat Energy.

We can compute the amount of energy required for pressuring the reactor knowing the amount of time needed for pressurization and the horse power of the motor which is used in the compressor. Therefore, energy for pressurization gets converted to electrical energy.

$$T_{E1} = T * PM1$$

where T_{E1} = electrical energy of the compressor,

T = amount of time required for pressurization,

$PM1$ = Power rating of the motor used in the compressor.

By using the power rating of the compressors being sold commercially by PDC machines, we can estimate the energy required for the process.

$$= 0.2 * 30 * 2684519.53$$

$$= 16107117.18 \text{ Joules}$$

Heat energy required to heat the reactor and maintain it at that temperature for the amount of time necessary for the reaction is computed below. Before the computations are made some assumptions need to be made as the super critical process is still in a development stage in the laboratory and the effects of scaling up of the operation for 2000 pounds of weight (the weight being used for comparison) is not known.

Assumptions:

1. The volume of the vessel in which reaction takes place is assumed to be 400 liters.
2. The density of super critical carbon di oxide can vary in the range of 0.1g/cc to 2.5g/cc. However for the purposes of calculation the density is assumed to be 1.5g/cc.
3. 70% of the volume is occupied by the boards and the rest 30% by the super critical fluid.

First we convert the value of 400 liters to cubic centimeters. This will yield us a value of 400000 cc, being the total volume.

$$\begin{aligned} 70\% \text{ of the total volume is occupied by printed circuit boards} &= 70\% * 400000 \\ &= 280000 \text{ cc} \end{aligned}$$

$$\begin{aligned} \text{The rest 30\% of the volume is occupied by super critical fluid} &= 400000 - 280000 \\ &= 120000 \text{ cc} \end{aligned}$$

We know the volume and the density of the super critical fluid, we can calculate the mass of the super critical fluid.

$$\text{Density} = \text{Mass}/\text{Volume}$$

$$\text{Therefore, Mass} = \text{Density} * \text{Volume} \quad (5.2)$$

$$m = d * V \text{ (where } d = \text{density and } V = \text{volume)}$$

$$= 1.5 \text{ g/cc} * 120000 \text{ cc}$$

$$= 180000 \text{ grams} = 396 \text{ pounds (using conversion tables).}$$

Therefore, the mass of the super critical fluid is 396 pounds. We know the mass of the printed circuit boards is 2000 pounds. Therefore, the total mass in the 400 liter reactor is 2396 pounds. The heat energy can be calculated by the following formula:

Heat energy = T_{HI} = mass * specific heat * (final temperature – Initial temperature) + amount of heat energy required to maintain that temperature for the reaction time.

The reason for the utilization of the second additional factor is explained in Chapter V in the case study section where in Newton's law of cooling equation is illustrated which can be made use of in practice. However, due to the lack of availability of data, the assumption of 20% of total heat energy is used to counter the heat losses is made and the energy calculations are arrived at.

$$T_{HI} = M_T * C_p * (T_{F2} - T_{I1}) + (\% T_{HI} * \text{Amount of time for reaction}).$$

Where M_T = mass of the boards + mass of the super critical fluid,

C_p = Specific heat of carbon di oxide,

T_{F2} = Final temperature,

T_{I2} = Initial temperature.

$$= (2000 + d * V) * 453.59/9.8 * 0.203 \text{ cal/g} * (150^0\text{c} - 40^0\text{c}) + 20\% * T_{H1} * 4.$$

$$= (2000 + 396) * 453.59/9.8 * 0.203 * 110 * 1 + 20\% * 2.476 * 4$$

$$= 2476355.165 \text{ Joules} + 1981084 \text{ Joules}$$

$$= 2.476 \text{ MJ} + 1.98 \text{ MJ}$$

$$= 4.456 \text{ MJ of heat energy is utilized.}$$

The total energy for the process is given by:

$$T_E = T_{E1} + T_{H1}$$

where T_E = Total Energy,

T_{E1} = Electrical energy consumed by the compressor,

T_{H1} = Heat energy used for the reaction.

$$= T * PM1 + M_T * C_p * (T_{F2} - T_{I1}) + (\% T_{H1} * T_{\text{Reaction}})$$

$$= T * PM1 + (M_{\text{Board}} + d_{\text{co2}} * V_{\text{co2}}) * C_p * (T_{F2} - T_{I1}) + (\% T_{H1} * T_{\text{Reaction}})$$

$$= 16.107 \text{ MJ} + 4.456 \text{ MJ}$$

$$= 20.563 \text{ MJ}$$

A comparison is made of the pyro metallurgy based process made use of in the case study and the super critical fluids process. Only the shredding and granulation portion of the energy consumption is compared with the super critical fluid-based process where in chemical reactions take place and delamination of the board occurs. In the pyro metallurgy process based on the case study of Gannon and Scott refining company, there are 3 main steps in the process namely, shredding of the boards, incineration and then granulation of the ash. In the super critical fluid process, there are 2 main steps,

pressurization and then increasing the temperature to the desired level (150°C). The time required in the traditional pyro based process is that made use of in shredding, incineration and granulation, which totals to 3 hours and 10 minutes (based on the calculations made in the case study). In the super critical fluid process, the experiment has been conducted for 4 hours. The energy calculations and comparison is only an estimate of the actual and since the process is in a development scale, the effects of scale up are not considered. The values obtained for energy are from a theoretical stand point of view.

However, we can observe a large gap or a wide difference in the energy consumptions of the two processes. Shredding and Granulation consume most of the energy in the process and account for more than 40% of the total energy consumption. However with the super critical fluids, the temperature range at which the process operates is quite low, at 150°C and the process of delamination is chemical rather than a mechanical approach. The following table gives us a comparison of the energy consumptions in the 2 processes.

Table 5.1: Energy Comparison of Pyro-technology and Super Critical Fluids

Parameters	Pyro metallurgy energy comparison(Gannon and Scott refining company)	Super Critical Fluids(estimates)
Number of steps in Process	3 main steps (based on process)	2 main steps (based on the process)
Temperature	High temperature 1200 c (process temperature obtained from case study)	Low Temperature 150 c (experimental data)
Pressure	Atmospheric Pressure (based on process details)	2500-5000 Psi (experimental data)
Time Required	3 hours(based on case study data calculation)	4 hours (based on experimental data)
Energy Consumption	Very High(650.62 MJ/ ton, based on calculation)	Low (20.563 MJ/ ton, based on calculation)

CHAPTER VI

CONCLUSIONS AND RESEARCH CONTRIBUTIONS

6.1 Conclusion

The problem of end of life management of electronic products and in particular printed circuit boards is a topic which still needs extensive attention. The problem becomes more acute because of the low technology being used and high volumes of electronic scrap which needs to be disposed. To solve these problems, new methodologies need to be developed which makes use of low cost and energies during the disposal stage. This is very important as the margin of profit in these recycling markets is very low and is entirely dependent on the volumes being processed. Hence, the need for a low cost and low energy consuming process. This research contributes towards this endeavor. The following are the conclusions that can be drawn from this research work and from the data obtained from Gannon and Scott refining. The data obtained from the company as previously mentioned is based on the expert judgment and estimation of the person providing us the data.

1. From, the case study and the calculations, we can conclude that the process of recovery of copper is profitable only when there are other precious metals also in the electronic scrap.
2. The weight of electronic scrap obtained plays a very important role in the process.
3. Smaller weights, such as weights lesser than 1 ton do not yield profits with pyro technology.
4. The energy consumption for pyrotechnology is very high(650.62 MJ/ton)

5. Shredding and pulverization consume nearly 40% of the total energy consumed in the process and is inefficient.
6. Innovative processes such as super critical fluids consume less energy when compared to pyro metallurgy technique, if they avoid the use of shredding and granulation.

6.2 Research Contribution

In this research work an attempt has been made to develop a model which focuses on assessing the cost and energy consumption of electronic products when they reach their end of life stage. The economic model will provide a basis for analyzing the cost and energy consumption used in the traditional recycling process. Also the model will help in evaluating various alternative processes which can be used for recycling based on the cost and energy criteria. The model provides a general step by step procedure which can be used by many products and processes when they reach their end of life stage. Also, in the model, the entire chain, the upstream and the downstream players in the process of end of life is considered and an integrated model is developed. The economic model unlike other models provides a common platform wherein both cost and energy can be evaluated for the process. Contributions of the proposed economic model are as follows:

1. Parameters affecting the various costs are identified and test of hypothesis for linearity is conducted.

2. A multiple regression methodology is used to establish the linearity of the process costs with the total cost, which is the dependent variable.
3. The activity or process costing approach is applied to end of life management of printed circuit boards using traditional recycling procedure.
4. An energy model is developed for pyro technology based process and the same energy model is used to estimate the energy of innovative process like super critical fluids.
5. The energy calculations are based on process parameter approach and as the parameters change, the effects of those changes are readily seen in the computation.
6. The economic model, unlike other models makes use of cost and energy in the same framework.

This research was carried out to build an economic model for the problem of costing when the products reach their end of life. The main idea was to provide a framework for the recycling companies which are still in their infancy to use an approach which computes total cost, total energy and at the same time know the cost and energy consumption for individual activities defined in the process or system. As the process parameters change, the individual cost and energies change too.

In summary, after reviewing the literature and working on this model, it was felt that the main problem in making this recycling and reuse strategies profitable is to develop new processes which make use of low cost and low energy. The traditional process which has been considered here for the recycling of printed circuit boards

consists of a lot of steps and procedures. Each step and procedure in the process involves cost and energy consumption. Also, the recycling process right now depends heavily on the volumes to make a profit as they do not know the content of the boards and the materials which can be recycled. If during, the design stage itself the boards are built in a fashion to accommodate recycling during their end of life, then process of recycling these electronic wastes will become profitable. Also, new technologies need to be developed for recycling these electronic components. Some of the technologies which are under development in laboratories all over the country use novel techniques like, leaching, hydro metallurgy and use of super critical fluids. These processes might offer low cost and energy consumption resulting in higher profits for the recyclers and making these recycled products competitive with the main stream ones.

6.2.1 Some suggestions for future work

1. Evaluating Alternatives: The concept of evaluating alternatives should be tried and developed using the activity based costing approach. This can be done in conjunction with the actual collection of data and testing the model.
2. Software development: The model can be converted into software by making use of the formulae used for cost and energy development. Also since a hierarchical approach is used the disassembly process plan can also be incorporated.

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APPENDIX

DATA OBTAINED FROM GANNON & SCOTT REFINING COMPANY

- What is the Cost of obtaining the printed Circuit boards? Cost/ Board
Approx \$0.80 per lb if you were buying off the street
- What amount in weight obtained for each batch? Weight
2,000 lbs minimum for our operation.
- What is the cost of transportation/ batch?
Depends on distance and volume but \$0.02 to \$0.06 per lb
- After the board reaches the company, what is the process of removal of the integrated circuits?
We do not remove ic's. Boards are hammer milled to half inch pieces and a representative sample size of 10% is taken and sent for incineration, ball mill, screen, melt and sampling
- How is the solder removed?
Solder is not removed.
- At what temperature is the solder removed?
Not applicable but our furnaces run at approx 900f when we burn circuit boards
- After the solder is removed what processes take place?
After we take a 10% sample, this is burned to an ash. The ash is ballmilled and screened to 40 mesh. The < 40 mesh is blended and sampled. The > 40 metallic fraction is melted with a ratio of 1:1 copper in an induction furnace and sampled.
- What amount of time takes place for testing of the circuits?time for testing/batch/circuit
Our payment terms are 30 business days from receipt
- What is the labor cost for the employees working at? \$ rate /hour
In the order of \$25/hour

- What is the **power rating** of the machine which shreds these pieces?
200 hp
- What is the amount of weight that is put in the shredder in one batch?
Up to 40,000 lb
- How many times should the batch be pulverized?.
Once
- What is the amount of time for pulverization?.
3,000 lbs per hour
- What is the cost at which the products are sold(repaired and remanufactured products)?
\$1.80 to \$3.00 lb
- What is the amount of time required for remanufacture/ repair?
Not applicable to our operation
- How does the separation of metallic and non metallic elements in recycling take place?
40 mesh screen
- What is the operating cost of the furnace/unit time
Very difficult to answer this question. It will vary on the material, and what type of furnace you are running. A rotary for example will burn faster than a box furnace.
- What is the amount of time/batch in the furnace?
Shredded pieces with limited air surrounding the particles could take 2-3 hours
- What is the amount of time required for electrolytic refining?
Not applicable to this operation
- What is the power rating of the source used for electrolytic refining?.
Not applicable to this operation
- What fraction of the weight obtained is used for recycling?, what fraction of the weight obtained is used for remanufacture and what portion of the weight is waste?.
100%, there is no waste

Table A1: Case Study Data

Parameters	Cost/Value	Comments
Cost of obtaining Printed Circuit Board/ unit weight	Varies	We pay for the recovered metals after assay
Cost of transportation/ order/unit weight	\$0.02/lb but will go higher if volume is less	
Time required for testing components	N/A	
What components are tested?	N/A	
Time to disassemble components/ computer(in particular printed circuit boards)	N/A	
Labour Cost/ Hr	\$25	
Time for Repair and Remanufacture(Printed Circuit boards)	N/A	
Price at which the Repaired and remanufactured Components are sold	N/A	
How is the separation of metallic and non metallic components done	40 mesh screen	
If the component is recycled, what is the method used?	N/A	
If a shredder is used, what is the power rating of the shredder?	200 hp	
What is the amount of weight or mass , put in the shredder at one time?	Continuous feed at about 3,000 lbs/hr	
For what amount of time does the shredder run?/batch	Variable depending on batch size	
After the separation of waste streams, what is the next process?.	Incineration	
Weight Acquired/ Order	30,000 lb	

Table A1: Continued

Parameter	Cost/Value	Comments
If the product is sent to a refiner, what is the cost at which the sale is made?	We are considered to be a secondary refiner. Our out turn of sweep and base bar is sent to contract smelters overseas. It is sold for its precious metal contents.	
What is the operating cost of the furnace/ time	Difficult to answer because of so many variables	
What is the amount of time the batch spends in the furnace	2-3 hours	
What is the amount of time required for electrolytic refining?	N/A	
What is the power rating of the source used for electrolytic refining?	N/A	
What fraction of the weight obtained is used for recycling? What fraction of the weight obtained is used for remanufacture and what portion of the weight is waste?	100% recycled	

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