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Assessing the impact of design for environment guidelines : a case study of office telephones

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ABSTRACT

ASSESSING THE IMPACT OF DESIGN FOR ENVIRONMENT GUIDELINES:
A CASE STUDY OF OFFICE TELEPHONES

by
Hussam F. Al-Okush

This research addresses a fundamental question: How much of the improvement in a product's environmental performance is directly attributable to the Design for Environment (DFE) tools and guidelines, and how much results simply from other design objectives or enabling technologies? The research examines four generations of a business telephone over the last thirty years, including the current generation, which has been designed using DFE guidelines. A lifecycle assessment (LCA) and demanufacturing analysis were performed on each of the first three generations to determine various technology and non-DFE trends. This information was used to forecast the progression to a 1997 non-DFE phone. By overlaying comparable information generated by analyzing the 1997 DFE-designed phone, the true impact of DFE on the product becomes apparent.

Relevant characteristics and metrics such as raw materials, energy depletion, environmental burdens, and others were used to analyze the environmental performance of the telephones. All of the trend characteristics are based on lifecycle data; consequently, LCA tools and methodologies are the basis for performing this study. Traditional LCA methodologies have been expanded to incorporate multi-lifecycle options for the product and its basic materials. In addition, techniques such as the Eco-Compass, developed at Dow Europe, and Resource Productivity, as proposed by Sony, are used to compare the various generations.

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A CASE STUDY OF OFFICE TELEPHONES

by
Hussam Fawzi Al-Okush

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May 1999

APPROVAL PAGE

ASSESSING THE IMPACT OF DESIGN FOR ENVIRONMENT GUIDELINES:
A CASE STUDY OF OFFICE TELEPHONES

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بسم الله الرحمان الرحيم

In The Name of God The Most Gracious, The Most Merciful.

أُهدي هذه الرساله
الى أَبي و أُمي الحَبيبيَن...
مَع كُل احترامي و تَقديري و امتناني لِجهودكما عبرَ السّنين...

This thesis is dedicated to my
beloved parents
with all respect, appreciation and gratitude for their everlasting support

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CHAPTER 1

INTRODUCTION

1.1 Background

Looking forward towards the millenium, the question of how to improve on the quality and standard of living of societies becomes a great concern. An environmentally safe and clean earth must be secured for the upcoming generation. Over the last decade, America's manufacturing industry has struggled to achieve a balance between economic security and environmental responsibility. While individual efforts to reduce process wastes and design green products have been initiated, overall progress has been slow. Due to increasing political and societal pressures, the need to increase the pace for more environmentally friendly products is felt by many companies.

Current practices have created a linear flow from raw material extraction and processing into products and packaging which are all too frequently used once and then discarded into a landfill. Numerous statistics point out the scope of the problem. The National Academy of Sciences reported that 94 percent of all natural resources extracted from the earth enter the waste stream within months [1]. The amount of plastics in the waste stream is projected to reach 60 billion pounds by 2010; currently, only 2 percent are being recycled [2]. And, according to US Environmental Protection agency (EPA), municipal solid waste (MSW) increased from 88 million tons in 1960 to a projected 223 million tons by the year 2000 [3].

As the manufacturing pace increased rapidly, efforts were concentrated on "easy assembled" products with no consideration for disassembly. The continuous decrease in the lifetime use of the electronic products due to technological advancements with lack of design for disassembly and upgradability resulted in a steady increase in the volume of discarded products. Due to this high volume of discarded electronic products, the electronics industry is facing a substantial problem in identifying the end-of-life options for these products. The need for alternative end-of-life options other than landfilling is a major concern of this industry for several reasons:

- As technology advances and improves, companies aim to make recycling or reengineering of products more profitable than landfilling them.
- In Germany and other European countries, new laws have been adopted to address the disposal of electronic products and promote reuse and recycling [3]. Typical of such legislation is a pending German product takeback law that requires manufacturers to takeback and recycle their products after consumers are through with them.
- All European Union (EU) members are in the process of imposing a takeback legislation through "The Priority Waste Stream Project" which aims at minimizing materials sent to landfills by encouraging reuse and recycling [4].
- In the United States, industry, research institutes and government agencies are studying several management strategies for discarded electronic products. According to the USEPA, over 12 billion tons of industrial waste is generated annually, of which 4.2 billion tons is classified as hazardous waste generated in manufacturing [5].
- Many of the electronic products contain a variety of toxic substances such as lead, cadmium, mercury and others [6]. Concern arises from products such as batteries, switches, cathode ray tubes (CRT) and other products, that contain lead in the glass,

which may leach out into the soil causing serious environmental damage and health concerns.

In the context of the above problems and environmental concerns, many methodologies and strategies have been utilized to help address these issues. Tools such as lifecycle assessment and Design-For-Environment (DFE) are widely used to evaluate the products environmental performance throughout its lifecycle. These tools aim to study and document the environmental impacts associated with materials flow, energy use, and environmental burdens including air emissions, waterborne waste, and solid wastes. This information will assist designers in identifying substitute materials, design alternatives and process options leading to better environmental performance of their products.

There is a growing body of literature devoted to the development of design for the environment tools using lifecycle assessment as the mechanism for quantifying the impact of design and production issues over the working life of a product [2,3]. The underlying approach of "material and energy balances" is a well-developed concept that has been the mainstay of chemical engineering practice and is embodied in chemical process flowsheet simulators. Use of the LCA complements efforts to extend "Design for X" metrics to include environmental issues in a formalized strategy that gives the designer feedback on the lifecycle impact of the evolving design. While significant research is underway to develop fully integrated product and process design systems with interactive DFE modules, the current state of practice is to translate environmental lifecycle concerns into design guidelines and assessment matrices. Check lists are used to assure relevant considerations are included during the design process; and product assessment matrices are used to evaluate the environmental "goodness" of a finished design [1,2,7].

1.2 Research Objectives and Desired Outcomes

Green design tools have been used by various manufacturers in the electronics and automotive sectors to improve the environmental performance of their products.

A fundamental question needs to be addressed: How effective are existing DFE tools? Or, stated more specifically, how much of the improvement in the product's environmental performance is directly attributable to the DFE tools and how much results simply from other design objectives or associated enabling technologies? For example, in electronic products, dematerialization is a basic design objective and a natural consequence of advances in semiconductor technology and newly developed materials. Dematerialization generally has a positive impact on all phases of the product's lifecycle environmental and energy performance—from raw material extraction and synthesis to production, packaging and shipment and on to customer use and eventual end-of-life management. Consequently, a product may have improved environmental performance over an earlier generation with the improvement attributable to considerations other than those explicitly embedded in DFE tools.

This research begins to address this critical question and assesses the true impact of current state-of-the-art DFE tools. The research focuses on a single product and examines four generations of this product over the last thirty years, including the current generation, which has been designed using DFE guidelines. The product chosen for the study is the basic business telephone designed as a terminal unit connected to a private business exchange (PBX). While some of the operational features of the phones differ, they are considered to be functional equivalents for the purpose of this study. Figure 1.1 displays a photograph of the four generations of business telephones. The desired outcomes of this research are as follows:

- To conduct a lifecycle material and component inventory and characterization on the four generations, with a focus on material use, energy consumption, and the environmental over the lifecycle of the product.
- To develop disassembly process flow charts, and reverse fishbone diagrams, for each product generation.
- To synthesize and evaluate this data and information into longitudinal trend diagrams to distinguish between the impacts of general technology evolution and DFE principles.
- Applying environmental performance metrics such as eco-compass and resource productivity to evaluate the product.
- Finally, to conduct a survey of existing DFE tools and techniques—including design guidelines, product assessment matrices, disassembly analysis and planning, and lifecycle analysis procedures.

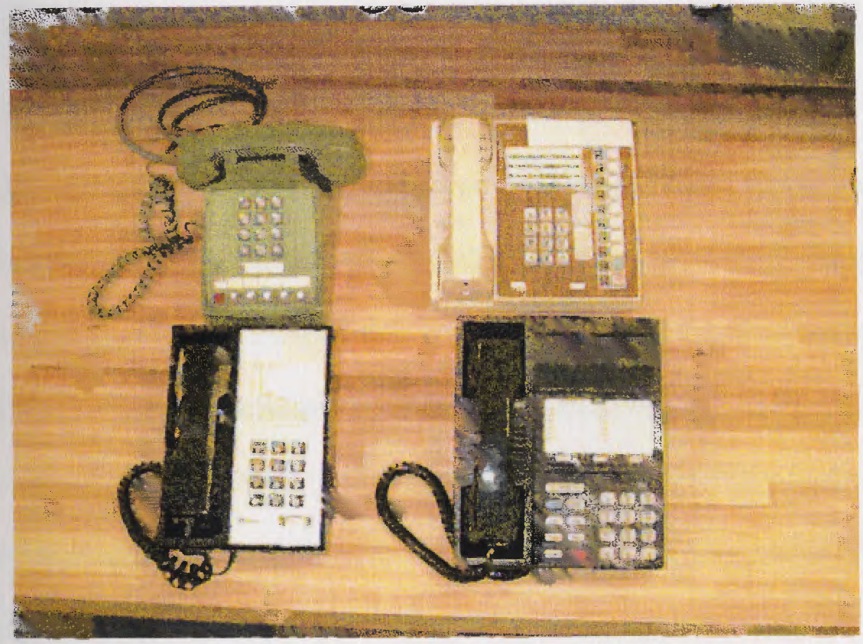


Figure 1.1 Photograph of Four Generations of Business Telephones for Study:
Top Row (Left to Right): 1965 1978
Bottom Row (Left to Right): 1989 1997

1.3 Multi-Lifecycle Engineering

Discarded consumer electronics, computers, and household appliances contribute significantly to the environmental burden placed on municipalities across the nation. If discarded products and waste streams, such as these, can be recovered and reengineered into valuable feedstocks, then we can break this trend and achieve sustainability.

A new approach is necessary, multi-lifecycle engineering (MLCE), that takes a systems perspective and considers fully the potential of recovering and reengineering materials and components from one product to create another, not just once, but many times. This is not simply recycling or design for the environment, but rather a complex, next generation engineering system that transcends traditional discipline boundaries in search of fundamental scientific knowledge, new methodologies and technologies [8].

Multi-Lifecycle Engineering is concentrated towards the following cross-interdisciplinary thrust areas [8]:

1. *Multi-lifecycle Product and Process Design* – Consideration of multi-lifecycle concerns into the earliest phase of product conceptualization and design with particular emphasis on material and form substitution, lifecycle assessment, next generation use, material recovery, and value analysis.
2. *Reengineered Materials from Waste Stream* – Characterization of material from waste streams, characterization of reengineered material systems, structure/property relationships, and predictive models for mixtures based on fundamental characterization of component elements.
3. *Separation Technologies* – Fundamental research associated with separation processes for material reclamation and purification and processing of gaseous, liquid and solid waste streams.
4. *Demanufacturing Systems* – Advanced Methodologies and technologies for systematic disassembly, mechanical sortation, and cleaning and testing of discarded products, components and materials.
5. *Policy, Economics and Management* – Methodological and theoretical frameworks and database development for examining product lifecycle assessment, corporate structures, management initiatives and policy issues affecting multi-lifecycle product innovation and implementation.

The methodologies developed by MLCE are adopted and implemented throughout this study ranging from MLC product and process design to demanufacturing processes and techniques.

1.4 Thesis Format

The remainder of the thesis is comprised of five chapters:

Chapter 2 presents a brief overview of Design for Environment (DFE), Lifecycle Analysis (LCA), and Performance Metrics, and, in general, the background information related to this research in the form of literature review.

Chapter 3 describes the methodology adopted in Multi-lifecycle Assessment, and in applying trend analysis and other performance metrics to evaluate and assess DFE guidelines.

Chapter 4 presents a telephone case study, dealing mainly with the demanufacturing process of the telephones and the results obtained.

Chapter 5 provides the assessment of the DFE guidelines and presents all the performance metrics utilized and the results obtained from the study.

Chapter 6 concludes the thesis by summarizing the results obtained from the research and suggests recommendations for further improvements and research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The world's population is now approximately 8 billion people and is predicted to increase to approximately 15 billion in the late 21st century. This human growth was a major factor in the explosive industrial growth witnessed over the past decades. Natural resources is the fuel for such an industrial growth, which is a must, to support such a huge population. At present rate consumption, the world is estimated to have approximately 30 years of oil supply, 25-year supply of natural gas and a 500-year supply of coal. Public awareness of environmental issues and their growing concern of depletion of natural resources have increased over the years [2].

Manufacturers of consumer electronic products are facing many challenges in developing cleaner technologies and environmentally friendly products. This need is mainly driven by pending regulations and legislation, especially in Europe and Asia, and also by public awareness of the value and fragility of an intact ecology. This will tremendously affect the industry's production methodologies and encourage them to identify cleaner processes. The concern on environmental issues is not directed towards the production stage only, but has extended to encompass the various lifecycle stages of the product, starting from materials extraction through disposal and end-of-life options. Towards this, the concept of lifecycle assessment applies, as an approach to quantify the various materials, energy and environmental burdens associated with the product over its entire lifecycle.

LCA is a time consuming, complex and expensive process of evaluating the environmental performance of products, yet it is considered the dominant tool available today for such an assessment. But its ability to affect environmental improvements and to accurately assess the environmental impact of a product through its entire lifecycle is still questionable. The Society of Environmental Toxicology and Chemistry (SETAC) was the first international organization that recognized the potential values of LCA's. SETAC conducted its first technical workshop on LCA's in august 1990, where the basic four components of an LCA were developed: Definition of Scope and Boundaries, Inventory Analysis, Impact Analysis and Improvement Analysis. Also, the International Organization for Standardization (ISO) has developed an environmental management standard ISO14000 Series, which is a set of environmental standards that can be applicable worldwide.

Various LCA research had been conducted on a wide stream of products ranging from electronic products and automobiles to plastic bottles and cloth diapers. The Ecobilan (Ecobalance) group is one of the largest companies conducting LCA studies, performing projects ranging from foods and cosmetics to electronic products. Their LCA study of telephones will be assessed in this chapter. Manchester Metropolitan University, UK, has also performed an LCA study on telephones, concentrating mainly on the end-of-life options of the telephone. The Society of Automotive Engineers (SAE), issued a study entitled " Uncertainty, Sensitivity, and Data Quality Assessment for Lifecycle Value Assessment (LCVA)". This paper deals with a major concern of LCA's and that is the quality of the data, which is the backbone of any LCA study.

Most of the studies conducted on electronic products were related to the various lifecycle stages of the product, or to the integration of DFE principles into the design process. As presented in the previous chapter, this thesis "begins" to address a fundamental question: how effective are existing DFE tools? In this chapter, previous research in the areas of DFE and LCA is presented, which focuses on the basis for this thesis research.

2.2 Design for the Environment (DFE)

Industry has concentrated its efforts on their production processes, with an aim to develop and modify processes to minimize environmental burdens and conserve energy and resources. To this, the concept of Design-For-Environment (DFE) applies. DFE is defined as " The systematic process by which firms design products and processes in an environmentally conscious way" [7]. DFE is being incorporated into traditional production processes, where these processes never accounted for environmental burdens associated with production. DFE introduces a methodology to be followed in the product/process development and in the overall facility in general.

The concept of DFE is still new and there is no universal methodology that is followed for implementing or integrating DFE into the product design stages. It is known that approximately 75% of a product lifecycle cost is determined in the design phase. The decisions made during this phase will have a profound impact on the total lifecycle of the product. Therefore, environmental concerns must be addressed at the design phase so that the overall costs associated with waste streams can be reduced.

DFE constitutes mainly of a checklist of questions that targets both product and process designers. This checklist mainly concentrates on materials consumption, energy use and production of solid residues, gaseous residues, and liquid residues over all the stages of the product lifecycle. Refer to "*Design for Environment*" by T. Graedel and B. Allenby [4], which contains more detailed description of DFE guidelines. More specific details on DFE guidelines will be stated and analyzed in chapter 5 of this thesis. Implementing and integrating DFE into the design of products and processes does not guarantee a 100% environmentally conscious product. It also does not guarantee that the company is compliant with all environmental regulations, nor does it guarantee that all environmental issues are resolved. On the other hand, if DFE is implemented properly, it should assist the company in minimizing the environmental burdens of the product throughout its lifecycle, and improve its environmental performance. DFE also promotes the return of materials back to earlier stages of the lifecycle through reuse, remanufacture, and reengineering of parts and subassemblies. Therefore, closing the loop on the product lifecycle instead of the traditional disposal methods [9].

Design for Environment works also at a level higher than products and processes. "DFE is related to and may be integrated with a number of environmental management practices, strategies, and frameworks including sustainable development, industrial ecology, product stewardship, pollution prevention, environmentally conscious manufacturing, and lifecycle analysis" [9]. Figure 2.1 illustrates the relationship between DFE and the above frameworks. Following is a description of the frameworks described above:

- **Sustainable Development**

The accepted definition of sustainable development is that of the Burtland Commission [9]: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." DFE can help attain this goal by using its framework to guide decision-makers to make more environmentally sound decisions.

- **Industrial Ecology**

According to T. Graedel, and B. Allenby [3], "Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital." Therefore, industrial ecology provides a generic framework that guides DFE decisions.

- **Product Stewardship**

Product stewardship refers to the environmental concern that producers show towards their products throughout the product lifecycle. Product stewardship promotes producers to evaluate the environmental performance of their products at both the use stage and final disposition. It also encourages concepts such as take-back, reuse, remanufacture, and reengineering of products instead of typical disposal. MERC recently conducted a survey evaluation of product stewardship programs and found great diversity regarding the definition and implementation of these programs [9].

- **Pollution Prevention**

Pollution prevention aims to eliminate manufacturing processes that generate waste and pollution. This could be done by utilizing DFE concepts to design products and processes that generate no pollutants and produce no harmful co-products. Many of the manufacturing processes need to be re-designed, since most of these processes were designed prior to environmental regulations. [2,9]

- **Environmentally Conscious Manufacturing (ECM)**

Environmentally Conscious Manufacturing focuses on manufacturing processes with the aim of minimizing environmental impacts by developing more environmentally conscious manufacturing methods. ECM deals with various measures of manufacturing ranging from efficiency of resource conservation to the environmental burdens generated from a manufacturing process. It not only concentrates on main operations, but also secondary operations that may be more polluting such as painting. DFE may be implemented not only to prevent pollution, but also to effectively manage materials as to reduce environmental burdens from manufacturing processes [2,9].

- **Lifecycle Assessment**

Following the general guidelines of the Society of Environmental Toxicology and Chemistry (SETAC), Lifecycle Assessment (LCA) is an objective process to better understand the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases, to interpret the results of those energy and material uses and releases on the environment, and to use this knowledge to identify and implement opportunities to affect environmental improvements.

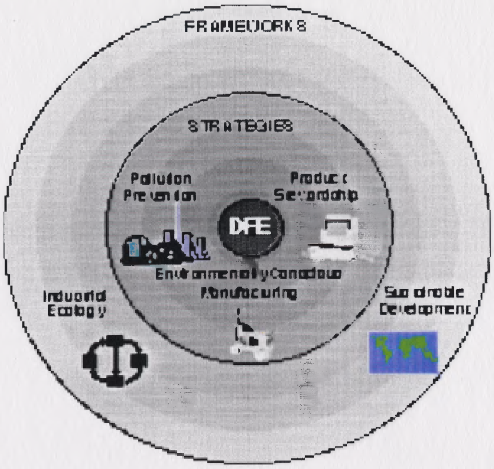


Figure 2.1 DFE as a Core Environmental Management Practice
[Source 9]

2.3 DFE Case Studies

Many companies have implemented DFE concepts on their products and processes. The key issue is to make DFE an integral part of the design process by emphasizing its importance. This section includes case studies of practical applications of DFE conducted by AT&T on their 5ESS Electronic Switch, and another by Apple Computer on the Power-Macintosh 7200.

2.3.1 AT&T's Flagship 5ESS Electronic Switch

This study aims at investigating AT&T's flagship 5ESS electronic switch's environmental performance by applying a selection of DFE tools. The first step in this study was to review and layout the lifecycle stages of the switches starting from fabrication of individual components and chips through the assembly of the printed circuit board and system assembly to use and finally end-of-life. To assess the environmental performance of this product, a tool must be used that takes into account all the products lifecycle stages, such as the matrix assessment. This requires a study of the products design manufacture, packaging, use, and the end-of-life scenarios. This tool assigns a value to each element in the matrix ranging from 0 - 4. To graphically display the results of this matrix, a "target plot" is used, see Figure 2.2. The elements of the matrix assessment are plotted as sequentially increasing angles which are multiples of 360 /24 = 15. The closer the elements are to the center, the better the performance of the product. The result showed that in general the switch was environmentally responsible, but more concentration was required on premanufacture and product delivery stages.

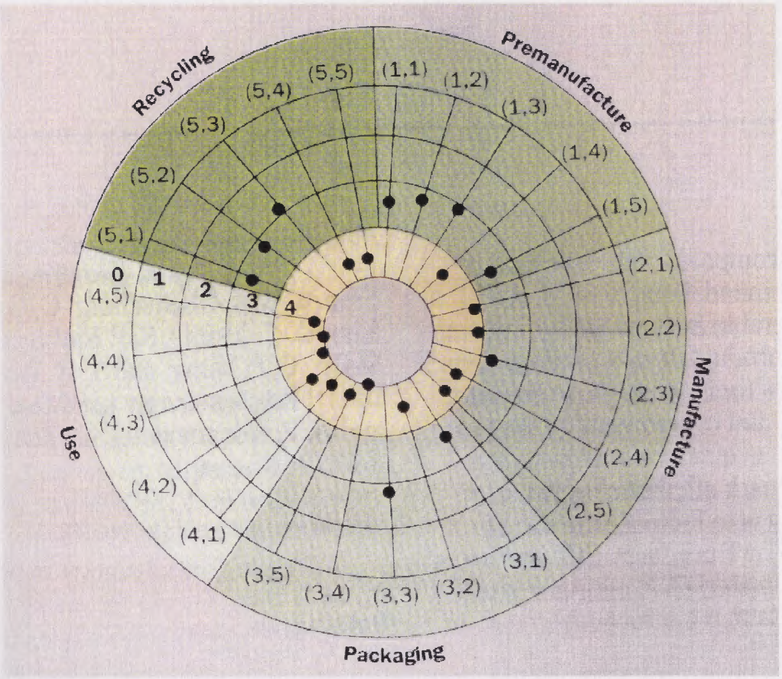


Figure 2.2 A Composite Target Plot for AT&T's Products
[Source 10]

Part of the DFE assessment is to provide recommendations for improving processes to reach the desired goals. Some of the recommendations suggested for packaging was to revise specifications for packaging material to encourage or mandate the use of some recycled material in their manufacture. Recommendations for the design phase included issues as marking of all plastics using the ISO standards, which simplifies recycling in the end-of-life options. Another recommendation was to minimize the diversity of metals and plastics used. After assessing the switch and making recommendations, the next step is to prioritize the recommendations for implementing and plotting the priorities using a Pareto plot. The highest priority rating for the manufacturing stage was to investigate the use of landfill methane, then label packaging for recycling and to specify the use of recycled material by suppliers. On the other hand, the high priority rating for the design area was to mark major plastic parts with ISO symbols, and then to use quick-release fasteners instead of screws.

In conclusion, this study provided a practical implementation of DFE using several tools. The tools used quantify the environmental performance of the 5ESS switch through its total lifecycle stages, and also produced a chart, visually illustrating the key issues to be resolved. Also, to simplify the implementation of DFE recommendations, a priority list was generated that categorized the most important issues to resolve. [10]

2.3.2 A Case Study of the New Power-Macintosh 7200

This study illustrates Apple Computer's implementation and integration of DFE principles into new product development. The product chosen for this study is the Power Macintosh 7200 CPU, where the concentration is on the environmental performance attributes of the finished product only. Previous lifecycle stages were omitted from the analysis. Also, systems components such as a monitor, keyboard, and mouse were also excluded from the study.

The main goal of this study was to quantify the contribution of the products features and design towards environmental and non-environmental performance attributes, and to identify improvement areas that are both cost-effective and environmentally beneficial. The DFE study was conducted through four basic steps:

- Determination of relevant product performance attributes

  This was divided into 2 categories: Environmental performance attributes, which included: Energy conservation, ease of disassembly, recyclability of materials, toxic materials, and material conservation. Non-environmental performance included: Ease of assembly, ease of service, and product economics.
- Selection of relevant metrics for each performance attribute
- Information gathering to support the assessment
- Assessment of product performance using selected metrics

The products performance was measured against the previous model, which is the 7100 CPU. In general, the 7200 CPU performed better than the previous model in most of the metrics analyzed. Energy consumption was reduced by 25%, weight was 12% less than the 7100 CPU, a reduction of 50% in the screws used, several toxic constituents were eliminated, and the product cost was projected to fall 15-20% below the 7100 CPU model. [11]

In conclusion, the case study presented a successful implementation of DFE concepts on a particular product. Future work could expand the scope of the study from concentrating on the finished product only, to include the total lifecycle stages. As a result, DFE guidelines such as " Is the product designed to minimize the use of materials whose extraction is energy intensive?" were not examined. This attribute combined with energy consumption at other lifecycle stage could have effected the results. The standardization of environmental performance metrics is also an issue under study, which requires more efforts for achieving comprehensive standardization.

2.4 LCA Background

There is fairly wide spread agreement on the formal structure of LCA, which contains four stages: definition of scope and boundaries, inventory analysis, impact analysis, and improvement analysis. The inventory stage is basic to all LCAs and includes measuring the inputs (e.g. materials, energy, and labor) and the outputs (e.g. waste, pollution, and usable product) that occur at each stage of the product's life. The interpretation stage, recently defined with the ISO standardization process, involves isolating the discrete portions of the product's life and simply "adding up" the inputs and outputs with, frequently, some translation into broad environmental and health impacts, ranging from global concerns to site-specific impacts (depending on the scope of the LCA). Some LCA's are performed to better understand the environmental performance of a particular product with the objective to identify opportunities for reducing the environmental impact of a product through process improvements.

- The first stage of LCA defines the scope and boundary of the study. The purpose of the study and all the assumptions and thresholds are identified at this stage.

- The second stage of LCA, inventory analysis, is by far the best developed. It uses quantitative data to establish the levels and types of energy and materials inputs to an industrial system and the environmental releases that result. In this study, the assessment is done over the entire lifecycle--materials extraction, synthesis, production, packaging and distribution, use, demanufacturing, and reengineering.
- The third stage in LCA, impact analysis, attempts to quantify and/or assign relative weighing factors to the consequences of each input and output. Impacts considered at this stage include global impacts, health effects, and greenhouse gas and others. Because the LCA is considering the entire range of end-of-life management, the factors identified may be realized in the early planning stages of a disposal process, during operation or even after a process has ceased.
- The forth stage, improvement analysis, is the explication of needs and opportunities for reducing environmental impacts as a result of industrial activity being performed or contemplated. It follows directly from the completion of stages one and two, and in implementation is termed " Design-for-Environment" (DFE).

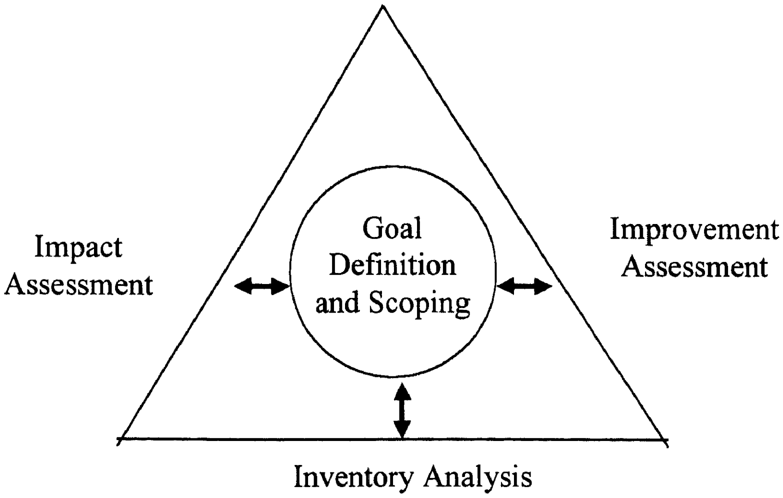


Figure 2.3 LCA Technical Framework
[Source12]

Figure 2.3 illustrates the original SETAC framework. For the most part, LCA methodologies are still in their infancy. As more experience is gained and more products, processes and materials are subjected to assessment, the LCA approaches will become more useful and more efficient. They will also become more accepted, if the results of implementing LCA studies prove to be cost efficient and profitable. It is reasonable to assume that the tools of LCA will become more sophisticated with time as more user-friendly LCA softwares are being developed [4,5].

2.5 Detailed Description of LCA Stages

This section describes in detail the LCA stages and methodologies [13]. Figure 2.4 illustrates the process flow chart for implementing an LCA.

2.5.1 Goal Definition and Scoping

- Defining the Purpose

The first step in implementing an LCA is to define the purpose of the system under study. The purpose could refer to a comparison of a new product to that of an older model, or to investigate the impact of new guidelines and policies introduced in an organization.

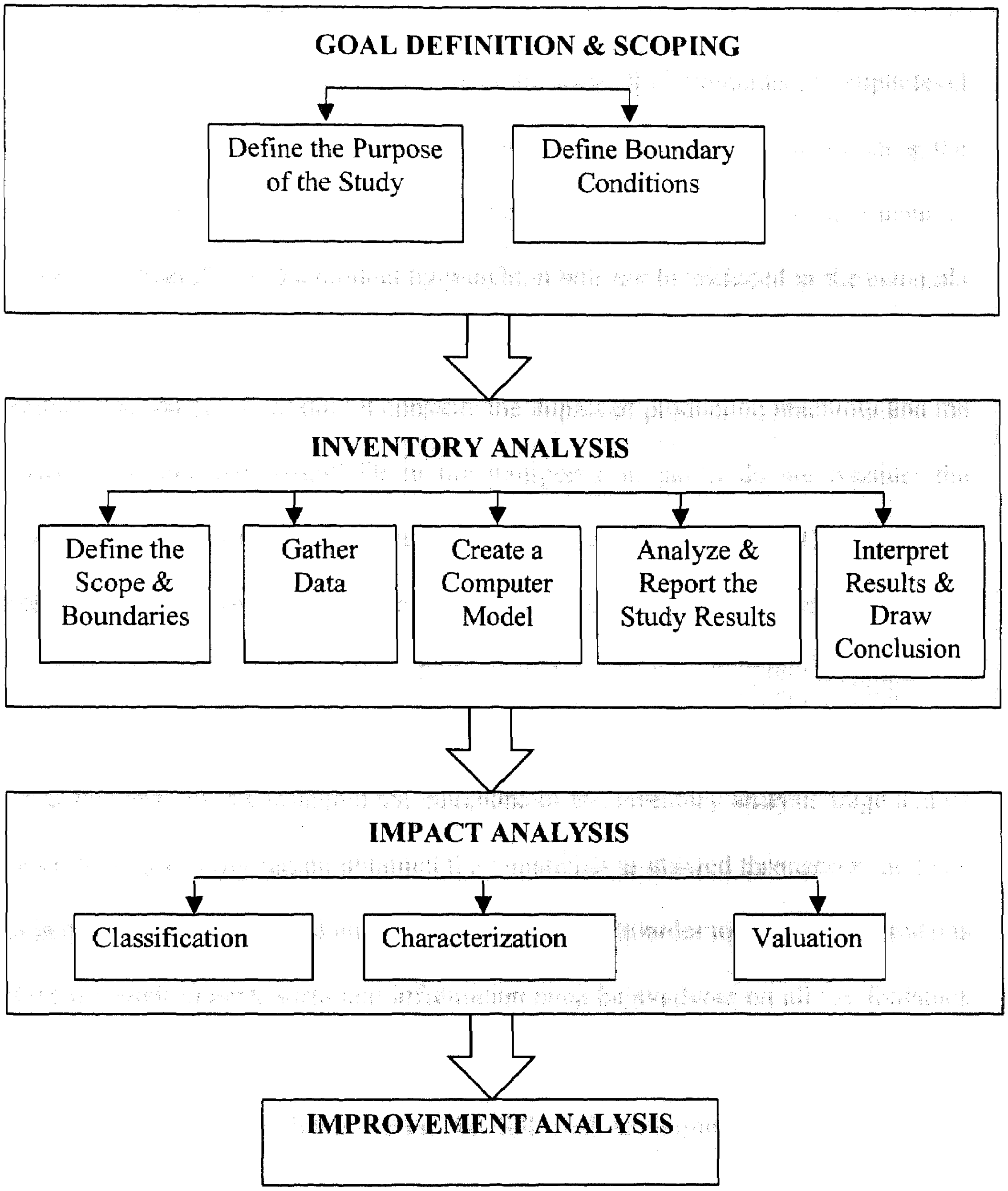


Figure 2.4 Process Flow Chart for Implementing an LCA

- Defining Boundary Conditions

After defining and understanding the purpose of the study, the boundaries and depth level of the system must be set. For example, what is the percent cutoff for including the materials of a certain product in the study? The assumption is that if a certain material constitutes less than 2% of the product by weight, it will not be included in the materials study. Does the study take into account only those factors that directly affect the materials extraction phase, or does it consider the impact of production machines and the associated environmental issues? Or in the transportation model do we consider the materials and processes required to manufacture the truck and the tires? Or do we only consider the energy consumption of the truck during transportation of the product?

2.5.2 Inventory Analysis

Materials information is considered the backbone of the inventory analysis stage and of all the LCA stages. Information obtained from materials is utilized throughout the LCA stages in quantifying energy and environmental burdens. In order to analyze the products effect on the environment, sufficient information must be available on all the feedstock materials composing the product, production processes, use and reuse of the product.

A structured methodology must be followed to implement an LCI. This methodology or approach has remained consistent over the past 20 years. The secret behind conducting an efficient LCI is to maintain a consistent and uniform information on materials, energy and environmental burdens balances for each process within the system. The source of the data, confidence level and uncertainty of the data are of great concern in any lifecycle study, therefore these sources must be readily recognized. This information helps in identifying the environmental performance of the product and will assist in later stages in conducting a sensitivity analysis, by comparing the performance of different materials. An important aspect is to define the system and its boundaries and document all the assumptions made throughout the methodology followed.

There are four major decisions that must be taken when implementing an LCI.

1. Allocation of inputs and outputs from an industrial operation in the various products that are produced.
2. The consumption at the use stage of the product.
3. Analysis of the recycling system, and
4. Reporting of energy that is embodied in the products entering the LCI system. [13]

Many stages and interrelations can be identified for industrial systems in terms of flows of material and energy from unit process to unit process. Energy, process materials, and transportation are necessary physical inputs for most of these stages, and feedback and loops make up part of the cycle. Though it is necessary to distinguish the acquisition and production of energy carriers in a distinct analysis, they are not considered in this study. Energy profiles were used only as input information to the various stages of material production. The lifecycle inventory implemented in this study included the materials, production, use and recovery stages. This constraint made the LCI more manageable to focus on unit production processes whose inputs and outputs can further contribute significantly for an environmental impact study. In this study, several polymers and metals were examined. For each of the materials studied, specific methodological considerations, assumptions and other details are documented. A common procedure was followed for conducting the LCI in the form of a generic process model, which will be described later in Chapter 3.

Thus, the analysis of each of the polymers consists of the following components:

- Basic initial data about the material,
- A brief description of the major production processes used in manufacturing of the feedstock material,
- Construction of the generic process model for the materials in terms of production process flow charts, which indicates the major raw and process materials and unit processes with quantitative energy and environmental values for the unit operations,
- A detailed inventory chart indicating the amount of raw and process materials and the total energy requirement, and
- Environmental impact issues associated with the production of the materials.
- Notes and references, which indicate the sources used to develop the generic model in the inventory chart.[13,14]

The categories of the inventory analysis are as follows:

- Define the Scope and Boundaries

This is a continuation of the goal definition and scoping stage of the LCA, but with more specific information on the system being incorporated.

- Gather Data

This stage involves gathering information on the raw materials consumed in the product and all subsequent information related to that material. Information relative includes mass of raw materials, energy use, environmental releases, and co-products must be quantified for all the process stages. This is necessary for all the LCA stages from raw material production and continues through product use and disposal.

- Create a Computer-Based Tool

Currently, almost all available LCAs are incorporated into computer based tool. These tools may vary from simple spreadsheets to sophisticated databases. The purpose of the computer tool is to allow users to define their product's structure and describe it, and then compile all the input and output data for the total lifecycle of the product. Also, computer based tools display the results in varying detail based on the need of the user.

- Analyze and Report the Study Results

After the computer-based tool is designed, the results obtained from the Lifecycle Inventory (LCI) must be analyzed and reported in a meaningful way. This stage is critical to the LCI since it represents the results from the inventory stage, which will assist decision-makers in their decisions. The complete LCA conclusions will be extracted from this analysis stage, various tools can be utilized to help present the extensive LCA data. Tools such as eco-compass, resource productivity, and various trend and graphs are used for this purpose. More details on the use of these tools will be presented in chapter 5. Metrics such as mass intensity, energy intensity and other environmental metrics were also considered.

- Interpret Results and Draw Conclusions

Once the results of the study are generated, they can be interpreted and conclusions can be drawn based on the purpose of the study.

2.5.3 Impact Methodology

This section is taken from reference Chapter 3 of " *Environmental Lifecycle Assessment*" by B. Vigon [13].

This stage converts the results obtained from the inventory stage to a set of common measures such as habitat disruption, acid rain problems and others, that allows interpretation of the total environmental effects of the product being evaluated. The impact assessment is still in the infancy stages and much research and effort is required to develop these tools in order to conduct a sound LCA. The following three-phase conceptual model of LCA impact assessment is being extracted from the framework set by EPA and SETAC:

- Classification

Is the process of assignment and initial aggregation of LCI data into relatively homogeneous impact groups. SETAC lists three impact categories:

1- Environmental or ecosystem quality. For example, suspended and dissolved solids affect the chemical oxygen demand (COD), Biochemical oxygen demand (BOD), and alkalinity measurements. All these pollutant categories impact water quality, which in turn impacts the ecosystem quality.

2- Quality of human life (including health), its potential impact categories are: human carcinogen (class A), irritant (eye, lung, skin), corrosive, respiratory system effects and others.

3- Social welfare. There is no agreement yet on how to conduct an impact analysis on social welfare issues.

- Characterization

Is the assessment of the magnitude of potential impacts on the chosen major categories, (human health or ecosystem quality), described above. For example, carbon monoxide and dioxide are all classified under the category of greenhouse and global warming. Each chemical has a potential impact on ecosystem quality. Various characterization models were developed to assess the contribution of each emission. Some proposed characterization models follow:

- Loading: these models assess inventory chemical data on quantity alone, with the assumption that less quantity produces less potential impact.
- Equivalency: These models use derived equivalency factors to aggregate inventory data with the assumption that aggregated equivalency factors measure potential impacts.
- Valuation: The assignment of relative values or weights to different impacts. This allows integration across all impact categories. When valuation is completed, decision-makers can directly compare the overall potential impacts of each product.

2.5.4 Improvement Analysis

This analysis is necessary in identifying and discovering new opportunities to reduce environmental emissions, energy and material consumption of products and processes. For example, a comparison to evaluate the environmental performance of the product as different materials are substituted can be conducted. A sensitivity analysis, which is a systematic approach for evaluating the variations in data input and their effect on the final result, can also be performed.

2.6 Product Lifecycle

Typical product stages include raw materials extraction, manufacturing, use/reuse/maintenance, and finally, recycle/waste management. Figure 2.5 illustrates those product lifecycle stages.

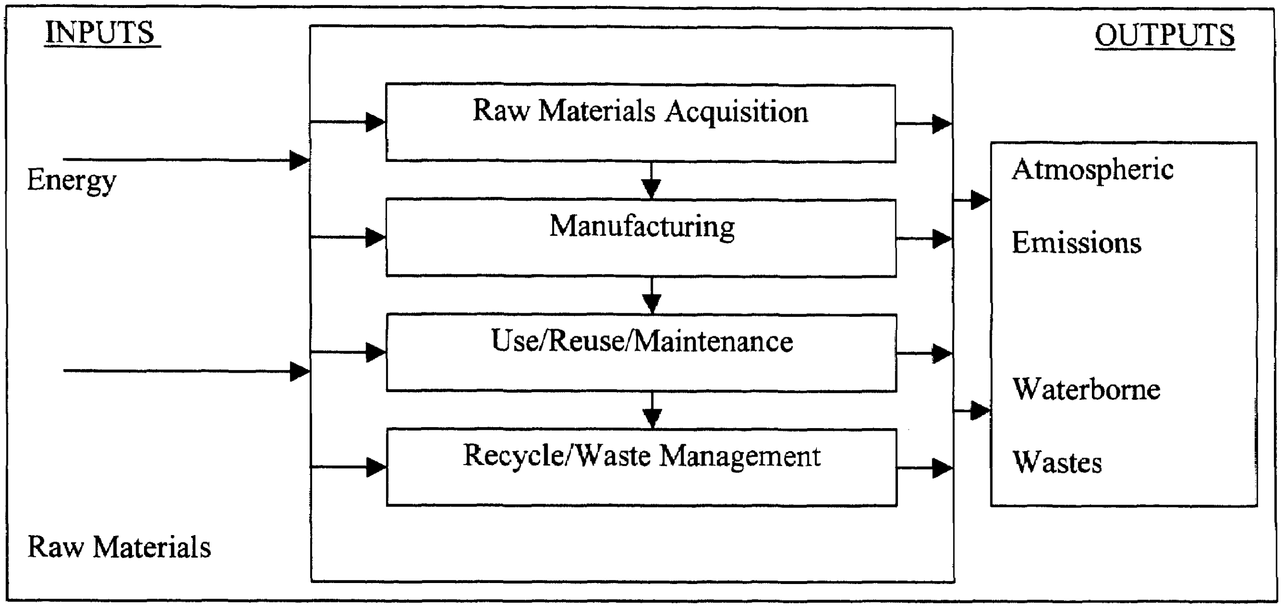


Figure 2.5 Typical Lifecycle Stages
[Source 12]

- Raw Materials Acquisition

Collecting data on materials production is one of the most tedious tasks in an LCA. Questions such as " do we start the analysis from Hydrocarbon production or take it back to crude oil production? " or "What level of detail is required for the production processes of raw materials?" These questions and many more must be addressed and answered consistently throughout the LCA study.

- Manufacturing

This stage involves detailed information on the production processes of the finished product. Details on the energy consumption of machines and environmental burdens associated with operating these machines are quantified. The level of detail of this stage could be either at a process level, or based on a specific factory or could be an industry average for that particular process.

- Use/Reuse/Maintenance

Quantifies the energy consumption and the environmental burdens associated with the product during its operation time. Assumptions should be made on the actual lifetime use of the product and the utilization factor, which is the percent of time the product is in the in-use & stand-by modes. Energy and environmental data associated with the reuse and maintenance of the product are also essential. Reuse refers to the parts or subassemblies that can be replaced into another product rather than disposing it. While maintenance refers to the effort required for fixing or performing maintenance on that product.

- Recycle/Waste Management

Examines the EOL method for the finished product and associated energy and environmental burdens. This stage is often referred to as the demanufacturing stage or the end-of-life management of a product. After demanufacturing the product, the parts and subassemblies can either be remanufactured or extract and recover basic material from them through reengineering or can finally be disposed of.

2.7 LCA Limitations

Even though LCAs are the dominant tools used for evaluating the environmental performance of products, many problems are faced when utilizing these tools. LCA is an expensive, time-consuming and very data intensive procedure that requires expert knowledge in materials, manufacturing, use and disposal. The main concern in an LCA is where to draw system boundaries, what are the assumptions made, and to ensure consistency throughout the lifecycle stages. For example, if the material feedstock is divided into materials extraction and synthesis, then this structure should be applied to all the materials understudy. Also, in the transportation model, are the materials used to manufacture the transportation mode, i.e. truck, included in the study? or the analysis will apply only to the energy consumption of the truck during transportation? All these assumptions must be clearly identified and be classified whenever applicable throughout all the lifecycle stages. Another concern in LCA studies is the availability of environmental data and energy information. Most companies refuse to provide information on the environmental performance of their plants or on specific processes, as they are considered proprietary information. Thus, data gaps are created in LCA studies whether it was in materials or production processes or any other stage of the product lifecycle.

The LCA methodology is another problem, since it is not standardized so far. Problems encountered in the methodology are:

- The different units by which system inputs and outputs are measured.
- There is no uniform unit by which costs and benefits can be converted into impact analysis.

- There is no standardized method for calculating the impact of products or processes on the health and environment.
- The uncertainty and quality of data. Many users are skeptical about the results extracted from LCA's if the data used is not from a reliable source. Section 2.8.3 illustrates a case study that deals with uncertainty of data in LCA's.
- It is difficult to compare old products to new products, since lifecycle inventory analyses and impact assessments have different approaches. Even thought that this comparison is what all decision-makers really need for assessing product improvement [4].

2.8 LCA Case Studies

The following section illustrates various studies conducted using LCA methodology. This section will describe the case studies and show the results and conclusion extracted from them.

2.8.1 Ecobalance Case Study

The Ecobilan (Ecobalance) group is one of the largest companies conducting LCA studies, performing projects ranging from foods and cosmetics to electronic products. They conducted a study entitled " Environmental Lifecycle Profile of End-of-Life options for two Electronic Products: Telephones and Televisions " August 1st 1996, which was commissioned by the Electronics Industries Association (EIA). The aim of the study was to compare the different end-of-life options for the telephones and televisions, and the resulting environmental impacts from each scenario. Three end-of-life options considered were: Landfilling, incineration or smelting, and recycling. The study accounted for energy credits that may result from reclamation or use of recycled material into new products.

The LCA methodology was applied throughout the study, to guarantee consistency in comparing both products. The first step was to define the system boundaries and to clearly identify the different assumptions made. The models used for each end-of-life option were also formulated. Since the input data is variant and uncertain in many cases, the Monte Carlo method for stochastic simulation was used to produce a good distribution of the output variable. Following is a description of the models followed for the telephone and television end-of-life options:

This part was taken from the study [15]

- Telephone end-of-life options
    1. Landfilling, after collection similar to that for municipal solid waste, where the model was based on diesel fuel requirements per 1000 lb. of landfilled material.
    2. Incineration in a municipal solid waste combustion facilities, after collection similar to that of municipal solid waste.
    3. Shredding / material recycling. i.e., recovery of the materials (plastics, metals) after a grinding and separation step. This option has been modeled after the operation of the Lucent Technologies (formerly AT&T) Material Reclamation Center (West Chicago, IL). In this option, telephones would be collected from households with a mail-back network.

- Television end-of-life options

This part was taken from the study [15]

1. Landfilling, after collection similar to that for municipal solid waste, where the model was based on diesel fuel requirements per 1000 lb. of landfilled material.
2. Overall recycling, i.e., copper smelting of the whole television after a shredding step, but without separation of the different constitutive materials.
3. Dismantling/material recycling, i.e., recovery of the materials (glass, plastics, metals) after a disassembly step. This option has been modeled after the operation of the Envirocycle dismantling facility (Hallstead, PA).

The results extracted form this study were as follows:

- Telephone Case Study
    1. The landfilling option showed consistently the worst profile, except for CO_2 emissions, where it was the best option.

       The balance between the recycling and incineration options were as follows:
    2. For energy consumption, particulate matter and CO_2 emissions, both options are equivalent. However, for these items, the spread of the recycling option is much bigger than the one of the incineration option, indicating that in some cases, it is worse than incineration.
    3. Incineration is better for NO_x emissions.
    4. Recycling is better for CO and SO_x emissions, COD effluents and solid waste.
- Television Case Study
    1. Landfilling option consistently showed the worst profile, except for CO emissions.

2. The recycling option showed a better profile than that of copper smelting for energy, particulate matter, CO_2, CO, NO_x, and COD. Recycling showed a worse (or equivalent) profile for SO_x and solid waste.

Conclusions extracted from this study show that the recycling efficiency and the materials recovered strongly influence the results of the recycling option. For example, HIPS which is 13% of the televisions weight was the main contributor to the televisions recycling, while the glass closed-loop recycling which is 63% of the televisions weight was minimal. The energy requirements of the dismantling / separation process also influenced the results of the recycling option. This study introduced methods to deal with uncertainty in data, by using a stochastic approach for solving the problem. An important end-of-life option that was not considered in this study is reuse. Many companies tend to emphasize the reuse option as it is usually more economic [15].

2.8.2 Manchester Metropolitan University Case Study

Manchester Metropolitan University, UK, performed an LCA study on telephones, concentrating mainly on the end-of-life options of the telephone. The study was entitled " Lifecycle energy modeling of a Telephone," by J.M. Young, April 1995 [16]. The aim of the study was to calculate the energy consumption of the telephones over all the stages of its lifecycle starting from raw materials production and through eventual disposal. The study also identifies the end-of-life scenarios based on the "3R's" model of reuse, remanufacture and recycle. J. Young presented the energy required for the production of feedstock materials of various metals and polymers. The energy for the manufacturing of the telephone (including the Printed Wiring Board, PWB) and the packaging, use, and disposal stages were also evaluated.

The results of his study showed that the highest energy consumption was during the use stage of the telephone, which was assumed to be five years and that improvements in current exchange technology can reduce this consumption. The second highest energy consumption was in the production of the material feedstock, with the PWB being the largest contributor to this figure. Recommendations were to use recycled PWB's and to produce more raw materials from scrap rather than earth. The third largest value was found at the manufacturing stage which can be readily reduced by promoting consumers to reuse existing telephones or by modifying the design of the phone itself by using fasteners, such as snap-fit covers, that would reduce the assembly time and increase the efficiency of production. By evaluating the end-of-life options, it was difficult to decide on the best scenario since it depends on variables such as transportation and additional energy process savings/costs. But the general result is " the more use cycles a product can survive the better" [16]. Consequently, from the "3R's" model, the reuse of telephones without maintenance was the preferred option [16].

2.8.3 SAE Case Study

The Society of Automotive Engineers (SAE), issued a study entitled " Uncertainty, Sensitivity, and Data Quality Assessment for Lifecycle Value Assessment (LCVA)". This paper deals with a major concern of LCA's and that is the quality of the data, which is the backbone of any LCA study. This study provides a methodology to qualitatively assess the quality of data and to estimate the uncertainty; also, it shows how to assess the sensitivity within an LCA study. Finally it shows how to provide credibility in the results obtained from an LCA. Following is a description of the methodology suggested:

1. Data Quality

The data is categorized into three ratings: Green, yellow and red.

- Green ensures that the data sources are known, meaning they have been directly measured and meet the needs of the LCA study. The uncertainty on this rating is +/- 10% and the results can be utilized with consideration to the uncertainty.
- Yellow refers to data that has been calculated using standard factors and does not completely represent the LCA understudy. The uncertainty on this rating is +/- 25% and the results can be utilized with caution especially where the sensitivity of the results is large.
- Red rating means that the data used has been estimated and is not representative of the LCA understudy. The uncertainty on this rating is +/- 50% and these data should be replaced if possible in order to utilize the results.

2. Calculating uncertainty

Data is divided here into two categories: single value data and multiple value data.

- Single valued data should use the ratings (green, yellow, and red) as described above in data quality. Therefore, an uncertainty is always integrated in the data used, which gives more credibility to the LCA.
- Multiple data sets utilize a different approach to calculate the uncertainty of the data. The t-distribution is utilized, which is a distribution of means of small selections drawn from a population of normally distributed values.

3. Sensitivity Analysis

"Sensitivity analysis is important in any lifecycle value assessment study for three reasons: 1) to highlight data sets which affect the overall lifecycle results the most, 2) to test the effects of assumptions made on allocating inputs and environmental outputs to different products, and 3) to recognize the relative significance of potential changes in efficiency and emissions reduction technology. Three different types of sensitivity analysis are performed in LCVA: sensitivity to different data sets, sensitivity to different allocation assumptions, and sensitivity to marginal changes in unit process eco-efficiency." M. Raynolds [17]

- Sensitivity to different data sets: to evaluate the sensitivity of the results, different data sets must be considered. The best procedure is to use an averaged data set and then compare it to the "best scenario", which could be a data set predicting a future plant with improved eco-efficiency. This will allow the assessment of the different alternatives and to choose the best performance.
- Sensitivity to allocation assumptions: Allocating environmental outputs between different products from a plant can be based on the volume or market value. These allocation methods are not suitable to all products at all situations.
- Sensitivity to marginal changes in unit process eco-efficiency: " This provides controlled changes that affect the eco-efficiency of individual unit processes and the opportunity to observe the end result of those changes. The eco-efficiency of a unit process can be improved by two means: Increasing the product efficiency by producing more product for the same amount of product. This means 1% increase in eco-efficiency can be obtained by increasing the products of the unit process by 1%

> while holding the inputs and environmental outputs static, or a 1% increase in eco-efficiency can be obtained by reducing environmental outputs by 1% and holding the inputs and product outputs static. This former method can be called marginal increase in "product efficiency" and the later "environmental efficiency". " M. Raynolds [17].

In conclusion, this study dealt with an important aspect of LCAs, that is quality of data, what methodologies are most applicable to assess them, how to estimate uncertainty, and how to deal with sensitivity of LCA results. Utilizing these methodologies, the users of LCAs can feel more confident on the results extracted from the LCAs as there are confidence intervals associated with the data used.

2.9 LCA Software

Some of the thoughts from this section have been taken from chapter 3 of "*Environmental Lifecycle Assessment*" by B. Vigon [13].

2.9.1 Introduction

The development of methodology for lifecycle assessment (LCA) is highly theoretical, where as the collection of data has a direct connection with practice. Software takes a position in between: it contains formalized methodology in a way that is accessible to the data, with its practical limitations. The development of software increases the practical usability of the methodology and the suitability of the data within the theoretical framework. Software may thus act as a bridge between theory and practice [18].

The typical users of LCA software are a combination of LCA experts and other individuals who want to utilize LCA concepts to evaluate the environmental performance of their product. Because LCA is being used more as a support tool in application of methods such as Design for the Environment (DFE) or Pollution Prevention (P2) engineering, LCA software must mesh at some level with the tools typically used by these disciplines. There are three major user requirements of LCA software:

- To organize the data and minimize the effort necessary to conduct an inventory analysis or impact assessment.
- To efficiently organize and document large amounts of data, recording decisions made by the investigators as they conduct the study, and to present the information in a coherent manner.
- Compatibility of LCA software with other information system components and software tools, such as marketing and sales data, or tactical one where LCA results would be used in conjunction with performance and cost measures [13].

2.9.2 LCA Software Models

LCA software products typically comprise a user interface, a database, computational engine, and a report processor. The most common type of LCA model, as distinguished from design or engineering LCA modeling tools, is referred to as an *input-output model.* The intent of this type of model is to capture the materials and energy balance at the system or the subsystem level and not to focus on process details. Figure 2.6 shows the typical structure of integrated LCA software.

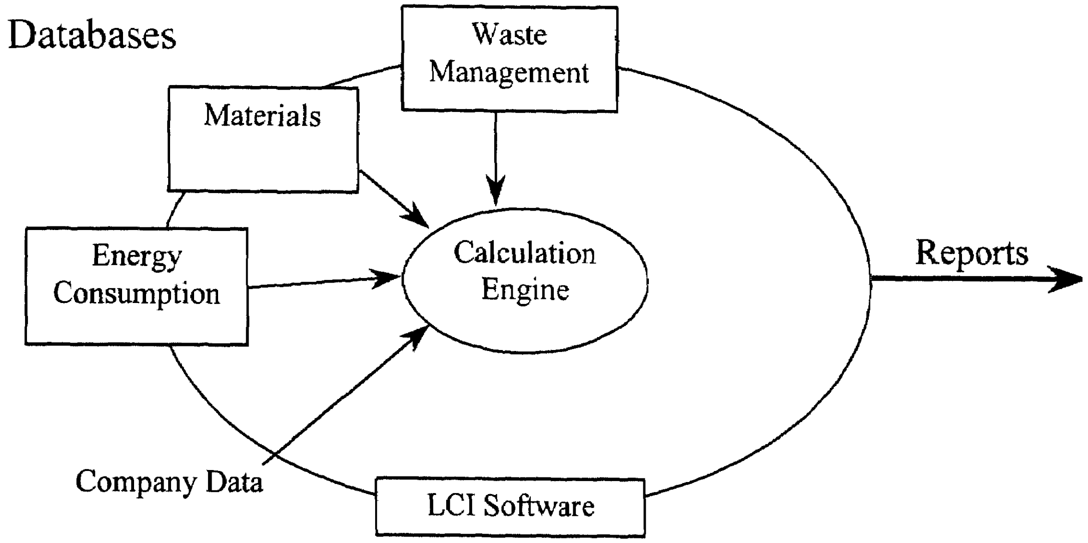


Figure 2.6 Typical Structure of Integrated LCA Software
[Source 13]

Product design-oriented LCA tools target a user audience that is not and probably will not become expert in LCA and has little or no knowledge or technical expertise in environmental issues. Product design software users can include mechanical design engineers, packaging designers, product concept specialists, and graphic designers whose primary interface with software is in computer-aided design (CAD) or mechanical/structural design packages. Product development support software incorporates LCA computations in a framework that has the appearance and the character of a software within the domain of expertise of the designer. Product design-oriented software also includes software intended primarily for development of environmentally sensitive packaging.

LCA software products developed for these users typically result in a kind of "green advisor" that provides recommendations on materials and process choices based on lifecycle considerations. The user is prompted for information about the physical form and/or the layout of the components or the product and is given choices regarding materials that may be used in a given application. Some software also provides the ability to select alternative processes for manufacture of the item. Within the software, a database and an expert system have been incorporated to translate the designer's choices into the necessary inventory and impact assessment computations. Choices on the depth and the breadth of the LCA may have been pre-selected by the developer in order to balance the complexity with the multidimensional nature of the decision process [19].

The following section provides an examination of the LCA software models with respect to the previously defined three stages of Lifecycle Analysis:

2.9.2.1 Lifecycle Inventory Analysis: Most of the current generation inventory software is based on commercial spreadsheet programs. Microsoft Excel and Lotus l-2-3 are two of the more popular systems. The most basic execution of this level of LCA inventory software uses the unadorned spreadsheet as the input data template, computational engine, and output form. A simple database on materials and processes may be included in a section of the spreadsheet so that users are not required to input anything more than basic functional units and product descriptions. The database is modified or augmented only with difficulty. Printing of tabular or graphical results is dependent on the internal capability of the spreadsheet used or the ability to download the output in a graphic or text post processor.

Some advanced features of contemporary spreadsheets have been used to advantage in recent incarnations of softwares of this type. These features include a multi-sheet capability so that input, intermediate calculation, and output sections can be separated. Many of the internal computational tools of practitioners as well as industry commodity data sets are maintained in spreadsheet format. Graphical capabilities of spreadsheets have been improving to the point where for many users it may not be necessary to use a separate stand-alone graphics package to present the results in a meaningful manner. Recently, models have been developed with extended interfaces between the program and the user. The software does not look like a spreadsheet and the user has no direct interaction with the underlying computational engine or database. Non-expert users may use these programs.

2.9.2.2 Lifecycle Impact Assessment: The spreadsheet and extended spreadsheet type of model does support impact assessment in some of the software packages. Although, impact assessment is less established in current LCA software packages it is progressing rapidly. It often includes classification into environmental issues, characterization of potential environmental impact, and impact evaluation.

2.9.2.3 Lifecycle Improvement Analysis: For improvement analysis, the LCA software can be used to bring findings back to the product system in a negative feedback mode to improve environmental compatibility and performance [20].

By posing a series of questions, the LCA software can be used to assist in the selection of improvement options. The following are some examples of general questions about the need/purpose of the product or the process:

- Are there areas where the substitute materials or processes could conserve energy and/or materials?
- Can the functions of more than one product or service be combined?
- Can the life span of the product be increased?
- Can the overall product efficiency be increased?
- Can toxic substances in the product or its associated manufacture, use, or disposal be eliminated or reduced?

Answering the above questions involves a data-intensive endeavor. The use of electronic databases incorporated within the LCA software can markedly increase the efficiency of performing an LCA. Thus, by requiring the user to supply certain information items, software can help ensure that LCA's are conducted in full recognition of the assumptions and the definitions involved.

2.9.3 Survey of LCA Tools

Several surveys have been conducted to evaluate the LCA software's available. Differences can be found in these tools, depending on the boundaries set by the tool and the specific problems it is designed to solve. For instance, some software may deal with energy at the materials extraction and synthesis stage rather than the total lifecycle. Others vary in the type of databases of materials it uses. Some use custom databases that address specific products and processes, while others may include large databases in which generic processes and their emissions and other effects are described. Europe is considered a pioneer in environmentally friendly manufacturing, and there exists a variety of LCA databases and software's produced. The following Table 2.1 lists some of the available tools and contact information:

Table 2.1 List of LCA Tools Available

LCA Tool	Name Contact	Address / e-mail
1. Boustead	Dr. Ian Boustead	Boustead Consulting Ltd. 2 Black Cottages, West Grinstead Horsham, RH137BD
2. ECO-it	Dominique Hes	Info@pre.nl Pre Consultants Bergstraat 6 3811 NH Amersfoot The Netherlands
3. GaBi	Dr. –Ing. Manfred Schuckert	www.pe-product.de
4. IDEMAT	Jan Remmerswaal	j.a.m.remmerswaal@io.tudelft.nl Section for env product design Faculty of industrial design eng. Delft University of Tech. Jaffalaan 9, 2628 The Netherlands
5. LCAiT	Lisa Person	Chalmers Industriteknik Chalmers Teknikpark S-412 88 Leoben Sweden
6. REPAQ	Doug A. Rethmeyer Bruce Kusko	Franklin@qni.com Franklin Associates Ltd. 4121 W. 83rd Suite 108 Prairie Village, KS 66208 USA
7. TEAM	Pascale Jean	Pjean@ecobilan.com ECOBILAN Immeuble LE BARJAC I, Boulevard Victor 75015 Paris France
8. SimaPro	Mark Goedkoop	Info@pre.nl Pre-product ecology consultants Bergstraat 6 3811 NH Amersfoort The Netherlands

2.9.3.1 Analysis of SimaPro 4.0 Software: SimaPro was chosen for analysis, because of the availability of a free demo and manual for evaluation. This software allows users to utilize LCA data to analyze the environmental impact of their products. It provides an extensive database of materials, processes, energy sources, transportation, use, and waste treatment scenarios. This database can be expanded and modified by the user to meet their specific custom needs. The software has the ability to conduct an inventory analysis and an impact analysis on the product. The user must first describe the product, specifying the various parts, subassemblies and components. To view the structure of the product, SimaPro provides a process tree that displays the process and materials used to create the assembly.

The inventory stage provides a list of raw material inputs and outputs of emissions associated with the product. This list is useful in showing the substances coming from the manufacture of an assembly. An impact assessment is also provided based on a weighing factor scaling the results to a certain level of seriousness. This measure is derived from the assessment of damage inflicted upon human health. SimaPro produces a list of the total impact of each material and process in the assembly. Other than analyzing the products lifecycle, the software also has the ability to compare the performance of products, and contains models for waste disposal, recycling and reuse.

In conclusion, this software contains a valuable and extensive database of materials, processes, and evaluating methods. Other than providing inventory analysis, as most softwares do, it also provides an impact analysis phase. In order to effectively use this software, the user must invest time in understanding the structure of the software and the flow of information between the screens. This is a problem faced in many LCA softwares, which is to develop user-friendly screens, where the user must not be an LCA expert in order to navigate through it.

2.10 Performance Metrics

All companies continuously strive to improve their products and services, whether compared to previous models or to competing products. A critical problem is how to measure this improvement and what method is used to measure the performance. A set of consistent and reliable metrics is required to track improvements towards the set goal. Improvements in environmental performance were previously set due to regulations and laws, whether state or federal. Presently, environmental performance is becoming more and more a competitive advantage. A committee has been appointed by the National Academy of Engineering to undertake a study to assess measuring progress in environmental performance of U.S. Industries, assess the successfulness of current methods of measuring environmental performance, and to set recommendations for a set of industrial environmental performance metrics. Several performance metrics were identified specifically to the electronics industry, these were divided into three main categories [21]:

1. Resource related

   This includes: Chemical management such as, Toxic Release Inventory (TRI) emissions, which is a database provided by USEPA, hazardous waste, global warming chemical and others. Natural resources such as, energy use, water use, and packaging materials. Finally, DFE tools such as: DFE, and environmental cost accounting.

2. Environmental burdens related (waste/impact)

   This includes regulatory issues, compliance issues, hazardous waste, landfill disposal, and others.

3. Human health and safety.

   This includes worker protection: accidents / injuries, OSHA recordable injuries and illnesses, and log and restricted day cases.

Therefore, there is a need to examine a variety of performance metrics and assessment technologies to clarify important issues. There are several tools that present environmental performance metrics and provide the ability to visually detect specific performance improvements of products. Techniques such as the Eco-Compass, developed at Dow Europe, are used to compare the various generations. The Eco-compass has six dimensions that quantify significant environmental issues: mass intensity, energy intensity, health & environmental potential risk, resource conservation, revalorization and service extension. Resource productivity, as proposed by Sony, is another comparison tool. The measure attempts to quantify economic value added related to consumption of material and energy resources.

2.10.1 Eco-Compass

Lifecycle assessment is a useful tool in analyzing the total environmental impacts of a product by calculating the inputs and outputs of each stage of the products lifecycle. But there is a need for a comparative tool that will display in a simplified manner the complex outputs of the LCA so that decision-makers can make sense of it. For this, the Eco-compass tool, which was developed in DOW chemicals Inc, can be utilized. Eco-compass is a comparative tool that has the following features:

- Can be used to compare one existing product with another, or for comparing a current product with new development options
- "Condenses environmental data into a simple model, which summarizes strategic issues, trade-offs and improvement opportunities for lay audiences"
- Does not over simplify and remains connected with the detailed analysis
- Can be reliably applied to a variety of business circumstances [22]

The Eco-compass has six dimensions that encompass all significant environmental issues, Mass intensity, Energy intensity, Health & Environmental potential risk, Resource conservation, Revalorization, and Service extension [22]. These dimensions will be presented and defined in chapter 3.

2.10.2 Resource Productivity

The ability to measure the environmental performance of products has been a major concern for industries and companies. The question is what measure is considered appropriate for environmental soundness? In an ideal situation, where production and the environment are in complete harmony, production must fulfill the following goals:

- All materials should be nearly 100% recycled
- Energy consumption should be in a clean manner and limited to only clearly utilizable sources such as solar energy
- Waste should be within the limit that natural processes are able to degrade

A new measure is introduced, Resource Productivity, which was developed by Seiichi Watanabe, Sony corp. Resource productivity is a measure for industrial performance compatible with environmental preservation. It is defined as the economic added value multiplied by the lifetime over the sum of (in monetary value):

- The difference between the amounts of material consumed and recycled
- The energy consumed for production and recycling
- The energy consumption by the average use over the product's lifetime

$$\mathbf{RP} = \frac{\text{Economic Value Added x Product Lifetime}}{\text{(Material Consumed-Recycled)+(Energy Consumed for Production +Recycling)+(Lifetime Energy Used)}}$$

If the technology for recycling is primitive and consumes a lot of energy, then the resource productivity will be low. The longer the lifetime the better the productivity. Applications of resource productivity are various and can be used as a comparison tool between competing products or different generations from the same product, as a way to quantify environmental improvement and awareness [23].

2.11 Demanufacturing Study

Demanufacturing is the process of separating a product into its smaller parts, subassemblies, and all the way to basic materials. This process is the first step in analyzing the end-of-life options for those products. Many methods and tools are utilized to evaluate the demanufacturing process of products. Some of these tools either quantify performance attributes and measure them, and others provide a structure for the sequence of disassembly. Tools such as the Disassembly Effort Index Metrics (DEIM), quantify performance metrics for the product and assign a score for each of the weighted performance metrics. On the other hand , tools such as the Reverse Fishbone Diagram, provide a visual graph of the sequence of disassembly. These two are further discussed in the following sections.

2.11.1 Disassembly Effort Index Metrics (DEIM)

DEIM focuses on nine different parameters, which are important while analyzing the Demanufacturing effort. Dr. Sanchoy Das and his group developed this concept, under the MERC research program, supported by the New Jersey Commission on Science and Technology, and was modified from analyzing fasteners only to incorporate a whole product. The total score for all the parameters adds up to 100 points. The weight assigned to each parameter is dependent on the importance of that parameter to the study, and could be modified based on the assumptions and needs of the users. The nine parameters are [24]:

1) Mechanism
2) Handling
3) Disassembly Technique
4) Time
5) Accessibility
6) Tools
7) Part-Hold
8) Force

9) Instructions

Three more parameters were added to the above nine to expand the concept of DEI and emphasize other parameters that have significant impact on the products disassembly. This integrated metric is referred to as revalorization (demanufacturing), which is a concept of the eco-compass tool that was mentioned earlier in this chapter. Those three parameters are:

1) Number of different materials
2) Number of different fasteners
3) Material type stamping

The first three DEIM parameters i.e. Mechanism, Handling and Disassembly Technique are descriptive and only used to guide the dissemblers.

- **Mechanism:** Describes the way the fasteners achieve their fastening effect. Different kinds of fasteners achieve their fastening differently.
- **Handling:** Describes the way the fastener relates to the part or the component and the way the fasteners can be used to assemble or disassemble a component.
- **Disassembly Technique:** This describes the way product can be disassembled easily and assists the dissemblers.
- **Time:** Time plays an important role while considering disassembling or unfastening, since it has to take into account a lot of dependent variables like set up time, disassembly time, instruction time and others.
- **Tools:** The tools that assist in disassembling a product are broadly classified into six different categories they are No Tools, Simple, Mechanic, Original Equipment Manufacturers (OEM) tools, Special and Unavailable. No tools refer to disassembly

by hand, while simple tools, for example, are a standard pair of pliers, screwdrivers and others.

- **Accessibility:** Accessibility explains or focuses on the way parts and subassemblies can be reached and disassembled. A lot of time and effort is lost since most fasteners these days are snap fits and it's difficult to approach and access them to unfasten. The ranges of Accessibility are Z-axis, X-Y Axis, ≥ 4 inch deep head, Dual Axis Complex Motion, Not Visible.
- **Force:** The forces that are needed to disassemble parts and subassemblies are cutting, high impact, low impact, leverage, torsional and axial forces.
- **Part Hold:** This is again a dependent variable of time because it adds on to the set up time and effort which then translated, adds on to the disassembly cost. The faster the set up is the easier it is to remove, if there is no set up time then it gets a higher score. The ranges of the resolution are from automated, complex fixturing, fixture necessary, two hand, and no hold.
- **Instruction:** Instruction as a parameter cannot be ignored because, nowadays a lot of different types of components need to be disassembled from aircraft's to Coffee Makers, so the dissemblers need to be trained accordingly. These Instructions involve training the dissemblers in terms of the feasibility of the disassembly of a part and where and when to stop disassembling. The ranges of the non-linear parameter considered are Special classes, Whole Day, Half Day 60-30 min, 5–30 min, and None.
- **Number of different materials:** This parameter is added since reducing the various materials used in a product makes the separation of parts and recycling process easier.

It also assists in the disassembly process, since the subassembly will not need further disassembly if all the parts are of the same material. If the number of various materials is greater than or equal to seven, then a score of zero is assigned to that product. If the number of various materials is six, then a score of six is assigned to that product, and so forth.

- **Number of different fasteners:** The way parts are fastened together tremendously affects the recyclability of the product after its useful life. Minimizing the number of fasteners, commonality of fasteners and so forth improve on the manufacturability and disassemblability of the product. If the number of different fasteners is greater than or equal to six, then a score of zero is assigned to that product. If the number of different fasteners is five, then a score of five is assigned to that product and so forth.
- **Material Type Stamping:** Identifying part material is a difficult task that tremendously affects the recycling efforts. The multiplicity of plastics in use makes it difficult to tell one from another, especially if recycling occurs a decade or more after product manufacture. To alleviate this problem, international standards have been developed for the marking of plastic parts. The most widely used version is the International Standards Organization (ISO).

Figure 2.7 shows material type stamping on the stand of the 1997 telephone. The scale corresponds to the percent of parts stamped using the ISO identification standard. If 0% of the parts were stamped then a DEI score of 0 is assigned. If 20% of the total number of plastic parts were stamped then a score of 3 is assigned to the product and so forth.

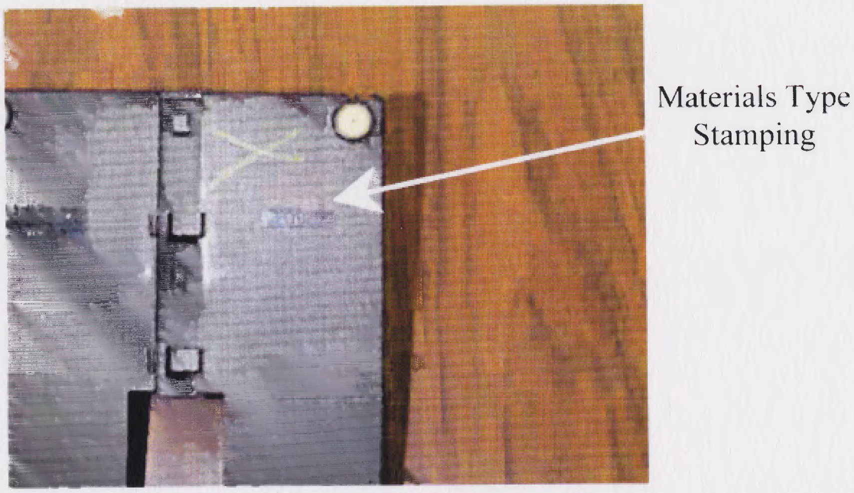


Figure 2.7 1997 Telephone Stand Stamped with ISO Standard >ABS<

2.11.2 Reverse Fishbone Diagram (RFBD)

The Reverse Fishbone Diagram (RFBD), proposed by Dr. Kosuke Ishii and Dr. Burton Lee, is essentially a disassembly tool, which graphically describes the disassembly process, promotes communication to designers and analyzes the design of product retirement process for minimal environmental impact.

Reverse fishbone diagram is a relatively new disassembly analysis tool in close concert with design for manufacturability tools. The concept of the reverse fishbone diagram can be explained as follows [14,25]:

- It is most effective when implemented at the layout design stage, so that designers can identify disassembly complications and ensure that product retirement concerns are addressed up front.

- Reverse fishbone diagram is a method of describing and evaluating disassembly sequences, which promotes a structured approach to advance planning of the disassembly and the sorting process.
- The diagram is an effective tool for a designer to assess the disassembly process, identify disassembly difficulties, analyze cost intensive disassembly tasks and steps that lead to defects, and synthesize towards solutions.
- The RFBD schematically describes the disassembly steps for the product and also specifies the retirement intent or fate category for each clump.

In short the concept is to graphically represent the disassembly procedure taking into consideration the sequence independency of the disassembly operations, and simultaneously identifying the fate category of each component. This technique is used in chapter 4 to illustrate disassembly for the office telephones.

CHAPTER 3

RESEARCH METHODOLOGY AND PROCESS MODELING

3.1 Introduction

This chapter describes the methodology implemented in this study and illustrates the process models developed for the lifecycle stages of a product. In assessing the DFE guidelines, several assumptions were made and certain metrics were chosen to quantify these guidelines. Also, performance attributes were used to illustrate improvement in environmental performance of the product, such as the eco-compass and resource productivity.

DFE utilizes the concepts and methodologies of lifecycle analysis to quantify environmental, energy and materials performance. Here, the concepts of Multi-lifecycle engineering and the process models for the various lifecycle stages of a product will be illustrated. Since lifecycle analysis is data-extensive and time consuming, a Multi-lifecycle analysis software tool was also developed to simplify the analysis. The methodology used to develop the software will be described, showing the various screens designed.

3.2 Design for Environment Guidelines

DFE constitutes mainly of a checklist of questions that targets both product and process designers. For the purpose of this study, certain questions from the checklist were addressed based on the availability of information and data extracted from the study. The aim of this study is to assess the true impact that these guidelines have on the 1997 DFE-designed telephone. To effectively assess the guidelines, a specific uniform methodology must be adopted, and applicable metrics must be evaluated. The methodology implemented and integrated into assessing the DFE guidelines is the Multi-lifecycle Analysis (MLCA), which will be further discussed in this chapter.

Following is an extensive look at the guidelines understudy, the methodology, and the metrics used to evaluate them. Each guideline assessed will be listed detailing its importance and the specific metrics used that best quantifies the guideline. The guidelines were classified under five main categories: Environmental burdens, material conservation, energy conservation, service extension, and demanufacturing.

1. Environmental Burdens

- *DFE Guideline: Has manufacturing solid residue been minimized to the greatest extent possible?*

This guideline aims at emphasizing the need for minimizing solid waste residue created through manufacturing processes during the production of feedstock material and later at each stage throughout the product lifecycle. The MLCA methodology was applied in capturing the solid residue created from manufacturing of the feedstock material. For the materials processing stage, the solid wastes generated from manufacturing of the feedstock material, including solid wastes from the power source, were calculated. For the other lifecycle stages: production, use, and recovery, the solid wastes generated from the power sources were only quantified. The metrics used to assess this guideline is the amount of solid waste residue created, calculations are based on the weight of the materials in the product.

- *DFE Guideline: Has manufacturing liquid emissions been minimized to the greatest extent possible?*

Same as solid residue above, with the exception of the metrics used to assess this guideline, which is the amount of water effluents created, calculations are based on the weight of the materials in the product.

- *DFE Guideline: Has manufacturing gaseous emissions been minimized to the greatest extent possible?*

Same as solid residue above, with the exception of the metrics used to assess this guideline, which is the amount of air emissions created, calculations are based on the weight of the materials in the product.

Since it is not feasible to add the values of air emissions, water effluents, and solid wastes together, a uniform metric is needed to integrate these values into one value. The metric followed is similar to that of the Eco-Compass, in which a value "2"is assigned to one product as a base case. Any improvement of more than 50% in the compared product is assigned a value of "4", and an improvement of more than 75% is assigned a value of "5". While a decrease of more than 100% is assigned a value of "0". These improvements are measured for each particulate or category of air emissions, water effluents, and solid wastes. A weight factor is given to each one, in this case, the assumption is that all variables carry the same weight. This weighting factor can vary based upon individual assumptions. Chapter 5 includes the results of this metric and illustrates how it has been applied to this study.

2. Material Conservation

- *DFE Guideline: Can materials use be minimized by improved mechanical design?*

This guideline refers to efforts for dematerialization, where the aim is to minimize the amount of materials used to meet the design requirements and the functional requirements of a product. The metrics used to assess this guideline is the total weight of the telephones and also weight of specific materials and subassemblies.

3. Energy Conservation

- *DFE Guideline: Is the product designed to minimize the use of materials whose extraction is energy intensive?*

This guideline aims at promoting the use of materials whose extraction requires less energy than others. The metrics used to evaluate this guideline is energy value of feedstock materials composing the product, concentrating mainly at the materials extraction and synthesis stage.

- *DFE Guideline: Is the product designed to minimized the use of energy-intensive process steps?*

This guideline aims at avoiding and minimizing production processes that are energy intensive. The metrics used to evaluate this guideline is the energy required for manufacturing the product, relative to the production stage only.

- *DFE Guideline: Has the product been designed to minimize energy use while in service?*

This guideline aims at decreasing energy consumption during the use stage of the product lifecycle, by promoting use of the lowest energy consuming components. The metrics used for evaluating this guideline is the energy consumption of the telephones during the use stage. This value is based on the summation of both the in-use mode and stand-by mode through the product life use.

- *DFE Guideline: Is the product designed with the aim of minimizing the use of energy-intensive process steps in disassembly? Is the product designed for reuse of materials while retaining their embodied energy?*

The metrics used for these guidelines is named "recovery" which equals the energy required to recycle the product minus the embodied energy in the plastics. This accounts for the two above guidelines that promote use of minimal energy-intensive disassembly processes, and the reuse of materials while retaining their embodied energy.

4. Service Extension

- *DFE Guideline: Are subassemblies designed for ready maintainability rather than solely for disposal after malfunction? Are modules designed for ready removal?*

These guidelines refer to issues that deal with the product after it is manufactured. Service extension is one of the six dimensions of the eco-compass tool, mentioned earlier in chapter 2, and is divided into three categories: modularity, commonality, and upgradability. The assumptions made for service extension will be discussed in details latter in this chapter in section 3.3.2.

5. Demanufacturing

- *DFE Guideline: Are all plastic components identified by ISO markings as to their content?*

Identifying plastic components by ISO marking simplifies the disassembly and recycling of the product. The metric used to quantify this guideline is the percentage of plastic components stamped.

- *DFE Guideline: Has the product been assembled with fasteners such as clips or hook-and-loop attachments rather than chemical bonds or welds?*

Using fasteners such as adhesives and chemical bonds increases disassembly time and makes separation of parts extremely difficult. Fasteners such as screws and fast assembly-disassembly snap fits and hook-and-loop attachments, on the other hand, reduce the disassembly time. The metrics used to quantify this guideline is the number of different fasteners used.

So, mainly the DFE checklists and guidelines concentrates on materials consumption, energy use and production of solid residues, gaseous residues, and liquid residues over all the stages of the product lifecycle. Refer to "Design for Environment" by T. Graedel and B. Allenby, which contains more detailed description of DFE guidelines [4].

3.3 Performance Metrics

3.3.1 Resource Productivity

Resource productivity is a measure of industrial performance compatible with environmental preservation. Resource productivity was presented earlier in chapter 2, in this section the methodology adopted and assumptions made will be discussed in details. This measure is calculated using the following formula:

$$\mathbf{RP} = \frac{\text{Economic Value Added x Product Lifetime}}{\text{(Material Consumed-Recycled)+(Energy Consumed for Production +Recycling - Embodied)+(Lifetime Energy Used)}}$$

There was no specific description of how to quantify the variables in the above formula, therefore, certain assumptions were made to meet the needs and limitations of this study. The assumptions made are as follows:

- **Economic Value added**

This is assumed to be the selling price of the product or the leasing price in this case, over the lifetime use of the product. This value is assumed to be $70 for the 1997 and 1989 telephones. The value assigned to the 1965 and 1978 telephones was $140, since during that period telephones were owned and leased through one company, AT&T [26].

- **Product Life Time**

This is the lifetime of the product during the use stage only. This is assumed to be 7.5 years for both the 1997 and 1989 telephones, since technology is advancing quickly in the electronics industry so is customer needs. On the other hand, the lifetime use for the 1978 and 1965 telephones was assumed to be 15 years, because if the telephones failed they were repaired and given back to the customer. Presently, if a telephone fails, it is directly disposed of and replaced with a new one since their prices are relatively cheap and the cost for repairing is high [26].

- **Materials Consumed**

Reflects the dollar value for all the feedstock materials in the telephones, which is obtained by summing all the materials weight. The yield rate is assumed to be 95%. The dollar value for the materials was obtained from the following sources:

    - Aluminum, Steel & Copper prices source: http://206.228.6.249/metalprice/index.cfm date posted was 5/19/1998.
    - ABS price source: Plastics Technology, 06/97

- **Materials Recycled**

Reflects the dollar value for all the recycled materials in the telephones. The material recovered is assumed to be only from metals, and copper content in printed circuit boards (PCB's), which was assumed to be 10% by weight. Plastics were not added because their recycled value is $0. The yield rate was also assumed to be 95%. The source of these values was from personal contact with Wade Environmental Inc., on 1/23/98.

- **Energy in Production**

Reflects the energy required to manufacture the telephones. The value was obtained by dividing the total facility consumption of energy in monetary value, for a certain facility, by the total volume of production. As a result, production of the 1997 telephone required 9.25 kWh, 99.89 MJ. This excludes the energy required for printed circuit board (PCB) production, which is calculated separately and then added to the energy required to manufacture the telephone. The energy required to manufacture 1 mm^2 of the 21090mm^2 1997 PCB was found to be 0.0019 MJ [16]. Production energy for the other telephones was predicted based on an historical production efficiency ratio, which will be further discussed in chapter 5. The cost of energy was assumed to be $0.10 / kWh, $0.02778 / MJ [26].

- **Energy in Recycling**

Reflects the energy consumed in a facility to shred and separate the telephones. The value was obtained by dividing the total facility consumption of energy in monetary value by the total volume of recycled telephones. The result was that the recycling of the telephone required 2 kWh /Kg (21.6 MJ /Kg) of material. This value was based on the AT&T Reclamation Center, located in West Chicago, IL. [15]. The metals in the telephones are assumed to be the only materials recovered from the telephones, since the value of recycled plastics is negligible. The cost of energy was also assumed to $0.10 / kWh, $0.02778 /MJ.

- **Embodied Energy**

This variable was not included in the resource productivity formula, and was added to quantify the importance of recognizing the efforts for conserving the embodied energy of polymers. The values used were extracted from reference [27].

- **Lifetime Energy Use**

Reflects the energy consumption of the product in the use stage of its lifecycle. This measure reflects the energy in both the "In-Use mode" and the "Stand-By mode". The utilization factor was assumed to be 3% over a 24-hour period, based on a small sample. For the 1997 telephone, the energy consumption rate was taken to be:

In-use mode: 5.5 Watts, Stand-by mode: 2.2 Watts.

These values were obtained based on personal contact with research staff at Lucent Technologies [26].

3.3.2 Eco-Compass

As mentioned earlier in chapter 2, eco-compass is a comparative tool that can be used to compare one existing product with another, or for comparing a current product with new development options. The methodology followed to utilize the concepts of this tool, is to choose one of the products as the base case for comparison and evaluate the performance of the other products to the base case. The base case always scores a 2 in each dimension. The alternative product is then given a score relative to this base case on a scale of 0-5 in each dimension. The precise score depends upon the percentage increase or decrease in performance. The scoring is more logarithmic than linear. The distance between a 2 and a 5 is a " factor of four" improvement. If the improvement in performance was of a magnitude of 2 or greater, then a score of 4 would be given to the product. If the improvement was of a magnitude greater than 4, then the applicable score would be 5. While a decrease in the performance by a magnitude of 0.5, would be given a score of 0. The results are plotted on a hexagon scale that provides a visual conception of the calculated results as seen in Figure 3.1.

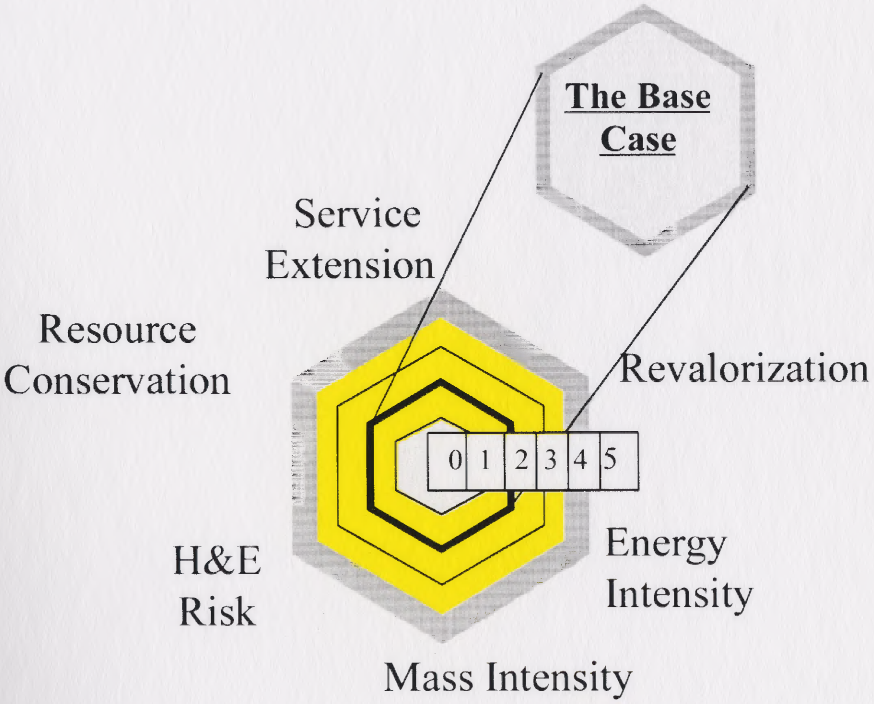


Figure 3.1 The Eco-compass

- **Mass Intensity**

Detects the change in the material consumption and mass burdens of products or service chains. The metrics used to measure the mass intensity is based on the weight of the product, regardless of the functionality of the parts and subassemblies.

- **Energy Intensity**

Detects the change in the energy usage associated with the product throughout its lifecycle. This metrics quantifies the energy required to produce the feedstock materials, energy consumption during production, energy consumption in the use stage, and finally energy consumption during recovery, which is energy required for recycling minus the embodied energy of polymers.

- **Health & Environmental Risk (H&E Risk)**

Detects the change in the environmental burdens associated with the production of the product over its lifecycle. Environmental burdens include air emissions, solid wastes and water effluents. This metrics quantifies the environmental burdens generated from the production of the feedstock materials only, since no data was available for other lifecycle stages. The methodology used to evaluate H&E Risk is the same as the one described earlier in section 3.2.

- **Revalorization**

Otherwise known as "demanufacturing" evaluates the changes and advancements in the demanufacturing technology, emphasizing on nine important performance attributes. Those performance attributes are: Material variety, material marking, fasteners comparison, ease of disassembly, which utilizes the DEIM to measure several factors that are crucial to the disassembly process such as disassembly time, accessibility of parts and subassemblies, force required to disassemble parts, specific fixtures required to hold the part, specific tools needed for the disassembly process, and finally, the instructions required, if any, to disassemble the product.

- **Resource Conservation**

This dimension is concerned with efforts to conserve material and energy usage. The metric used is the denominator of the resource productivity (RP), which was discussed earlier in chapter 2. The formula used to calculate resource conservation is:

(Material Consumed - Recycled) + (Energy Consumed for Production + Recycling – Embodied Energy) + Lifetime Energy Used.

The assumptions used for each variable were discussed earlier in the previous section.

- **Service Extension**

This dimension concentrates on the extent of service delivery to customers from a given amount of environmental input. Variables under study are commonality, upgradability and modularity. The above three metrics were defined as follows

1. Commonality: Refers to the compatibility of the current generation subassemblies with the next generation.
2. Upgradability: The ability to easily upgrade subassemblies to meet new design requirements.
3. Modularity: Whether the product and subassemblies are designed so that they can be easily serviced, replaced and disassembled.

3.4 Multi-Lifecycle Assessment (MLCA)

Multi lifecycle assessment is a new methodology that extends the traditional lifecycle stages set forth by SETAC and EPA. It puts greater focus on quantifying materials, energy and environmental burdens associated with end-of-life options and on value of returning parts and materials back to use, through demanufacturing, reengineering and remanufacturing. It also allocates appropriate benefits to the product over multiple generations rather than one. The aim is to introduce a next generation engineering system in which the quality of the waste stream is engineered with the same concern as the product itself, and where discarded products and waste material are reengineered into valuable feedstocks.

MLCE concentrates on investigating, developing and creating new applications for materials and components from discarded products. The objective is to enhance the use of materials and components from discarded products so that they could be used over more than one product lifecycle, hence the Multi-lifecycle methodology is introduced.

MLCE is more of a systematic approach in analyzing a product, since it accounts for the multiple lifecycles that materials or components pass through. This requires a clear vision and understanding of the product from its raw material extraction through use stage and finally demanufacturing and reengineering. Hence efficient demanufacturing of the product is one of the prime goals of multi-lifecycle engineering. Design for disassembly helps in attaining this goal and efforts are being made towards developing a methodology for it. In order to quantify in a simple and consistent manner, the inputs and outputs to each of the MLCA stages, a generic process model was developed that would quantify these values. Also, a generic framework for those stages was developed as to analyze different materials and processes in a consistent way. These generic processes were previously presented in a master's thesis by D. Badwe [14]. Figure 3.2 shows the generic process modeling structure utilized in the MLC methodology.

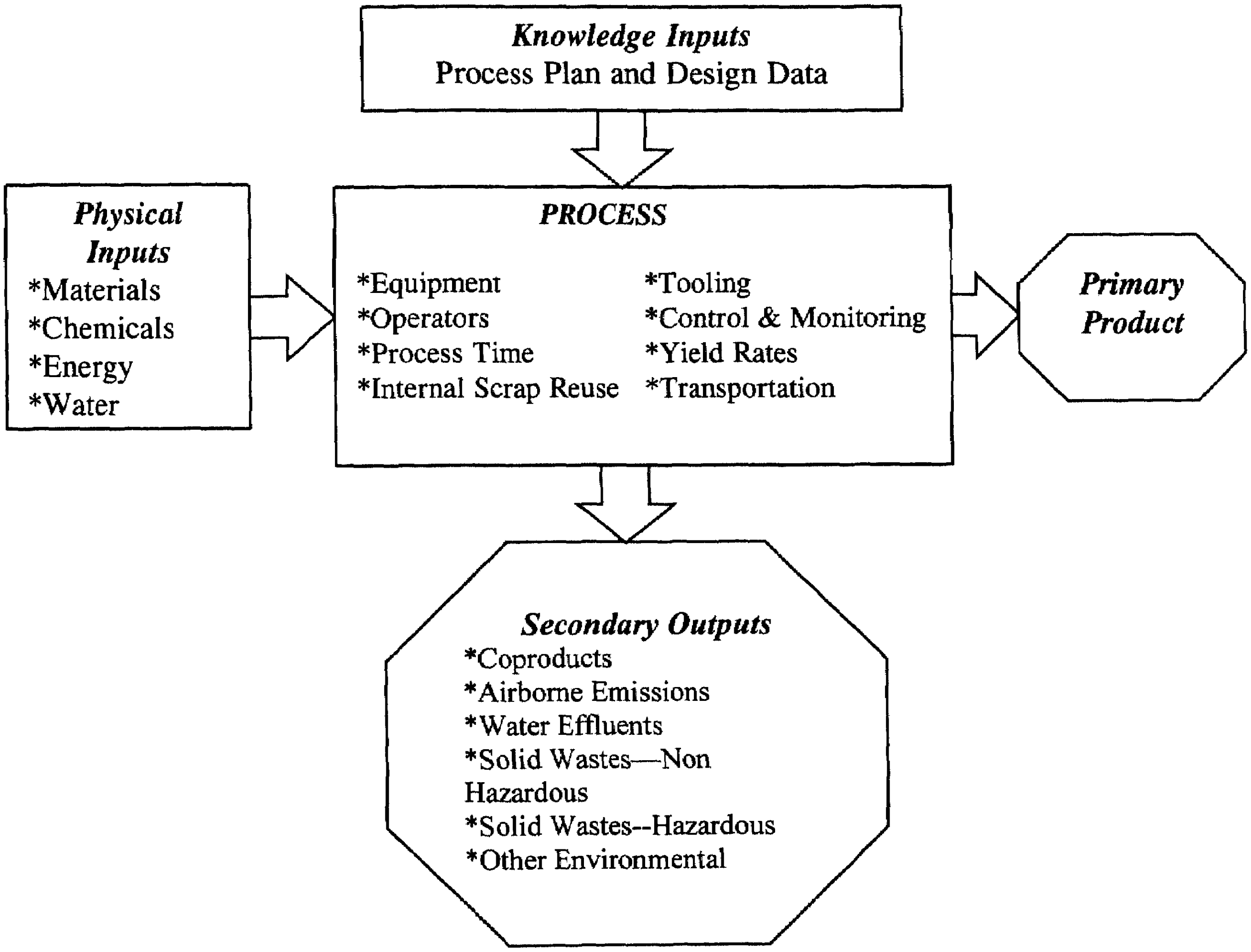


Figure 3.2 Generic Process Modeling Structure

In this generic process, the center of the figure refers to any process or stage of an LCA under study. The process model quantifies all the necessary information that is needed to analyze the product. Information obtained refers to the equipment used, tools, process time, environment yield rate and others. The inputs to this process are concentrated on raw materials, energy, water, chemicals, process materials and the knowledge of the process planner and designer. The outputs from the process box are divided into the primary product and the secondary outputs. The secondary outputs refer to any co-products produced, airborne emissions, solid wastes, and water effluents. By completing the data in the above model, one should be able to obtain a balance of energy, raw materials, air emissions, and solid wastes for a particular process or stage.

An important aspect of lifecycle assessment is balance flows of energy and materials and quantifies emissions, solid wastes and water effluents throughout the product life. Figure 3.3 shows the total lifecycle engineering framework in terms of the considerations for analysis and modeling.

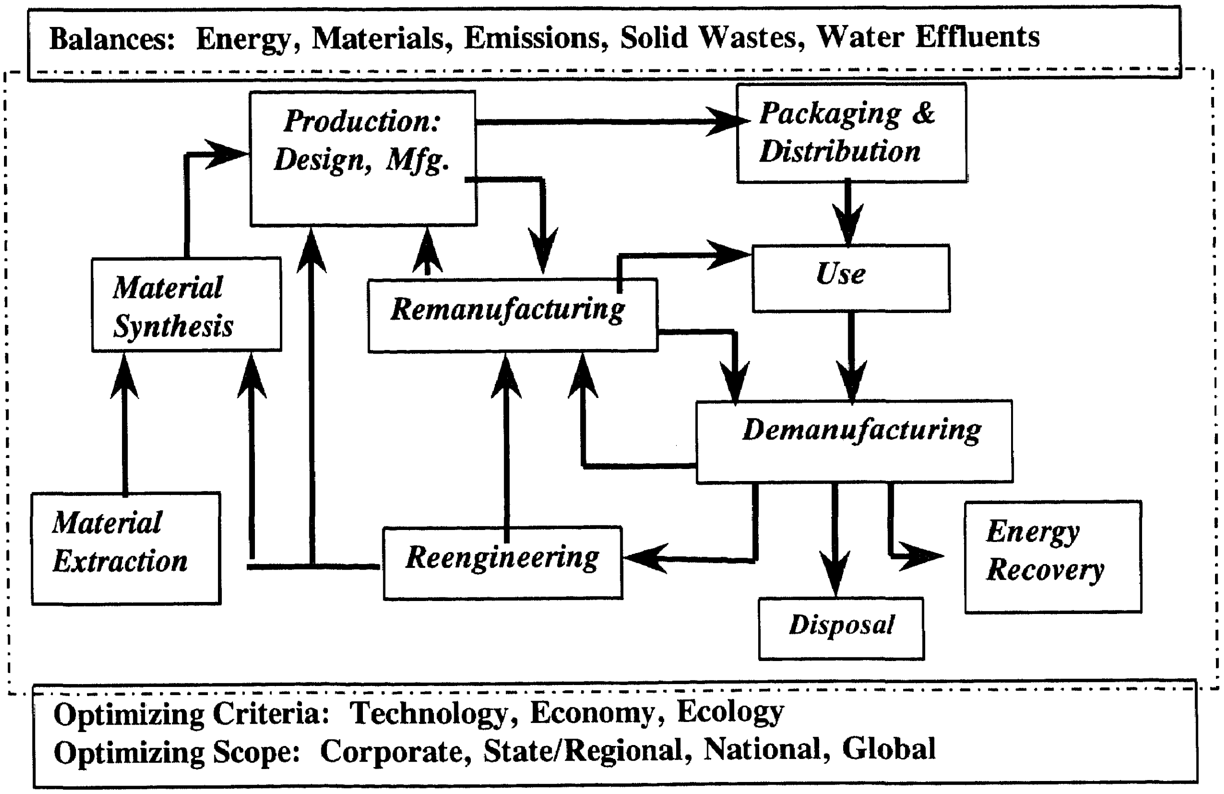


Figure 3.3 Total Lifecycle Considerations for Analysis & Modeling

As seen in Figure 3.3, materials production has been divided into two separate stages, materials extraction and materials synthesis. This breakdown is useful in defining the depth and level of the study as it gives more options for designers to evaluate their product based on their specific needs. Another stage that is further quantified in the MLC methodology is the packaging and distribution stage, which has been separated from the production phase as a unique stage. This stage quantifies the materials used in the packaging process, the packaging process itself, as well as methods of transportation, distance traveled and energy and emissions associated with these processes.

The last stage in the traditional LCA is of recycle/waste management. It has only three options namely recycle, compost, or discard the waste generated after the full usage of the product. The main option to consider and where MLCA differs from LCA, is in the recovery and new life options of the product. LCA addresses two types of recycling processes, open loop recycling and closed-loop recycling. Closed-loop recycling occurs when a product is recycled into a product that can be recycled over and over again. Whereas in open-loop recycling system, a product made from virgin material is recycled into another product that is not recycled, but disposed off, possibly after a long-term diversion. So, LCA looks into this as two separate distinct recycling options. This is where MLCA plays its role, in addressing these two recycling options simultaneously, rather than in isolation, and not only at the end of products life but also throughout its life from raw material extraction to final disposal. MLCA calls this transitional stage of product life cycle as Demanufacturing.

Traditional LCA talks about recycling in which some material is ultimately disposed to land as in closed-loop / open-loop recycling. Thus, LCA is a cradle-to-grave analysis, whereas MLCA tries not to landfill any material as far as possible and so is a cradle-to-cradle analysis tool. MLCA finds new options for the waste disposed at every stage so that it can be reengineered into useful products and not just once but again and again. This reengineering stages acts as the link that closes the lifecycle loop. Finally, the remanufacturing stage is where the parts and subassemblies are refurbished. Those parts could then be used in new products at the production stage or for replacements and maintenance at the use stage or could be sent back for demanufacturing.

3.5 MLCA Stage Description

As mentioned earlier, the MLCA methodology relies on the consistency of the information throughout the product life stages. Therefore, generic frameworks for the MLCA stages: Materials extraction and synthesis, Production, Use, Demanufacturing, Reengineering, and Remanufacturing have been developed. These frameworks capture product information in a consistent and uniform manner. Following is a description of the generic frameworks.

3.5.1 Generic Framework for Feedstock Material

A common framework, as shown in Figure 3.4, was developed to serve as the model structure for each feedstock material in order to have a consistent and standard process description of all the materials. For polymers, this model indicates the various stages involved in the production of the resin from extraction of crude oil to final blending and formulation. For metals, this model incorporates the extraction of ores and initial beneficiation to finished metal.

This model is composed of two parts: raw material extraction and material synthesis. Materials synthesis consists of intermediate processing, final processing and end-use preparation. The model quantifies energy and material inputs and provides the output, by-products and environmental impacts of the processes. Through the use of mass and energy balance equations, the total energy, mass and environmental requirements for the production of each material were determined.

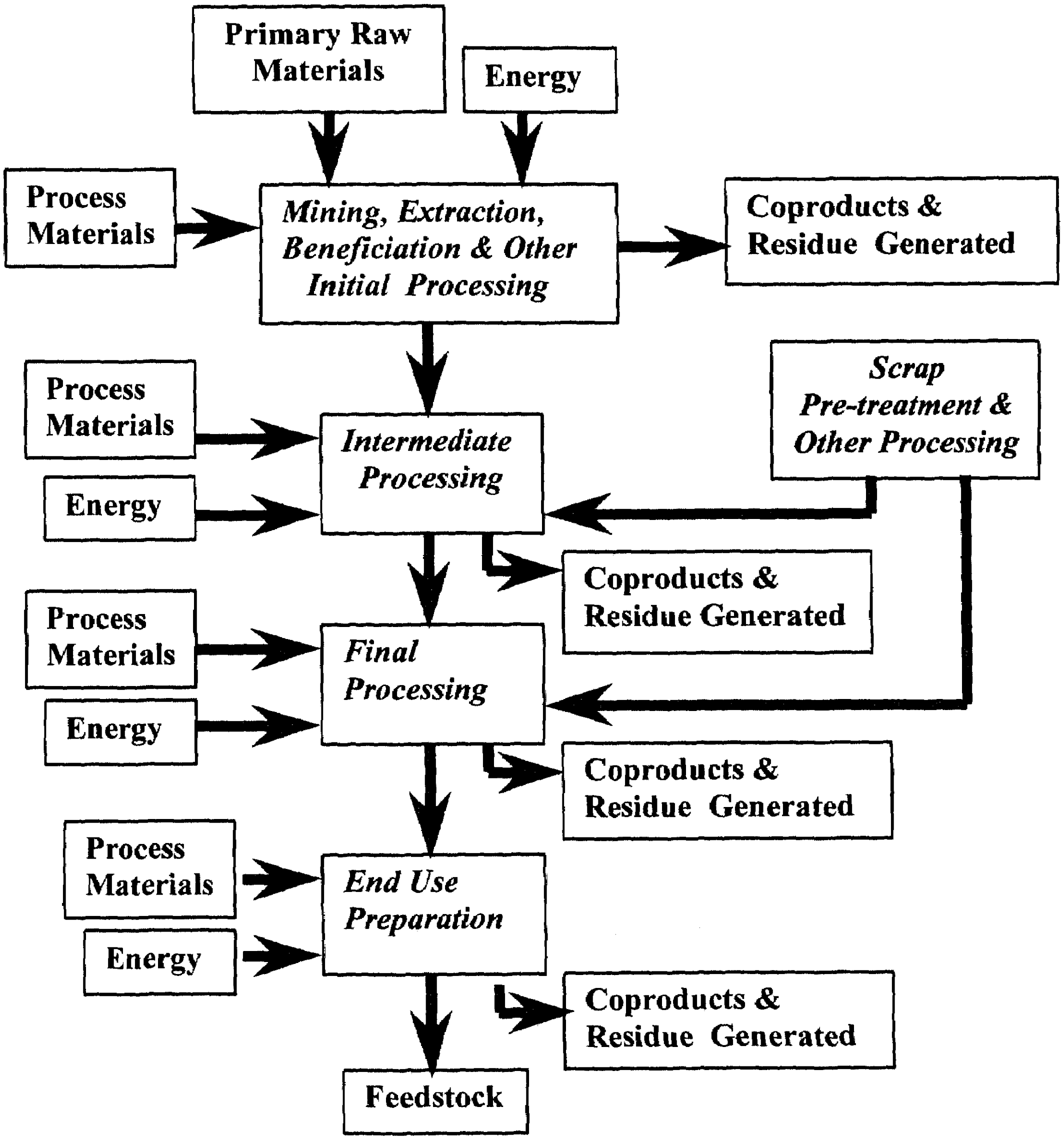


Figure 3.4 Modeling Framework for Primary and Secondary Processing of Feedstock Materials

3.5.1.1 Materials under Study: The generic framework for primary and secondary processing of feedstock materials described earlier in this section is implemented on the materials composing the telephones. Necessary information, such as energy and environmental burdens for the materials composing the product, must be gathered. The information is then sorted in the generic framework structure. The next step in analyzing a material is to develop a process tree for the production of materials, as in Figure 3.5. This structure provides information on the process steps and materials needed to develop or produce a certain material. Materials analyzed in this study are divided mainly into polymers and metals. The polymers presented here are Acrylonitrile-Butadiene-Styrene (ABS), Polyvinyl Chloride (PVC), High Impact Polystyrene (HIPS) and Polycarbonate (PC). The metals include Steel, Aluminum, and Copper which, were described in another thesis developed in MERC by D. Badwe [14]. The processing of ABS will be discussed in details, since the majority of the electronic products housings are made out of ABS plastic, and because all the plastics used in the telephones understudy are also assumed to be ABS.

3.5.1.1.1 Acrylonitrile-Butadiene-Styrene (ABS): ABS is an amorphous engineering thermoplastic whose main features are impact resistance, rigidity, high gloss and low cost versus other engineering plastics. ABS resins are used in a variety of applications including, automotive, appliances, construction, electronics and business machine housings. It is one of the most widely used platable plastics. Figure 3.5 shows the process tree that was developed for ABS, that displays the various stages involved in the production of ABS pellets.

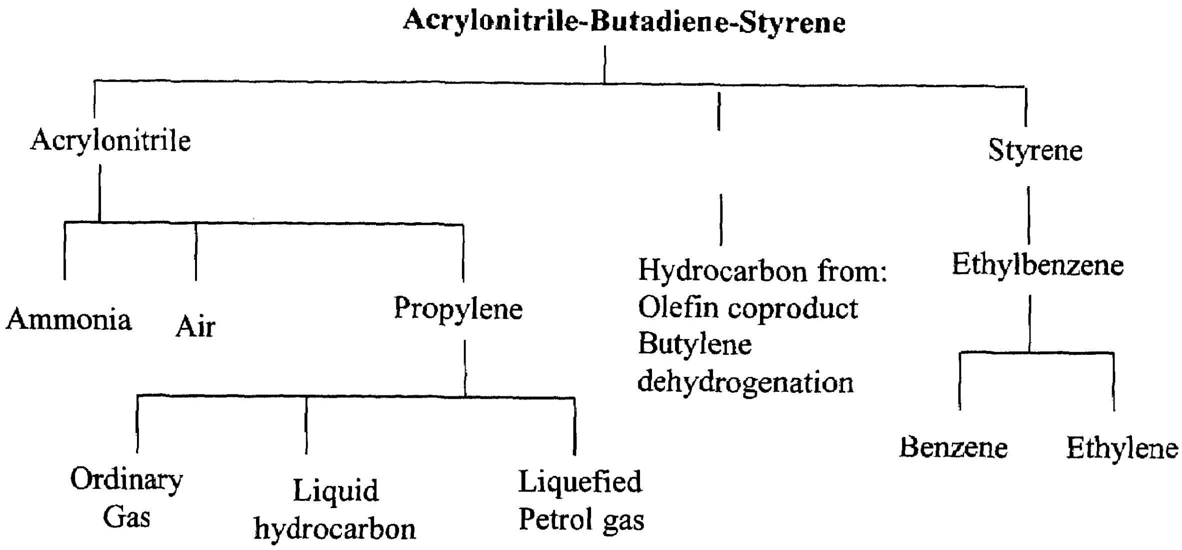


Figure 3.5 Process Tree for Production of ABS Polymer Feedstock
[Reference: Table 3.2]

For each of those stages, a production process was generated. These specific processes were chosen due to their being the most common commercial production processes for that material. There are three types of polymerization processes used for the commercial production of ABS polymers: emulsion, suspension, and bulk. Historically, emulsion and suspension processes have dominated the field of ABS manufacture. Recently, however, the bulk process has achieved commercial importance. Because bulk polymerization does not proceed in water, it has two inherent advantages over suspension and emulsion polymerization. First, wastewater treatment is minimal. Second, less energy per pound of product is consumed since dewatering, drying and compounding steps are not necessary. Disadvantages of the bulk process include less product flexibility, greater mechanism complexity, and less complete conversion of monomer into finished polymer. This means that most ABS materials made by bulk require devolatization to remove residual monomers prior to compounding of the final product.

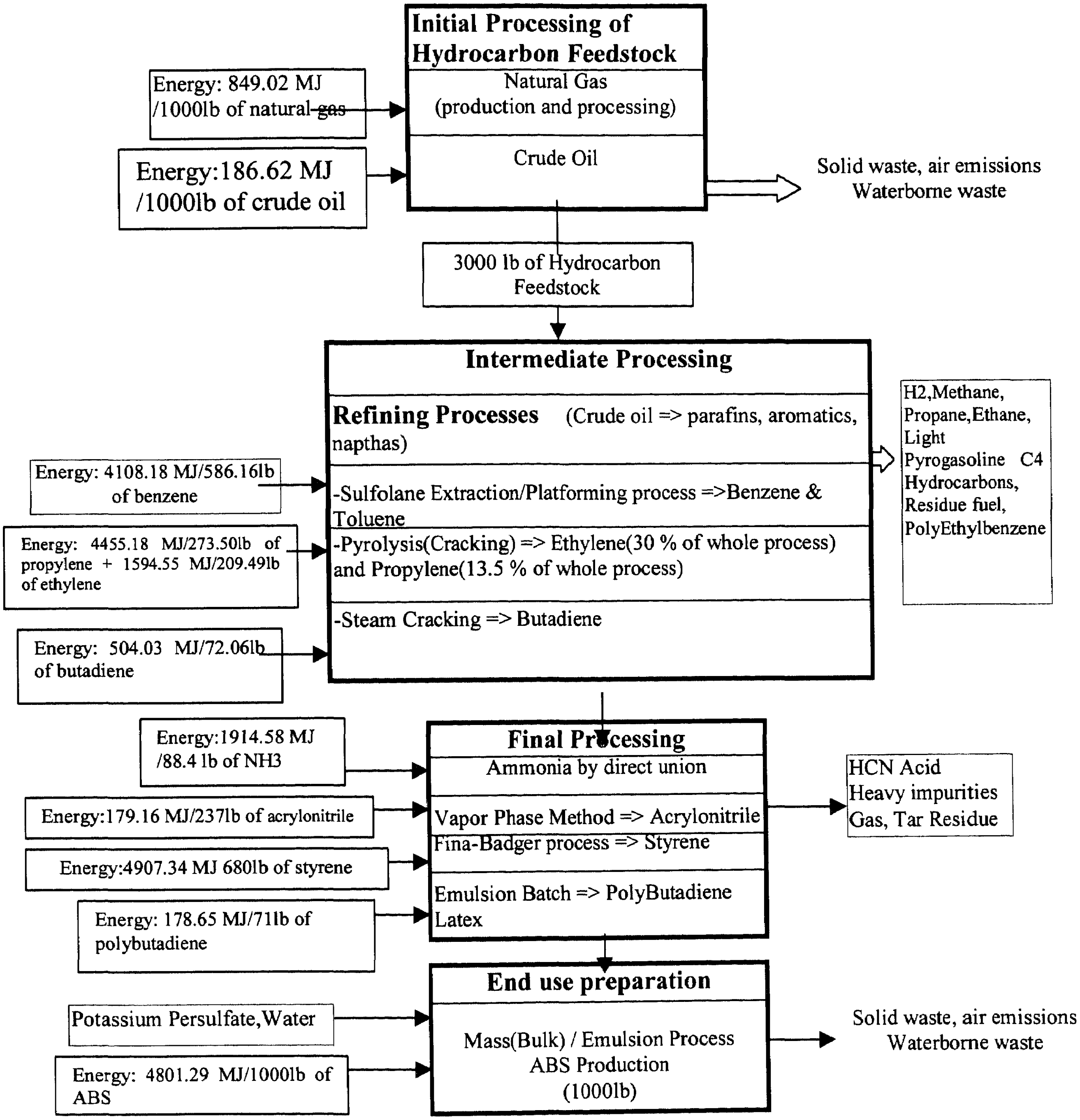
After analyzing the various materials composing the ABS resin, the information gathered was integrated into the generic framework for primary and secondary production. This framework allows us to visualize the entire production process that formulates the ABS resin. Mass, energy, environmental emissions and co-products are all balanced throughout the framework. The consistency in the measurement units used is critical in analyzing a product and conducting a sensitivity analysis. The units used in this study for each of the materials was based on a 1000-LB unit. The energy values are all calculated in Mega-Joules (MJ), to account for the difference in efficiency of energy from different sources such as natural gas and electricity. So the units used to measure the energy required for producing the materials is in MJ / 1000 Lbs. Figure 3.6 shows the generic framework for ABS processing. The detailed environmental burdens for the processing of ABS are displayed in Table 3.1. Table 3.2 shows the references from which information on energy and environmental burdens for the processing of ABS were extracted. Similar details for the other polymers are given in Appendix A.

The assumptions made when calculating the energy consumption for the production of the feedstock materials is as follows: Process energy used by the actual manufacturing operations was considered, energy used for space heating of buildings and other miscellaneous categories was excluded from the study. Finally, embodied content of polymers was also not included. Following is a sample of the calculation methodology for ABS, which is applicable to all the other processes. The values for the environmental burdens are the actual numbers extracted from the reference, see Tables 3.1 and 3.2. Energy calculations for manufacture of ABS:

Natural Gas Industrial heat: 2386 scf x 1.0799 MJ / scf = **2576.67 MJ**

Electric: 206 kWh_e * 3 * 1 MJ / 0.2778 kWh_e = **2224.62 MJ**

Total Energy = 2576.67 + 2224.62= **4801.29 MJ**



Total Energy: 23678.60 MJ/1000lb of ABS.
Note: (Total energy is excluding transportation energy)

Figure 3.6 Generic Framework for Processing of ABS

Table 3.1 Environmental Burdens Associated with Processing of ABS.

Processes	**Solid Wastes(lb.)**	**Air Emissions(lb)**	**Waterborne Wastes**
Initial Processing (Drilling and processing)	?	Particulate:0.004 Nitrogen Oxide:0.258 Sulfur Oxides:0.009 Carbon Monoxide:0.094 Hydrocarbons:0.594	Acids:0.037 Metal ions:0.011 Dissolved Solids:0.22
Natural Gas Production	?	Hydrocarbons: Methane: 10	Dissolved solids: 3.9 (inform of brine)
Crude Oil Manufacturing	0.6	Hydrocarbons:1.4	Dissolved solids: 11
Intermediate Processing (production of ethylene, propylene, benzene, ethyl benzene, butadiene)	?	**Refining of 1000 gal. Liquid hydrocarbon fuel:** Particulate:3.17 Nitrogen Oxide:11.3 Sulfur Oxides:25.6 Carbon Monoxide:3.17 Aldehydes:0.34 Other Organics:0.37 Ammonia:0.39	**Refining of 1000 gal. Liquid hydrocarbon fuel:** BOD:0.23 COD:0.78 Suspended Solids:0.46 Dissolved Solids:1.4 Phenols:0.06 Sulfides:0.085 Oil:0.13 Metal ions:1.64 Acids:5.68
	Ethylene: 0.209	**Ethylene:** Hydrocarbons:0.209	**Ethylene:** BOD: 0.418 COD: 1.089 Oil: 0.377 Suspended Solids:0.607
	Propylene: 0.4304	**Propylene:** Hydrocarbons:0.4304	**Propylene:** BOD:0.8608 COD:2.398 Suspended Solids:1.248 Oil: 0.746
	Benzene: 0.586	**Benzene:** Particulate: 0.205 Hydrocarbons:1.817 Sulfur oxides:1.9929 Aldehydes:0.029 Other organics:0.029 Ammonia:0.035	**Benzene:** BOD: 0.0205 COD: 0.0703 Oil: 0.011 Suspended Solids:0.041 Sulfides:0.007 Phenols:0.005
	Butadiene: 0.053	**Butadiene:** Hydrocarbons:0.09648	**Butadiene:** BOD: 0.054 COD: 0.2369 Oil: 0.0036 Suspended Solids:0.015

Table 3.1 (continued)

Final Processing (production of Acrylonitrile, styrene, polybutadiene latex)	**Ammonia:** 0.044	**Ammonia:** Hydrocarbons:0.2036 Ammonia:0.2036	**Ammonia:** BOD: 0.005 COD: 0.0233 Oil: 0.005 Suspended Solids:0.005 Ammonia:0.0509
	Acrylonitrile: 0.1896	**Acrylonitrile:** Hydrocarbons:1.0428	**Acrylonitrile:** BOD: 0.711 COD: 1.469 Oil: 0.01896 Suspended Solids:0.1896 Cyanide:0.0001896
	Styrene: 0.68	**Styrene:** Hydrocarbons:3.4	**Styrene:** BOD: 1.992 COD: 4.821 Oil: 0.3196 Suspended Solids:1.992
	Polybutadiene: 0.0071	**Polybutadiene:** Hydrocarbons:2.911	**Polybutadiene:** BOD: 0.0291 COD: 0.0589 Oil: 0.0049 Suspended Solids:0.089
End Use Preparation (production of ABS)	1	Hydrocarbons:2.7	BOD:0.46 COD:2.36 Oil:0.02 Suspended Solids:0.49 Chromium: 0.0016 Iron: 0.016 Aluminum: 0.016 Nickel: 0.008 Cyanide: 0.0008

Note:

- All figures are from Reference No. Table 3.2
- All figures refer to requirements for production of 1000 lb of ABS.
- Since propylene comes out along with ethylene in the fining process, we assumed types and quantities of emissions coming along with propylene are same as that of ethylene.

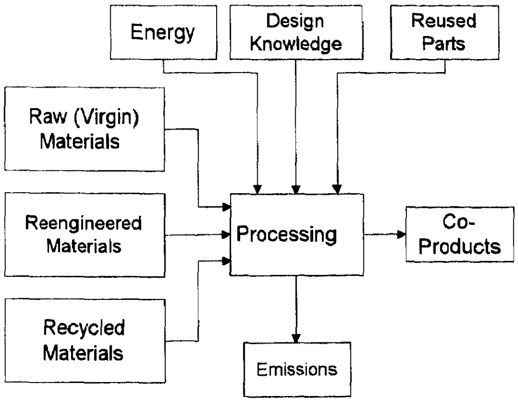
Table 3.2 References for Energy and Environmental Burdens from Processing of ABS

#	Product	Energy for 1000lb ABS (MJ)	Source	Assumptions (if any)
1	ABS	4801.29	Plastics: Resource and Environmental Profile Analyses, 1974, [6], pg:90	
2	Acrylonitrile	179.16	Plastics: Resource and Environmental Profile Analyses, 1974,[6], pg:81	
3	Ammonia	1914.58	Plastics: Resource and Environmental Profile Analyses, 1974,[6], pg:76 Energy Analyses of 108 Industrial Processes, Sep'85, [17], pg:212	We choose the latest one.
4	Styrene	4907.34	Energy Analyses of 108 Industrial Processes, Sep'85, [17], pg:196	
5	Polybutadiene	178.65	Plastics: Resource and Environmental Profile Analyses, 1974, [6], pg:87	
6	Butadiene	504.03	Plastics: Resource and Environmental Profile Analyses, 1974, [6]. Pg:84	
7	Ethylene	1594.55	Energy Analyses of 108 Industrial Processes, Sep'85, [17], pg:204 Plastics: Resource and Environmental Profile Analyses, 1974, [6]. Pg:46	
8	Benzene	4108.18	Plastics: Resource and Environmental Profile Analyses, 1974, [6]. Pg:73	
9	Propylene	4455.18	Plastics: Resource and Environmental Profile Analyses, 1974	Based on ethylene
10	Natural Gas	849.02	Plastics: Resource and Environmental Profile Analyses, 1974, [6], pg:43,44	
11	Crude Oil	186.62	Plastics: Resource and Environmental Profile Analyses, 1974,[6], pg:70	
	Total	23678.6		

Note: Environmental burdens information for each process were extracted from the same above sources.

3.5.2 Generic Process Model for Production

The data resulting from the modeling framework for primary and secondary processing will be integrated into the production stage of the product. A generic production module was developed that incorporates the concepts of multi-lifecycle engineering and simultaneously maintaining the balance of materials, energy and environmental data. As seen in Figures 3.7 and 3.8 below, the processing of parts and subassemblies was separated to emphasize the different inputs and processes required. The initial inputs to the parts production process are reused parts that are recovered in the demanufacturing process and raw (virgin), recycled and reengineered material from other (or same) products, this also includes process materials. While the inputs to the subassembly production process includes refurbished subassemblies that are also recovered from demanufacturing and feedstock inputs rather than materials. The output from these two processes is integrated into the final assembly process, which results in the finished product. Throughout the above processes, materials, energy, emissions, co-products and knowledge are quantified and balanced in each process. Figure 3.9 illustrates the generic structure of production from a MLCA perspective.



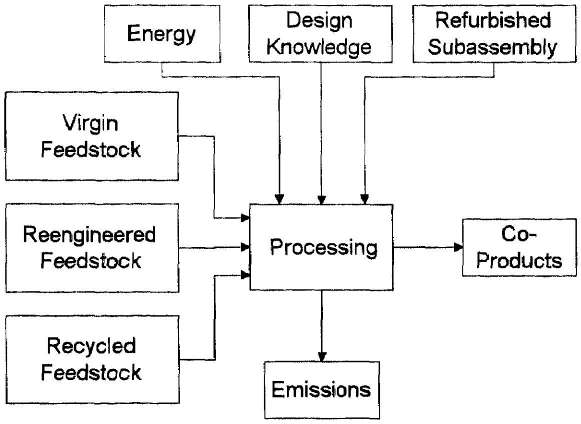


Figure 3.7 Generic Production Module of Parts

Figure 3.8 Generic Production Module of Subassemblies

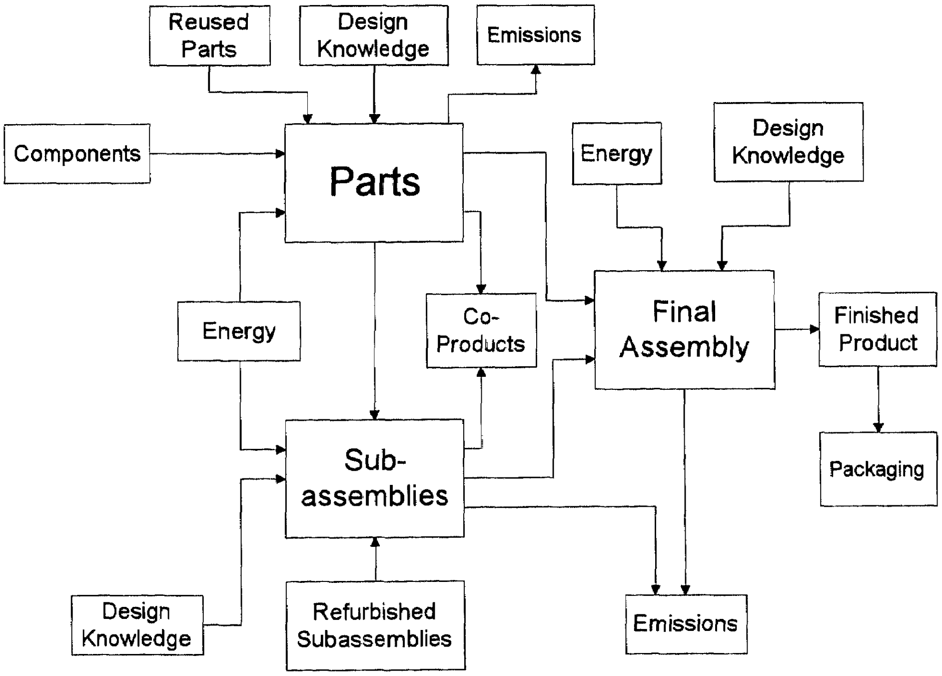


Figure 3.9 Generic Production Module

3.5.3 Generic Process Model for Use Stage

Measuring the environmental performance of a product during the use stage is very crucial, since energy consumption during this stage is usually the highest. A generic structure was developed as seen in Figure 3.10, that illustrates the various inputs and outputs to a product during its use stage. Generally, electronic products consume energy during use in four modes: Active, Idle, Power save, and Off modes. Energy consumption must be measured in each of those modes, in order to quantify energy consumed during the products lifecycle. Similarly, environmental burdens are measured during those modes and quantified. After the product is consumed and disposed of, it is sent to demanufacturing, where its end fate is identified.

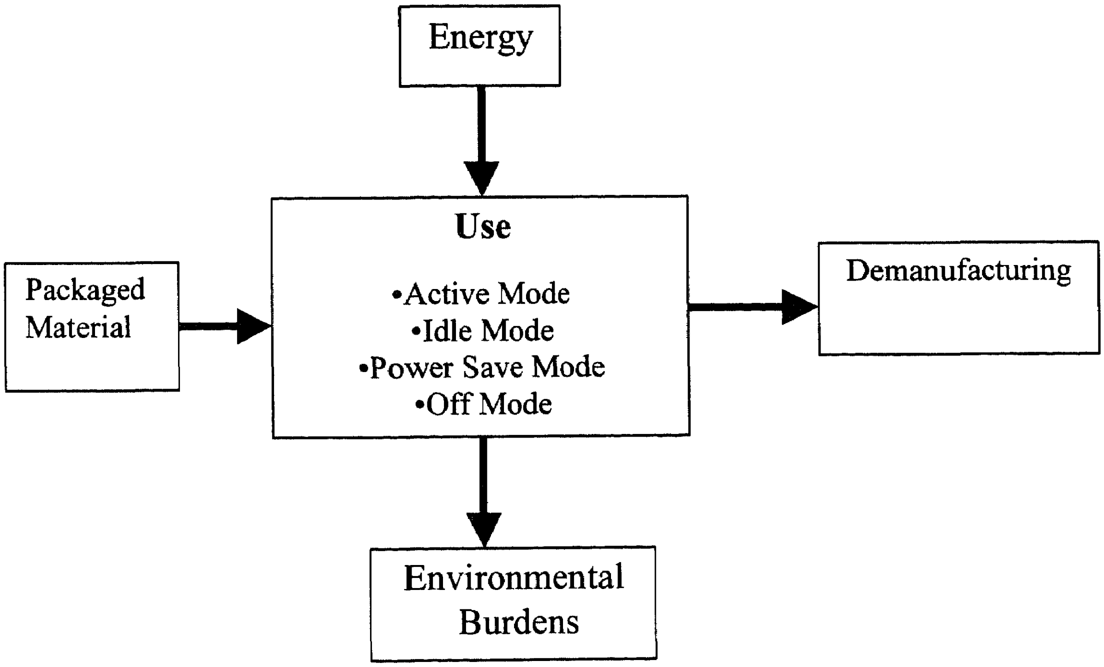


Figure 3.10 Generic Process Model for Use Stage

3.5.4 Generic Process Model for Demanufacturing System

Discarded products and materials flow into the demanufacturer from a variety of sources, including distributors, manufacturers and municipal collection systems. Upon receipt, the demanufacturer performs a preliminary screening to determine if the product is to be tested for reuse, disassembled or sent to the shredder. Depending on the product, its condition, and current market demand for parts and materials, the demanufacturer establishes a disassembly plan to maximize the value to be recovered. This value may be to resale or remanufacture the product; recover parts, components and subassemblies; recover basic materials for recycling and reengineering; send commingled materials to a smelter to recover high-valued constituents; or to an incinerator for the recovery of energy content. In most demanufacturing activities, small amounts of residue (or fluff) must be sent to disposal in a landfill or incineration unit. Figure 3.11 is a flow diagram showing the basic operation of the demanufacturing process, taken from concurrent research at MERC, by K. Limaye [28].

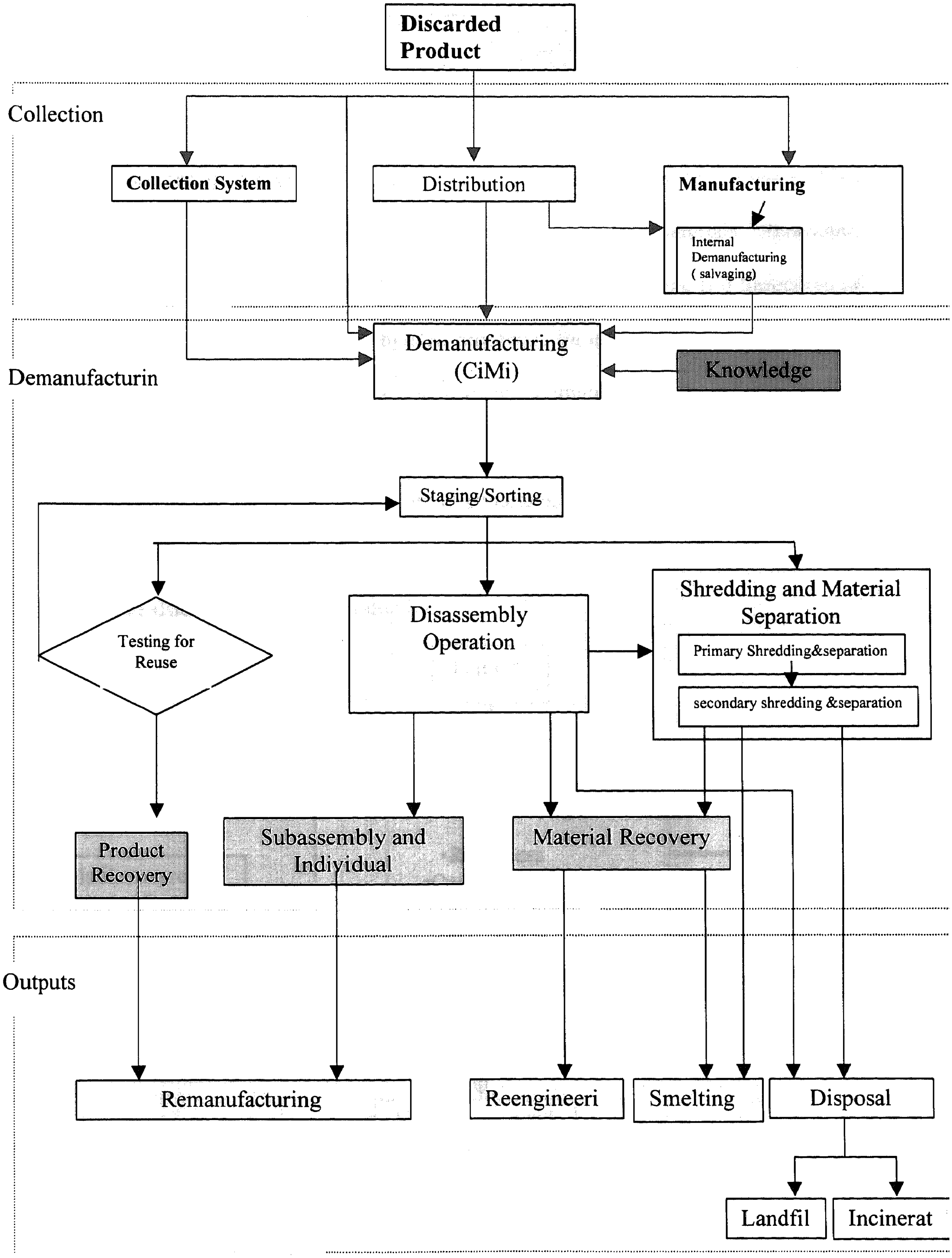


Figure 3.11 Generic Model for Demanufacturing

3.5.5 Generic Process Model for Reengineering

Reengineering involves the characterization of waste streams and the reformulation of materials derived from these waste streams [8]. Figure 3.12 illustrated the generic process for the reengineering stage, quantifying the major reengineering processes. Five major reengineering processes were identified for recovered materials: Reprocess, Compatibilize, Pyrolysis to Fuels, Pyrolysis / Hydrolysis to Monomers, and Shredding of Metals. Table 3.3 illustrates the step-by-step procedure for each of the above processes. Material inputs to this stage are mainly obtained from demanufactured products, through processes such as shredding and separation. Energy consumption and environmental burdens are measured at each step in the above processes. Finally, the materials resulting from reengineering can be either integrated into materials synthesis, or can be inputted directly as feedstock material for production.

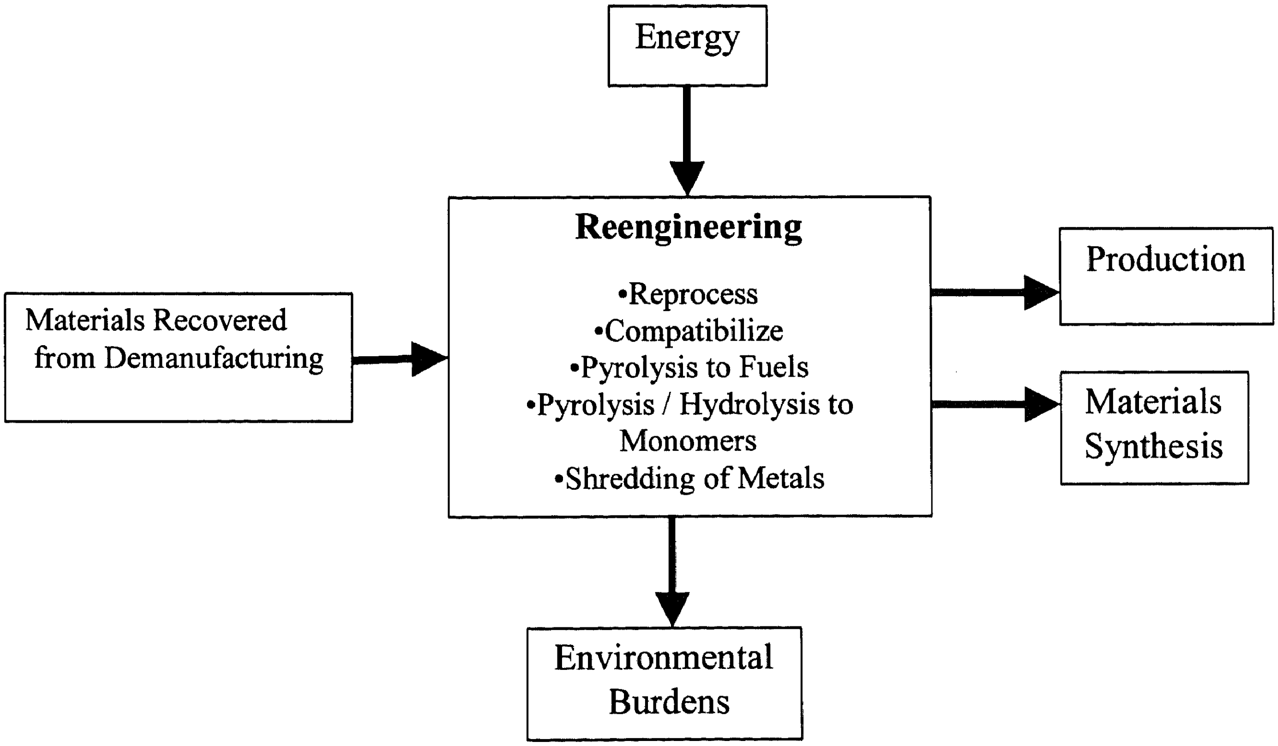


Figure 3.12 Generic Process Model for Reengineering

Table 3.3 Reengineering Processes for Discarded Parts and Subassemblies [27]

Reprocess	Compatibilize	Pyrolysis to Fuels	Pyrolysis / Hydrolysis to Monomers	Shredding of Metals
Collect	Collect	Collect	Collect	Collect
Sort	Sort	Sort	Sort	Sort
Clean	Clean	Pyrolyze	Clean	Clean
Reclaim (Flake/Pellet)	Reclaim (Flake/Pellet)	Transport	Reclaim (Flake/Pellet)	Shred
Dry	Dry	Fuels	Pyrolyze / Hydrolyze	Package
Package	Compatibilize / Modify		Purify Monomer	Transport
Transport	Package		Transport	
	Transport		Polymerize	
			Transport	
			Package	
			Transport	

3.5.6 Generic Process Model for Remanufacturing

Remanufacturing is the process of refurbishing parts and subassemblies for reuse in new products. Parts and subassemblies entering the remanufacturing process can either be from demanufactured products, or from manufacturing processes. Figure 3.13 shows the generic process model for remanufacturing, where the flow of a remanufacturing process is as follows:

Sort → Pretest → Disassemble → Clean → Rebuild / Upgrade → Reassemble → Final Test → Packaging → Transport

Energy and environmental burdens must be quantified at each of the above steps. The resultant is either an assembly or a product that is fed back into the manufacturing process or back to the use stage through maintenance. Also, products and subassemblies that can not be remanufactured are sent back to demanufacturing for further processing.

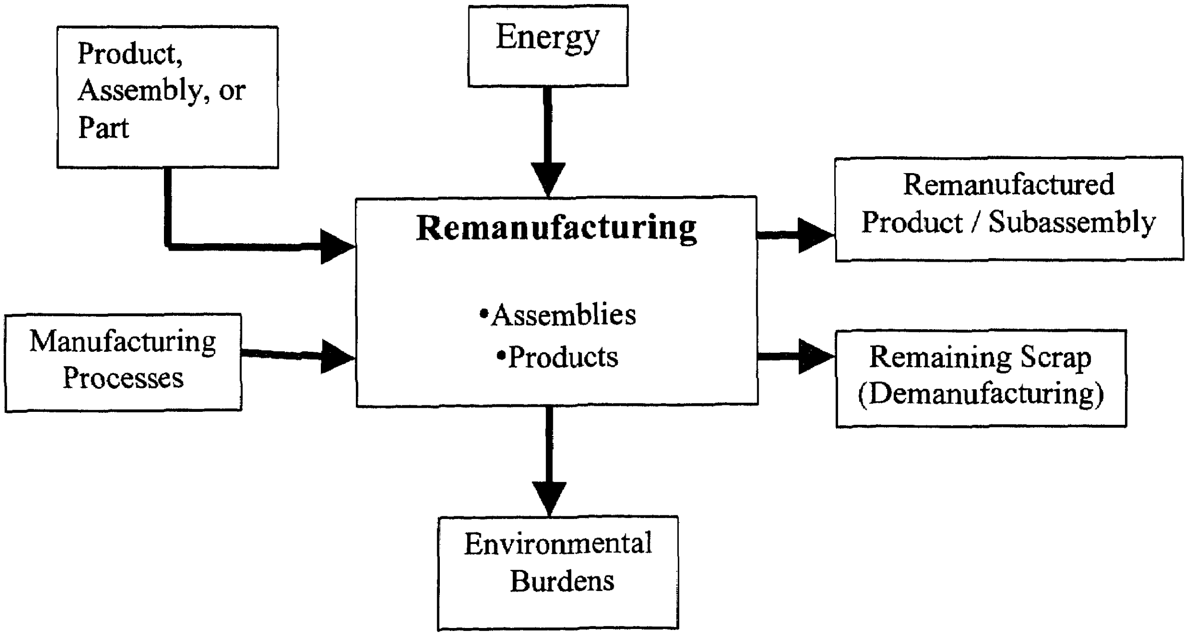


Figure 3.13 Generic Process Model for Remanufacturing

3.6 Multi-lifecycle Analysis (MLCA) Software Development

The MLCA software is an analysis tool that incorporates the concepts of multi-lifecycle engineering (MLCE). The software introduces a new concept, which is reengineering of materials and reengineering of parts back into production. As it is known, LCA is a data extensive and time consuming process. Utilizing databases and software to analyze a product and efficiently save all the information related to its is crucial. This software aims to:

- Utilize the MLCE methodology as the backbone of the lifecycle analysis of the product.
- Develop generic screens that can be utilized by most consumer electronic producers
- Produce a user-friendly tool to evaluate the environmental performance of consumer electronic products.
- Have environmental information on products and processes readily accessible to designers, which simplifies the integration of DFE into the design process.
- Help decision-makers to track the environmental performance of products, by using performance attributed such as eco-compass and trend analysis.

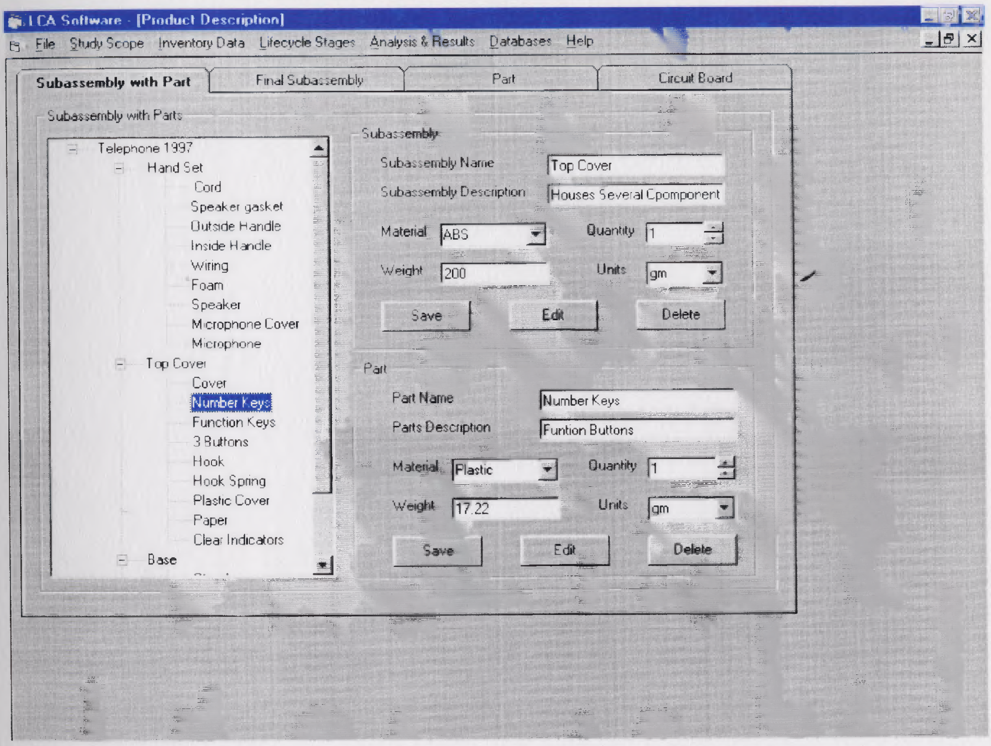
The software is divided into three main levels: Product Description, Lifecycle stages, and finally, Analysis and Results, which is still under development. This software is developed using Visual Basic 5.0 as the front-end, and MS Access 97 as the back-end database. The following sections describe the screen development for the software. Ji Jin, a graduate student in the computer engineering department at NJIT, assisted in the design and coding of the software.

3.6.1 Product Description

These screens allow the users to describe and document the structure of their product in terms of the different subassemblies and parts. This information is the basic inventory control of the product, from which a list of all the materials, weights, and quantities of parts and subassemblies is produced. As seen in Figure 3.14, the screen contains four major tabs: Subassembly with Part, Final Subassembly, Part, and Circuit Board.

- Subassembly with Part: This tab is used for subassemblies containing several parts or for subassemblies containing other subassemblies within its structure. For the subassembly section, the user inputs information such as the subassembly name and a brief description of the subassembly. The user also inputs information such as the material type and the total weight of the subassembly. Similar information is inputted into the parts section.
- Final Subassembly: This tab was designed for subassemblies that require no further disassembly, such as a power unit. The information entered through this screen relates to the various materials and the total weight of the subassembly.
- Parts: This tab was designed to describe parts that are not part of any subassembly. Similar information is entered into this screen as the above.
- Circuit Boards: This screen is still under development. It relates to the circuit board design, mainly quantifying a physical description of the circuit board.

Currently, efforts are concentrated on connecting this stage to a Computer Aided Design (CAD) tool, so that the product description is automatically retrieved form a CAD file, rather than being manually inputted.



Subassembly Name: Top Cover
Subassembly Description: Houses Several Cpomponent
Material: ABS
Quantity: 1
Weight: 200
Units: gm

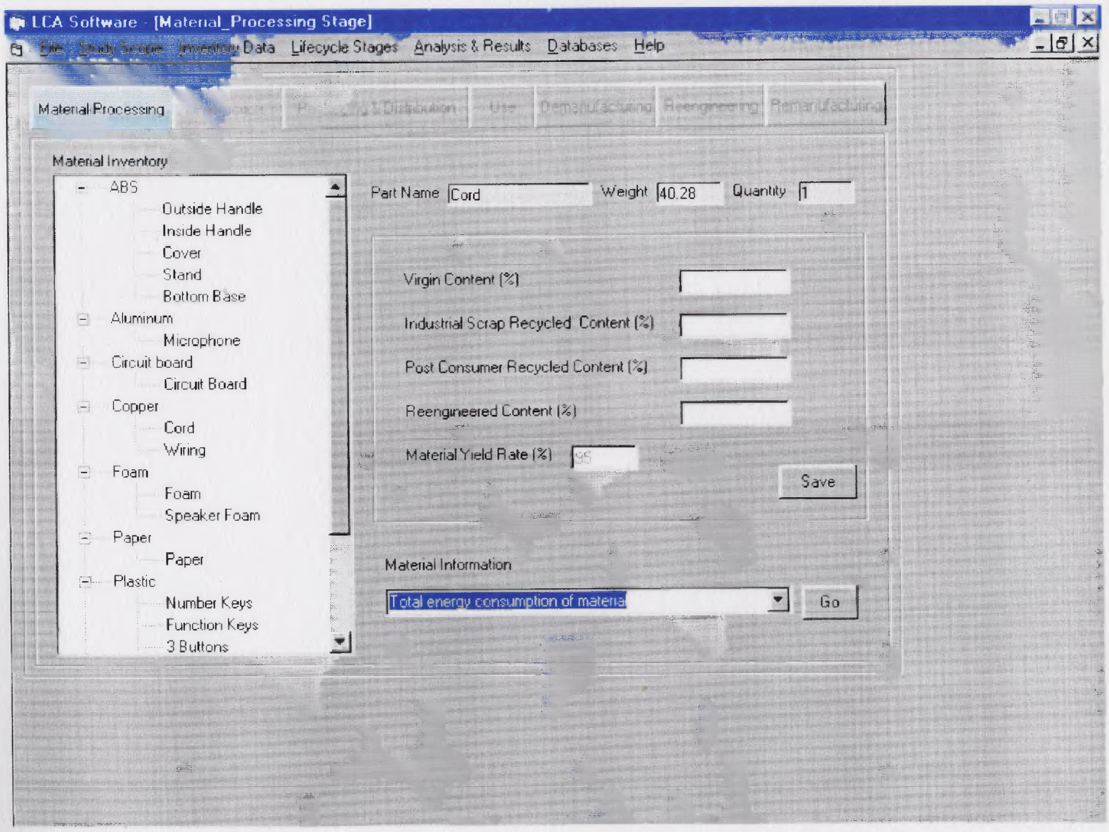
Part Name: Number Keys
Parts Description: Funtion Buttons
Material: Plastic
Quantity: 1
Weight: 17.22
Units: gm

Figure 3.14 Product Description Screen for Subassemblies with Parts

3.6.2 Lifecycle Stages Screens

After the user completes the product description stage, they then access the lifecycle stages screens and input information specific to each stage of the products lifecycle under study. The lifecycle stages of a product are divided into 7 stages: Materials Processing, Production, Packaging and Distribution, Use, Demanufacturing, Reengineering, and Remanufacturing. Detailed description of the above stages was described earlier in this chapter.

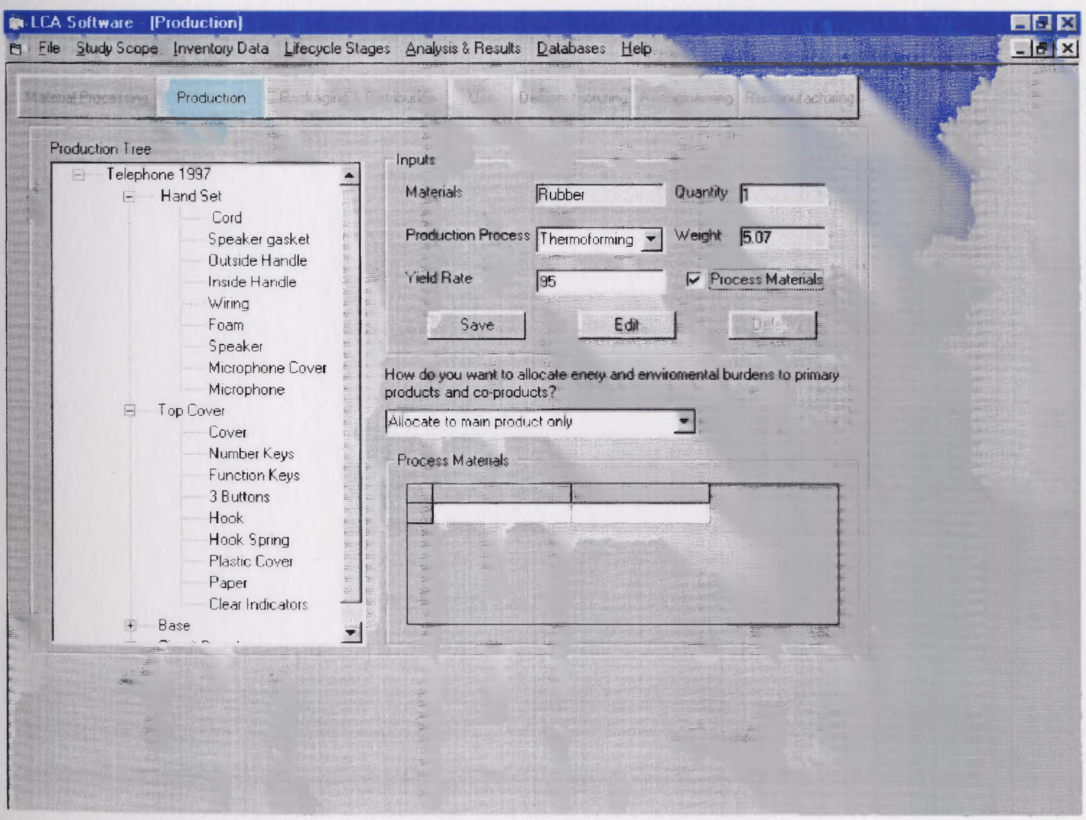
3.6.2.1 Materials Processing: This screen helps to gather more information on the materials used in the product. The system automatically displays a Material Inventory Tree, which retrieves the information entered in the product description stage. The tree displays a list of all the materials in the product, and lists under each material the parts made out of that specific material. The user then inputs information related to the composition of the material, such as the virgin, recycled and reengineered contents. Also information on the percentage of industrial scrap and post consumer recycled content are required from the user. This information helps in allocation of energy and environmental burdens to the product, based on the MLCE concept. The information from this stage helps analyze the energy consumption and environmental burdens associated with the production of material feedstock for the product understudy. A modeling framework for primary and secondary processing of feedstock materials was developed as described in section 3.5.1. Energy and environmental information is available for metals, polymers and glass. The data is divided into two sections: Materials Extraction and Materials Synthesis so that users can specify which stage of feedstock production they are interested in. This software also gives the users the flexibility to modify the information on materials extraction and synthesis to meet their specific needs. The users can also develop their own user-defined framework for existing and non-existing materials in the database. Figure 3.15 displays the materials extraction and synthesis screen.



Part Name: Cord
Weight: 40.28
Quantity: 1
Material Yield Rate (%): 95
Total energy consumption of materia

Figure 3.15 Materials Extraction and Synthesis Screen

3.6.2.2 Production: In this screen, the production process used to produce each part is specified. The production tree displays the product parts and subassemblies. The user then selects a part or subassembly from the tree, upon which information about that part or subassembly is retrieved from the database. The user is then prompted to select the production process form a given list of processes. The use of process materials is also considered where the user can input different materials used and specify their weights. The user also specifies the yield rate for that particular process and defines the allocation of energy and environmental burdens either to the product only, or by mass ratio of product to co-product, or by the price market or it could be user defined. The database contains information on eight production processes: Extrusion, Injection, Thermoforming, Stamping, Milling, turning, Semiconductor processing, and Glass forming. The database quantifies mainly materials, energy and environmental burdens associated with those processes. This information is used to help evaluate the total lifecycle energy, materials and environmental burdens of the product. Figure 3.16 displays the production screen.



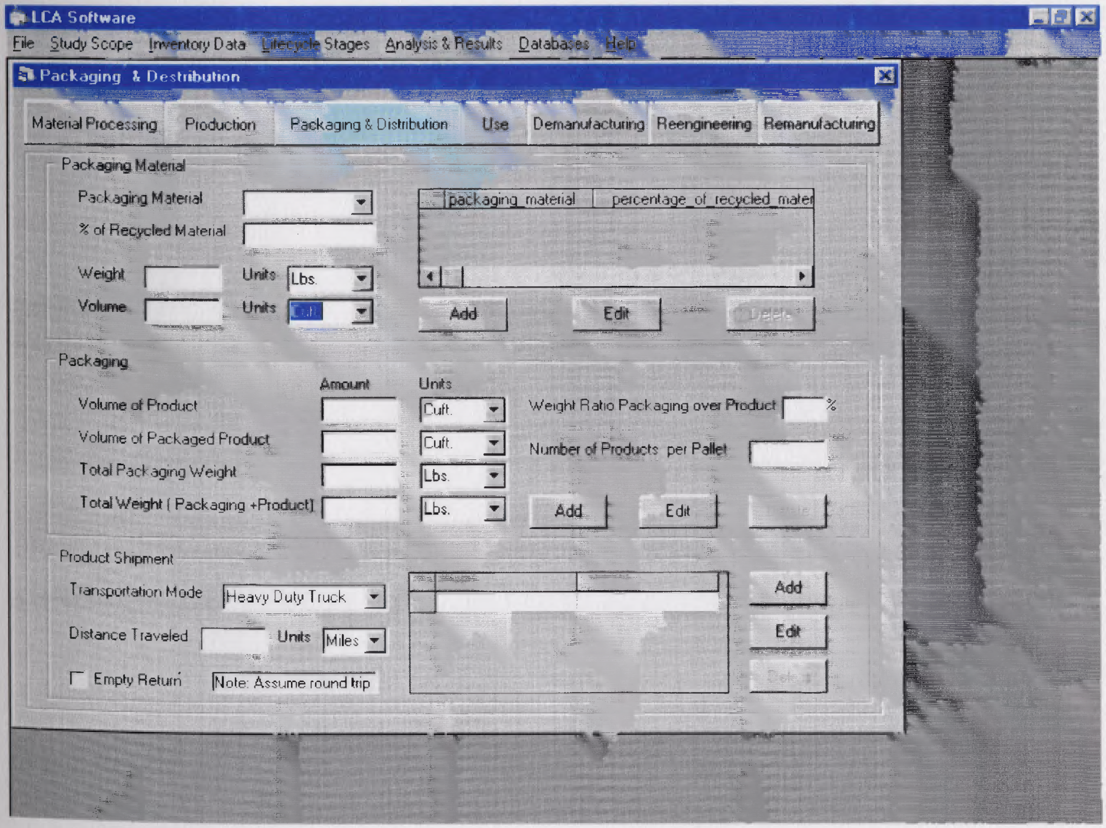
Telephone 1997
- Hand Set
  - Cord
  - Speaker gasket
  - Outside Handle
  - Inside Handle
  - Wiring
  - Foam
  - Speaker
  - Microphone Cover
  - Microphone
- Top Cover
  - Cover
  - Number Keys
  - Function Keys
  - 3 Buttons
  - Hook
  - Hook Spring
  - Plastic Cover
  - Paper
  - Clear Indicators
- Base

Materials: Rubber
Quantity: 1
Production Process: Thermoforming
Weight: 5.07
Yield Rate: 95
☑ Process Materials

How do you want to allocate enery and enviromental burdens to primary products and co-products?
Allocate to main product only

Figure 3.16 Production Stage Screen

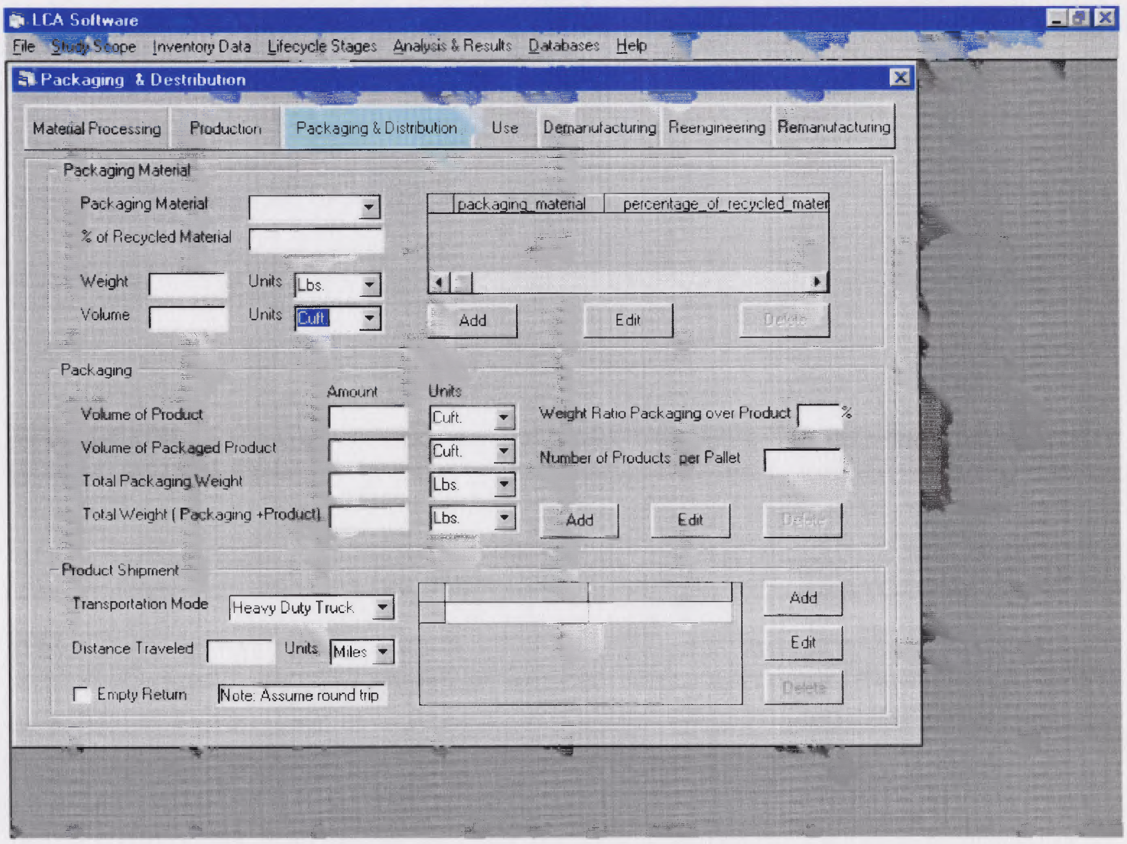
3.6.2.3 Packaging and Distribution: Packaging and distribution is part of the lifecycle of a product, and information on the packaging material and transportation of the products is considered essential. The packaging and distribution screen allows the user to input such specific information on the packaging material and transportation. The user specifies the packaging material used for the product, the percent of recycled material, weight, and volume. Information on the volume of the product, total packaging weight and other information are also quantified. The software also allows the user to specify the mode of transportation and the distance traveled, assuming distance traveled to be roundtrip. Figure 3.17 displays the screen for the packaging and distribution stage.



Weight Units: Lbs.
Volume Units: Cuft
Volume of Product: Cuft.
Volume of Packaged Product: Cuft.
Total Packaging Weight: Lbs.
Total Weight (Packaging +Product): Lbs.
Transportation Mode: Heavy Duty Truck
Distance Traveled Units: Miles
Note: Assume round trip

Figure 3.17 Packaging and Distribution Screen

3.6.2.4 Use: This stage relates to the energy consumed by the product while in different modes. These modes are divided into the active mode, idle mode, power save mode and off mode. In each mode the product consumes a certain amount of energy that must be entered into this screen. The user also inputs the amount of time the product is in each mode. The total energy consumption of the product during its use stage is then calculated by summing the energy consumption at each mode and multiplying the answer by the expected life use of the product. Figure 3.18 displays the use stage screen.



Weight Units: Lbs.
Volume Units: Cuft
Volume of Product: Cuft.
Volume of Packaged Product: Cuft.
Total Packaging Weight: Lbs.
Total Weight (Packaging +Product): Lbs.
Transportation Mode: Heavy Duty Truck
Distance Traveled Units: Miles
Note: Assume round trip

Figure 3.18 Use Stage Screen

3.6.2.5 Demanufacturing: Demanufacturing is an important stage of the product lifecycle, since the end fate of the various parts and subassemblies is determined here. The first stage in analyzing the demanufacturing process is to explain the facility structure used in terms of the size of the facility, yearly energy consumption, cost of energy, the volume of products handled per year and, the total disassembly time of the product. The assumption made for demanufacturing is that it occurs manually. The user then chooses the end fate options for the parts and subassemblies. A list of end fate options is provided for the user to choose from, in which he/she assigns the end fate for each part and subassembly. The end fate options provided are: reuse product, remanufacture parts and subassemblies, recover basic material, or remaining carcass. As the user specifies and selects the end fate option for each part or subassembly, that part or subassembly is deleted from the product tree automatically when its end fate is determined. Figure 3.19 displays the demanufacturing screen, and shows the recovering of basic materials process.

- Reuse Product

  If the end fate chosen for the product is reuse, then product must have undergone a test that evaluated its functionality. The user must then input the passing rate of the test and the reselling price of the product. If the product fails the test, the user then clicks on the " demanufacture product" button, where other end fate options are specified for the product.

- Remanufacture Parts and Subassemblies

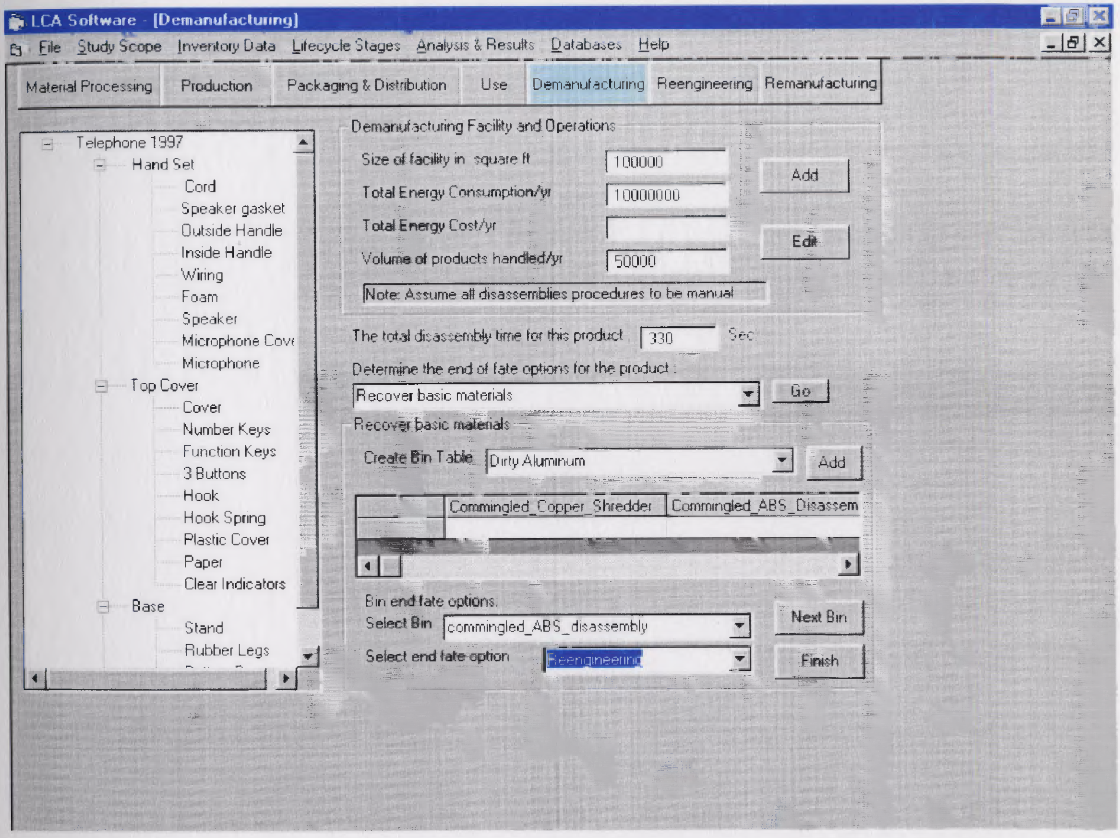
  If the user decides that the optimum value obtained from a part or subassembly is through remanufacturing that part, then the user must add those parts and subassemblies into the table provided.

- Recover Basic Material

  Material can be recovered from parts and subassemblies by either: disassembly or shredding. The user creates a custom bin table from a preselected list. This list includes the various recovered materials, e.g., pure aluminum, commingled aluminum, and also includes the recovery method: disassembly or shredding. For example, if commingled plastic is part of the material in the product, then the bin table will include: commingled plastic–disassembly and commingled plastic–shredding. The same method applies to all other materials. The user has to input the parts and subassemblies to the various bins displayed. The user then specifies the four end fate options for each bin, which are: Reengineering, Waste to Energy, Smelting, and Landfilling. Having this structure assists the demanufacturers in specifying the number of various bins they need to allocate for this product.

- Remaining carcass

  The remaining parts and subassemblies "fluff", that do not apply to the above end fate options are entered in this stage. The user can either select all the remaining parts and subassemblies in the product tree or can select them individually. The options available to the user are either to smelter, waste to recovery, or landfill the "fluff".



Size of facility in square ft: 100000

Total Energy Consumption/yr: 10000000

Total Energy Cost/yr:

Volume of products handled/yr: 50000

Note: Assume all disassemblies procedures to be manual

The total disassembly time for this product: 330 Sec

Determine the end of fate options for the product: Recover basic materials

Create Bin Table: Dirty Aluminum

	Commingled_Copper_Shredder	Commingled_ABS_Disassem

Bin end fate options.

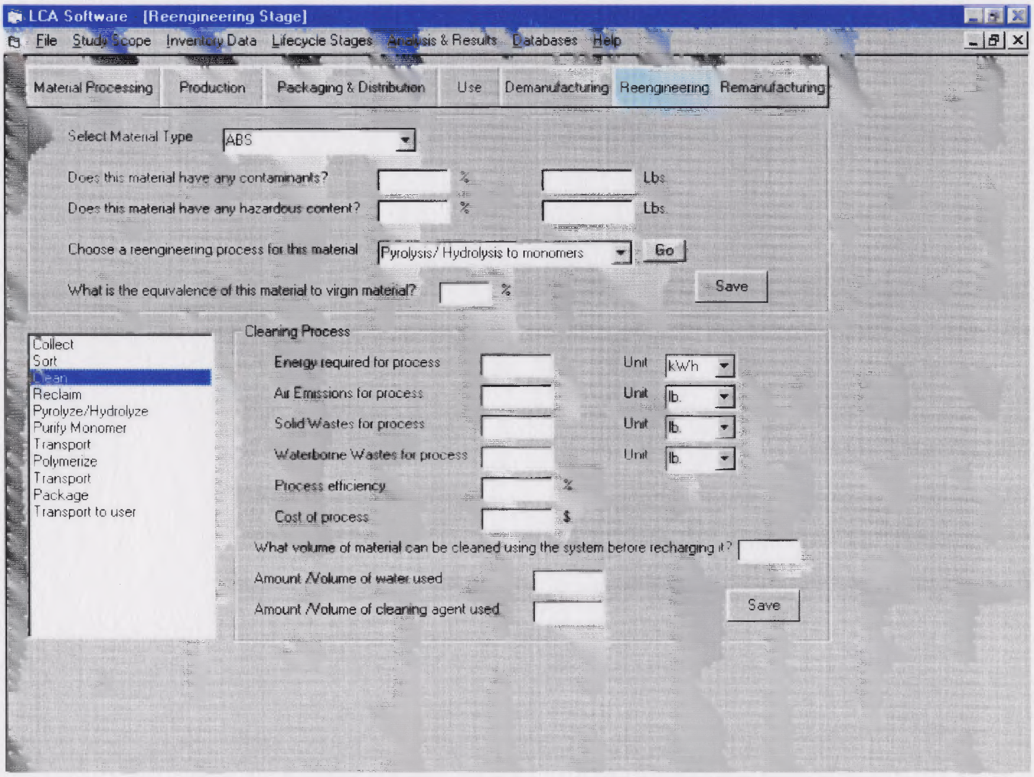
Select Bin: commingled_ABS_disassembly

Select end fate option: Reengineering

Figure 3.19 Demanufacturing Screen, Illustrating Recovering of Basic Materials

3.6.2.6 Reengineering: This screen aims at specifying the process required to reengineer selected materials, simultaneously capturing the materials, energy and environmental burdens information at each step of the reengineering process. Six different reengineering processes were identified for the materials: Smelting, Compatiblization, Pyrolysis to fuels, Pyrolysis/ Hydrolysis to monomers, and finally, Shredding for metals.

For each of the reengineering processes, the main questions that are addressed are: The environmental burdens, energy requirements, material flows, additional process materials, and cost of the process. Figure 3.20 displays a screen detailing the cleaning step in the reprocessing of materials. The user selects a material for reengineering, after which the percentage of hazardous material or contaminants in the material is specified by weight. The user then selects the reengineering process from a given list. An interactive tree appears, displaying the step by step procedure for the selected process. The user then selects each step in the process, upon which a window frame pops similar to the cleaning process window frame in Figure 3.20. Here, the user inputs information on energy requirements for the cleaning process, environmental burdens associated with the process and a list of others. The same procedure is repeated for all the materials to be reengineered.



Select Material Type: ABS

Choose a reengineering process for this material: Pyrolysis/ Hydrolysis to monomers

Energy required for process — Unit: kWh

Air Emissions for process — Unit: lb.

Solid Wastes for process — Unit: lb.

Waterborne Wastes for process — Unit: lb.

Figure 3.20 Reengineering Screen, Illustrating the Cleaning Process

3.6.2.7 Remanufacturing: This screen describes steps that parts and subassemblies undergo for remanufacturing. Similarly, the main data to be quantified is material flow, energy consumption, and environmental burdens. The first step for the user is to describe the remanufacturing facility, where this description is similar to that of the demanufacturing facility. The user then selects the part or subassembly for remanufacturing from a given list. This list is taken from the demanufacturing stage, where the user selected earlier the parts and subassemblies for remanufacturing. The step by step remanufacturing process is shown in an interactive box at the left hand side, where the user selects each step and inputs the required data on the opposite window frame. Figure 3.21 presents the remanufacturing screen.

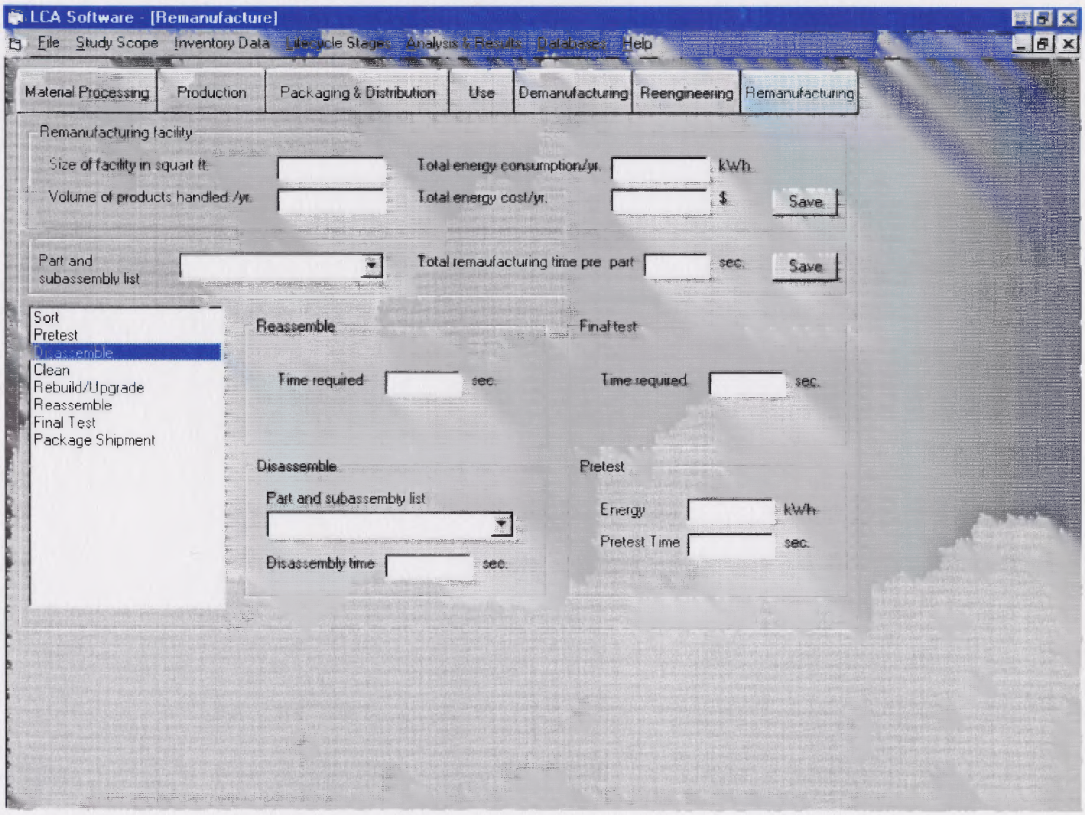


Figure 3.21 Remanufacturing Screen

CHAPTER 4

TELEPHONE CASE STUDY

4.1 Introduction

Four generations of low-end business telephones will be the focus of the DFE evaluation. This product was selected because of the availability of multiple generations of the product of which the most recent was designed using current DFE guidelines; and, the product has a reasonable level of complexity balanced with product simplicity. Phones designed and manufactured in 1965, 1978, 1989 and 1997 are already available for study. The research methodology is straight forward: Initially, an LCA and demanufacturing analysis was performed on each of the first three generations to determine technology and non-DFE design trends. This information was used to forecast the progression to a 1997 non-DFE-designed phone. These trends represent the environment performance of the business telephone without explicit DFE consideration but fully accounting for the advancements in enabling technologies and use of standard design objectives. By overlaying comparable information generated by analyzing the 1997 DFE-designed phone, the true impact of DFE on the product becomes apparent. For example, if no significant difference was found between the non-DFE projection and the DFE-designed product for a specific characteristic, then any environmental improvements associated with the new design is attributable to causes other than DFE. Without examining these baseline technology trends, the direct impact of DFE on the product lifecycle can not be determined.

4.2 System Boundaries

The inventory analysis generally includes energy consumption, waste emissions and process material requirements at each stage in the production of any raw material. In this study, process materials and energy required for the production of the materials understudy will be considered to be inside the system boundary. Energy consumption during the production, use, and recovery of the telephones will also be quantified. The environmental burdens associated with the production, use, and recovery were unavailable to be included in the study. Materials used to fabricate fundamental equipment and tools as well as those indirectly consumed during the production and operation of a transportation vehicle will remain outside the boundary. Finally, assumptions and adjustments were necessary to simplify the analysis. Materials considered for this study had to meet a threshold of being more than 2 % by weight of the product or else they were excluded from the study, because their impact was considered to be negligible. Generally the limits placed on the breadth and depth of LCA analysis can be classified as restriction on (1) the lifecycle boundaries of a system or (2) the actual information collected, whether it is limited in its specificity or number of inventory categories. [14]

4.3 Demanufacturing Analysis

A complete disassembly of the four telephones was conducted. The disassembly process was recorded by photo images of the various steps and a time study also was performed simultaneously. The different parts and components of the telephone were identified and recovered by part name, functionality and material composition. A record was kept on the number and different types of fasteners used. Finally parts were weighed using a balance with an accuracy of +/- 0.01g, and each part was then classified under its functional subassembly. The result of the disassembly process is captured in the components inventory list, and, the step-by-step procedure sheet contains the time required for each process and the tools used in performing the disassembly.

4.3.1 Disassembly Procedure Sheet

The key behind successfully analyzing the results of the demanufacturing process is documentation. A disassembly procedure sheet was created and used to document step-by-step, the disassembly of a product. The disassembly sheet is divided into four columns:

- The subassembly column, referring to the subassembly which has been taken apart
- The tool column, referring to the tools necessary to perform the disassembly
- The procedure column, which informs the operator how to disassemble the part or subassembly
- Finally, the time column, which is an estimate of the time required to disassemble the part or subassembly

These disassembly procedure sheets provide data to develop an operational disassembly process plan. The disassembly sheet describes the end-of-life option for the components, parts, and subassemblies to capture the maximum value from the product at the end of its life. The sheet can be distributed amongst disassembly operators, which will make them more familiar with the product and the disassembly procedure. It will also reduce their learning curve for disassembling the product, which will minimize the disassembly time. On a larger scale, this sheet could be inputted into a database, and utilized by an automated demanufacturing facility, by feeding the machines on how and what parts to disassemble. For this study, the total disassembly time is used as a metric to evaluate the improvement in the disassembly time over the four generations.

4.3.1.1 Disassembly Procedure for the 1997 Telephone: In this section, the detailed disassembly procedures and the tools used to demanufacture the 1997 telephone will be illustrated. For each of the four phones, a disassembly procedure sheet was created similar to Table 4.1, which illustrates the disassembly procedure for the 1997 phone. A note to be made is, the disassembly of all the phones took place in a laboratory environment. Therefore, the disassembly time values may not reflect the actual time taken to disassemble the phone in a demanufacturing facility, but the purpose here is to illustrate the methods used for documenting the disassembly of products and to use this information for our purposes not absolute performance.

The first step in disassembling this phone was to unhook the handset cord and snap off the stand attached to the bottom base. Figure 4.1 displays the bottom base and the stand separated. The next step was to disassemble the unit, separating the base from the top. There are two screws and four snap fits located on each corner of the unit. After unscrewing the two screws using a medium-sized straight blade screwdriver, the snap fits must be pressed and removed two at a time. This process will separate the top and bottom bases of the unit. The bottom base has no extra parts attached to it, all the parts and subassemblies are connected to the top base.

Table 4.1 Disassembly Procedure Sheet for the 1997 Telephone

Disassembly Procedure (1997 Phone)

Subassembly	Tool	Procedure	Time(sec)
Base			
	Hand	Remove handset assembly, Cord.	5
	Hand	Snap off stand	10
	Tool 1	2 screws & 4 tabs- Separate base From Top	60
Base Top			
	Tool 1	Remove function label & handset hook	10
	Hand	Remove speaker foam	5
	Hand	Remove circuit board & Speaker	2
	Hand	Remove Keypad	2
	Hand	Remove Keys, hook & latch spring, clear indicators	30
Handset			
	Tool 1&2	Saw Covers apart & Pry	180
	Hand	Remove speaker & rubber housing	5
	Hand	Remove mic. & foam	4
			313
			5 Min 12 Sec

Tools Used:

1- Screw driver, medium size, straight blade

2- Hack saw

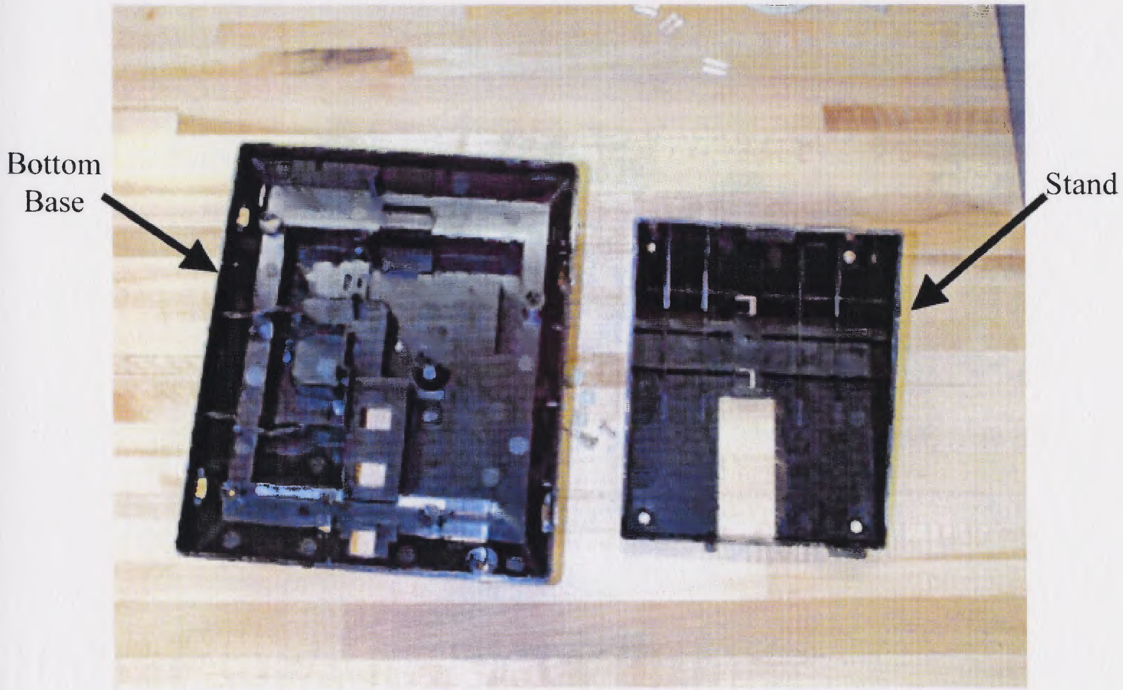


Figure 4.1 Bottom Base and Stand for the 1997 Phone

Due to the simplified design of the internal unit, the remaining components which are the circuit board, speaker, keypad, keys, hook, latch spring and clear indicators, can be removed easily without tools. With this, the unit is completely disassembled. Figure 4.2 illustrates the top cover of the unit with the circuit board and other components.

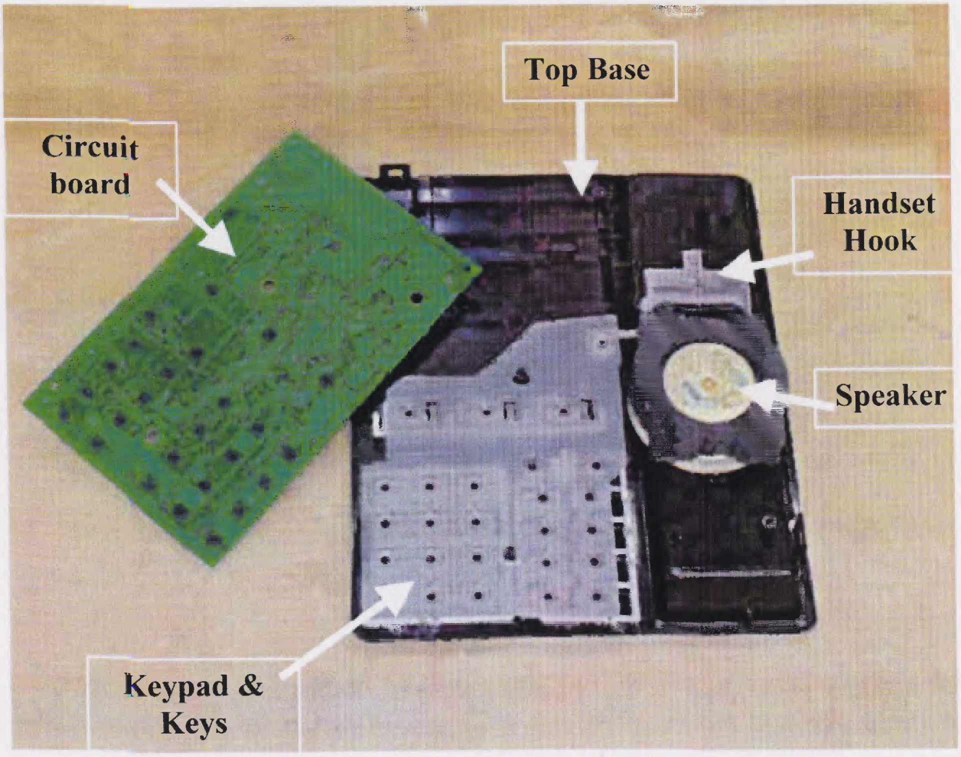


Figure 4.2 Top Base, Circuit Board and other Components of the 1997 Phone

The subassembly that remains to be disassembled is the handset subassembly. The handset covers are attached by snap-fits, and strong adhesive. Due to this strong adhesive, a hack saw well be used and the disassembly of the handset will be considered a destructive one. Separating the handset covers took an extensive amount of time, approximately three minutes. The remaining parts, the speaker, rubber housing, microphone and foam. Figure 4.3 displays the handset disassembled, showing the various inner components. Similar disassembly procedures for the other telephone generations are shown in Appendix B.

Figure 4.3 Handset Subassembly of the 1997 Telephone

4.3.2 Inventory Tables

As the disassembly process is progressing, it is important to categorize and separate the different subassemblies, especially with more complex products. An inventory table is necessary as it provides a detailed list of all the parts in the product, quantifying for each part the quantity, function, color, weight, material type, number of screws, number of snap-fits and market value. Following is a detailed description of each column in the inventory table.

- The first two columns identify the names of the various sub-assemblies and parts in the telephone. This identification helps the disassembly workers to understand the disassembly operation.
- The third column refers to the quantity. In this column the quantity of each component is indicated. With few exceptions everything is just a single quantity.
- The fourth column refers to the function of each part.
- The fifth column refers to the color. This assists in visually differentiating certain parts, and sorts out parts made from the same material but with different colors, as to eliminate contamination, if the material is to be recycled.
- The sixth column consists of the 'weight' of these sub-assemblies and parts. By knowing the weights of the parts, the part which has the most weight, can be identified and action can be taken to reduce it. The weights indicated here, are the total weights and not of just one quantity. Therefore, if some parts have a quantity of eight, then the weight indicated is for all eight parts.
- The seventh column refers to materials. This column characterizes the sub-assemblies and parts identified in the earlier step. The type of material of which the sub-assembly

or the part is manufactured is identified. This identification is particularly important in deciding the fate categories of these sub-assemblies and parts.

- The eighth and ninth columns refer to the number of screws and snap-fits attached to each part. This helps in analyzing the ease of disassembling the products.
- Finally, the tenth column refers to the current market value of the part or subassembly, which helps in identifying the optimal end-of-life fate for the part.

Table 4.2 shows the inventory table of the 1997 telephone. Detailed Inventory tables for the other telephone generations are shown in Appendix B.

Table 4.2 Inventory Table of the 1997 Telephone

Subassembly	Part	Quantity	Function	Color	Weight(g)	Material	No. of Screws	No. of Snap fits
Handset								
	cord	1	transmit signal	black	40.28	plastic / copper	0	2
	spkr. Gasket	1	block debris	black	5.07	rubber	0	0
	outside handle	1	house spkr/Mic..	black	53.54	ABS	0	0
	inside handle	1	house spkr/Mic..	black	56.64	ABS	0	6
	wiring	1	transmit signal	multi	2.86	plastic, copper	0	0
	foam	1	sound enhancer/cushioning	Grey	0.12	foam	0	0
	spkr	1	transmit voice	tan/brass	35.31	steel/plastic	0	0
	Mic Cover	1	Protects Mic	white	0.71	rubber	0	0
	microphone	1	transmit voice	white	0.85	Aluminum	0	0
Top Cover								
	Cover	1	house internal parts	black	187.96	ABS	0	0
	Number keys	1	function buttons	Grey	17.22	plastic	0	0
	function keys	1	function buttons	Grey/ black/ red	10.12	plastic	0	0
	3 buttons	1	function buttons	Grey	2.95	plastic	0	0
	hook	1	turn phone "on"	Grey	4.85	plastic	0	2
	hook spring	1	tension for hook	silver	0.41	steel	0	0
	plastic cover	1	cover information	clear	9.7	plastic	0	0
	paper	1	display information	white	0.6	paper	0	0
	clear indicators	4	indicate extensions	Clear	1	plastic	0	0

Table 4.2 (continued)

Subassembly	Part	Quantity	Function	Color	Weight(g)	Material	No. of Screws	No. of Snap fits
Base								
	Stand	1	support phone/ upright display	black	145.61	ABS	0	3
	rubber legs	4	support phone	white	1.12	rubber	0	0
	bottom base	1	house internal parts/ support phone	black	263.65	ABS	5	4
Internal Circuit Board								
	Circuit board	1	electronic functions	mix	110.83	circuit board	3	0
	Speaker	1	Transmits voice	Mix	110.79	steel/plastic	0	0
	Speaker Gasket	1	block debris	white	2.05	rubber	0	0
	speaker foam	1	cushion speaker	Grey	1.29	plastic (foam)	0	0
	keypad	1	makes contact with circuit board	white/ black	19.55	rubber	0	0
Total		32			1085.08		8	17

4.3.3 Disassembly Effort Index (DEI) for 1997 Phone

As mentioned earlier in chapter 2, DEI is a metric that assesses certain parameters associated with disassembling a product and quantifies them on a linear scale. DEI has six main parameters: Time, Accessibility, Tools, Part-Hold, Force, and Instructions. These six parameters were integrated with another three: Number of different material, Number of different fasteners, and Material type stamping to form what's called Revalorization. Revalorization expands DEI and provides a more detailed analysis of ease of disassembly for recovering materials, which is quantified by the parameters: number of different materials and material type stamping.

The weights assigned to each parameter in the DEI, reflect the relative importance that each demanufacturer assumes for that parameter. These weights can be modified according to the needs of each user. Following is a description of how the different parameter values were extracted for the 1997 phone.

- Number of different materials

  Five materials were found in this phone: ABS, Rubber, Steel, Aluminum and Copper. Based on the revalorization scale, if a product is composed of five materials, then the linear score assigned is 12.

- Number of different fasteners

  Three different fasteners were identified in this phone: Screws, Snap-fits, and Adhesives. Converting this to a linear scale, the assigned score was 15.

- Material Marking

  This scale was developed based on the percentage of plastic parts stamped as per the ISO identification standards. The 1997 DFE designed phone was the only phone that had ISO material stamping on its plastic parts. The percentage of plastic parts stamped was 20%, converted through the DEI scale to a score of 3.

- Time

  The time required to completely disassemble the 1997 phone was 5 minutes and 12 seconds, of which 3 minutes was required to disassemble the handset subassembly due to the use of adhesives and snap-fits, instead of screws for fastening the covers. The DEI score assigned was 7.5.

- Tools

  Tools needed for disassembling the 1997 phone were simple, mainly a medium sized straight blade screwdriver, hands, and a hack saw that was used to separate the handset covers. The linear score assigned to this parameter was 5.

- Accessibility

  Accessibility to the various subassemblies of the phone was easy, and all the fasteners had a z-axis accessibility, which gave this parameter a linear score of 6.

- Force

  The force required for disassembly and unfastening was an axial force, which had a linear score of 4.5.

- Part-Hold

  Hands were the only fixture use to hold the parts as they were disassembled, which converted to the linear scale gets a score of 2.5.

- Instructions

  No instructions were necessary for disassembling this phone. The disassembly process was easy and straightforward. The score assigned for this parameter was 3.

Summing up the points for all the parameters, the final DEI score for this phone was 58.5, which was the highest compared to the other three telephone generations. A high score corresponds to better performance. Figure 4.4 displays the DEI for the 1997 phone. The scores for the other phones were 55.3, 44.7 and 25.5 for the 1989, 1978, and 1965 phones respectively. Appendix B displays the DEI for those phones.

1) # of different Mat.	>7	6	5	4	3	2	POINTS
POINTS	0	6	12	18	24	30	12
2) # of diff. Fasteners	<6	5	4	3	2	1	POINTS
POINTS	0	5	10	15	20	25	15
3) Mat. Marking	0%	20%	40%	60%	80%	100%	POINTS
POINTS	0	3	6	9	12	15	3
4) Time (MIN)	30	25	20	15	10	5	POINTS
POINTS	1.25	2.5	3.75	5	6.25	7.5	7.5
5) Tools	Unavailable	Special	OEM	Mechanic	Simple	No-Tools	POINTS
POINTS	1	2	3	4	5	6	5
6) Access	(Not-Visible)	Complex-Motion	Dual-Axis	(≥ 4" Deep-Head)	X-Y Axis	Z- Axis	POINTS
POINTS	1	2	3	4	5	6	6
7) Force	Cutting	High-Impact	Low-Impact	Leverage	Torsional	Axial	POINTS
POINTS	0.75	1.5	2.25	3	3.75	4.5	4.5
8)Part -Hold	(Automated ......)		Complex-Fixture	Fixture-Necessary	Two-Hand	No-Hold	POINTS
POINTS	0.5	1	1.5	2	2.5	3	2.5
9)Instruction	Special-Classes	Whole-Day	Half-Day	≤ 5 - 30 min	Simple	None	POINTS
POINTS	0.5	1	1.5	2	2.5	3	3

SCORE : 58.5

Notes:
No of different materials: ABS, Rubber, Aluminum, Copper and Steel.
Fasteners: Snap Fits, Screws and adhesives.

Figure 4.4 DEI for the 1997 Telephone

4.3.4 RFBD for 1997 Telephone

A RFBD was generated for each of the four telephones. In this section, the 1997 telephone RFBD will be described in detail. Figure 4.5 illustrates the RFBD for the 1997 telephone. From the diagram, one could see that there are three major stages for completely disassembling the phone. The first stage is separating the handset subassembly and stand simultaneously. The second stage involves separating the units top and bottom bases. Finally, the third stage, which is the removal of the internal components in the unit. From the material variety shown in the RFBD, it can be concluded that five bins are required to separate the parts and subassemblies into the different material compositions. Based on the results obtained from the RFBD, designers and demanufacturers can analyze and conclude different scenarios for the End-of-Life options. Utilizing the RFBD and the disassembly procedure for the 1997 telephone, the following analysis was concluded:

- 5 major sort bins are required for separating the parts into the following grades: ABS, commingled plastics, PCB's, commingled metals and fluff.
- The majority of the components in this phone can be refurbished and reused into the same line of production or into similar products.
- Demanufacturer can perform a partial disassembly to extract valuable parts or subassemblies, instead of disassembling the entire telephone.

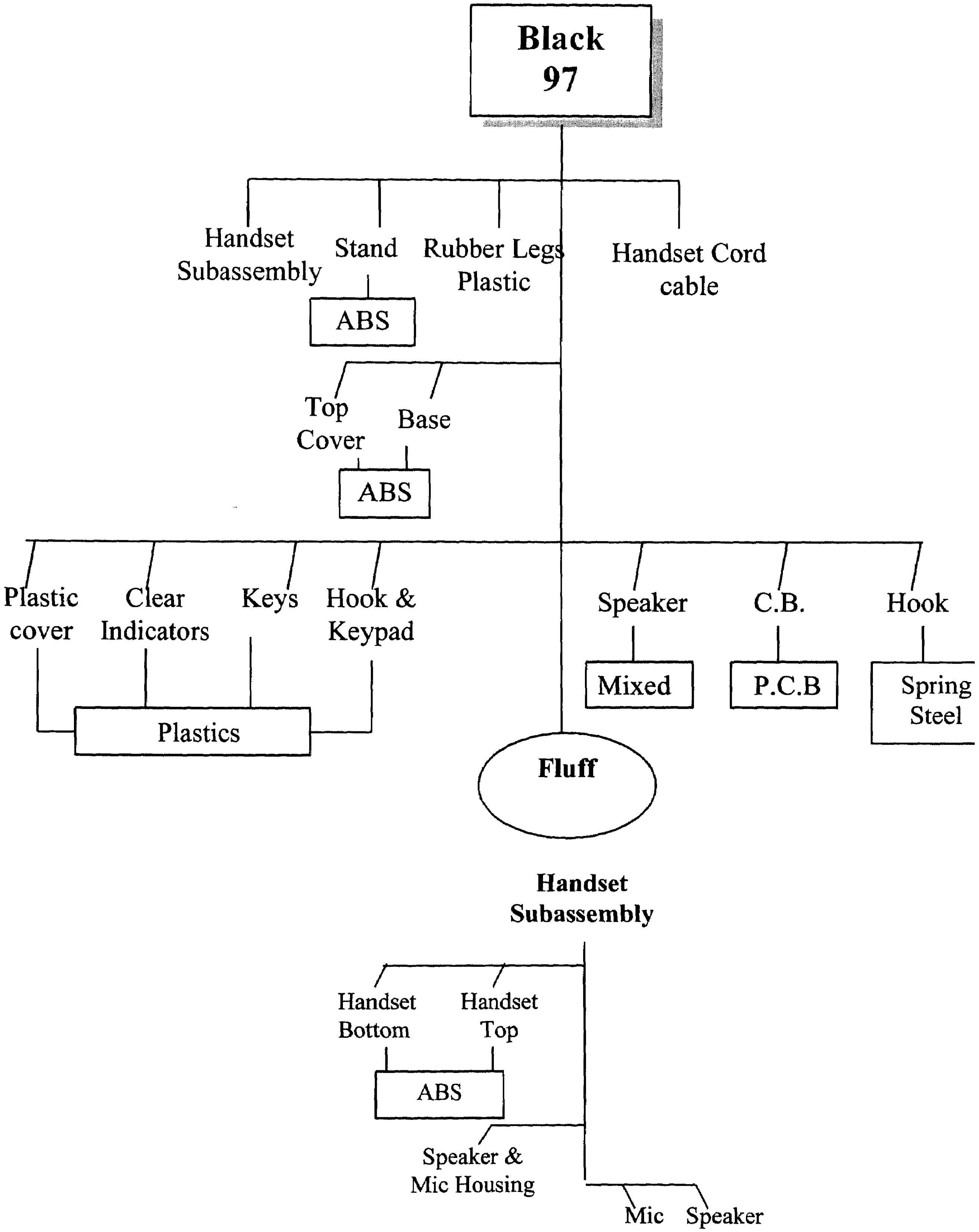


Figure 4.5 Reverse Fishbone Diagram for 1997 Telephone

4.3.5 Disassembly Comparison

This section compares the disassembly of the four telephones, detailing the major obstacles faced if any. Advancements in the technology of electronic products and components had a huge impact on the noticeable changes in the design of the telephones. Table 4.3 highlights the comparison between the telephones as a result of disassembly.

Table 4.3 Disassembly Comparison of the Telephones

Telephones	Number of screws	Number of snap-fits	Total No. of Fasteners	Number of parts	Time (Sec)	Disassembly Index (DEI)	Comments
1965	140	19	159	165	1902	62	Extensive use of screws and rivets and the large number of parts and their complexity increased the disassembly time and the ease of disassembly.
1978	68	41	109	165	1640	71	Disassembly time reduced as subassemblies are more easily accessible. % of plastic used increased by 30%, while percentage of Metals used decreased by 30 %
1989	12	12	24	43	354	93	Enormous change in design, # of parts reduced by 74% compared to 1965. No problems faced in disassembly process
1997	8	17	25	32	133	94	Handset disassembly time > disassembly time for the rest of the phone, because of use of strong adhesives and snap-fits instead of screws.

Notes:
* Disassembly index includes: Time, Tools, Accessibility, Force, Part-hold, and Instructions. The higher the DEI, the better the improvement.
* Disassembly time for 1997 telephone excludes the handset disassembly which is 180 sec.

- **1965 Telephone**

The time required to disassemble this phone, 32 minutes and 15 seconds, was the largest among all the telephones. Many variables had an affect on the disassembly time. The complexity of the parts, the accessibility to parts and subassemblies, and the fastening method all contributed to the long disassembly time. For example, the wiring harness had 48 leads connected to the board with screws. The time required to separate the wiring harness from the board was approximately 3 minutes and 40 seconds. The time required to completely disassemble the " Line select subassembly" was the longest, approximately 15 minutes, accounting to half of the time required to disassemble the whole telephone. This was due to the large number of screws, the different fasteners used, the complexity of the design, large number of parts used, and the soldering of the joints.

- **1978 Telephone**

The major differences noticed when comparing this phone to the 1965 phone was the use of more circuit boards. Even though some subassemblies of the 1965 phone were replaced with newer technologies, such as the ringer subassembly that was replaced by a speaker, the number of parts did not change. Parts were more accessible than the 1965 telephone parts, as they were less complex. Disassembly time improved due to the large number of parts used in the subassemblies. The keypad subassembly, for example, remained the same with negligible changes over the years. Also, percentage of plastics used increased by 30%, mainly in the covers, while the percentage of metals used decreased by 30%.

- **1989 Telephone**

This telephone showed a remarkable change over the 1978 telephone. Technology advancement in electronics made the telephone solely dependent on one major part, the circuit board, which replaced all the mechanical parts and subassemblies used in previous designs. This change reduced the number of parts by more than 70%, disassembly time was reduced from 30 minutes to 6 minutes, and generally, the disassembly process became much easier due to less design complexity.

- **1997 Telephone**

This telephone was designed using the state-of-the-art DFE guidelines. Improvements over the 1989 telephone are negligible and in some cases, the 1989 telephone out performed the new design. This could be mainly noticed in the handset subassembly. The 1989 telephone handset was fastened with 2 screws and snap-fits, which required minimum effort for disassembly, while the 1997 telephone handset was fastened using a strong adhesive and snap-fits. Disassembling the later handset required a saw and took approximately 3 minutes to take apart! On the other hand, the keypad subassembly improved in this phone by reducing the number of parts to three by integrating the keys into one unit instead of separate parts, which reduces both assembly and disassembly times.

CHAPTER 5

DFE GUIDELINE ASSESSMENT AND TREND ANALYSIS

5.1 Introduction

A lifecycle assessment (LCA) and demanufacturing analysis were performed on each of the first three generations to determine various technology and non-DFE trends. This information was used to forecast the progression to a 1997 non-DFE-designed phone. By overlaying comparable information generated by analyzing the 1997 DFE-designed phone, the true impact of DFE on the product becomes apparent. For example, if no significant difference was found between the non-DFE projection and the DFE-designed product for a specific characteristic, then any environmental improvement associated with the new design is attributable to causes other than DFE guidelines. Relevant characteristics and metrics such as, raw material and energy depletion, environmental burdens, disassembly complexity, demanufacturability and resource productivity have been utilized to analyze the environmental performance of the telephones.

Various performance metrics and assessment technologies are needed to evaluate the environmental improvements in products over the years. Techniques such as the Eco-Compass, developed at Dow Europe, are used to compare the various generations. The Eco-compass has six dimensions that quantify significant environmental issues: mass intensity, energy intensity, health & environmental potential risk, resource conservation, revalorization and service extension. Resource productivity, as proposed by Sony, is another comparison tool. The measure attempts to quantify economic value added related to consumption of material and energy resources. To integrate LCA with these metrics, the multi-lifecycle analysis tool has been developed. Using a database of materials, processes and product information, the software generates results and reports, utilizing various calculation engines, which help in assessing environmental impacts and product improvement.

5.2 DFE Guideline Assessment

As mentioned earlier in chapter 3, DFE guidelines were divided into five major categories: Environmental burdens, material conservation, energy conservation, service extension and demanufacturing. This section analyzes the effectiveness and the true impact of the DFE guidelines on each of the metrics quantified. The general equation, $\ln Y = aX + b$ ($Y=e^{ax+b}$), applied to the data from the previous three telephone generations, was used to estimate the values of the 1997 telephone for the different metrics used. Using such a uniform equation guarantees consistency in the analysis of results.

5.2.1 Environmental Burdens

The following analysis of air emissions, waterborne effluents and solid wastes is for the production of the feedstock materials and the emissions generated from the power sources used during this stage. For the other lifecycle stages: production, use and recovery, the only environmental burdens included are those generated from the power sources used in those stages, which is assumed to be electric energy. The US grid mix for 1990 was used as the default electric power mix, where the mix is composed of 54.5% coal, 3.9% oil, 9.3% gas, 21.7% nuclear, and 10.2 % hydroelectricity [29]. The environmental burdens generated from plastics processing was based on the data presented in chapter 3, while for metals processing, the data was extracted from D. Badwe's masters thesis [14]. The environmental data generated from the power sources, which are mainly natural gas and electric, were from S. Young's Ph.D. Dissertation [29]. Appendix C displays the data and the method followed for calculating air emissions, waterborne effluents, and solid wastes for each of the four telephone generations.

- *DFE Guideline: Has manufacturing gaseous emissions been minimized to the greatest extent possible?*

Following is the analysis for air emissions over the product lifecycle: Materials processing, production, use, and recovery.

- **Materials Processing**

The values quantified in this stage, are the summation of air emissions generated from ABS production, metals production (steel, aluminum, and copper), and from the power sources used in materials processing. For the feedstock material, air emissions was measured based on the amount of each material in the telephone, while the power source was measured based on the energy required for primary and secondary processing of the materials, whether it was natural gas or electric.

Figure 5.1 displays the materials processing air emissions of carbon monoxide (CO), nitrogen oxide (NO_x), particulate, and sulfur dioxide (SO_2) for the four telephones. Carbon monoxide emissions were reduced dramatically from the 1978 to the 1989 telephone, mainly due to the reduction in the quantity of aluminum used, which dropped from 62g to 0.93g in those years. Reductions in particulate emissions were attributable to the decrease in the use of aluminum and copper from 1965 to 1989, while SO_2 reduction was mainly due to reduction in the copper content used in the telephones. 50 grams of

SO_2 were emitted only from copper use in the 1965 telephone, and was reduced to 6.2 grams in the 1978 telephone, a reduction of more than 85%.

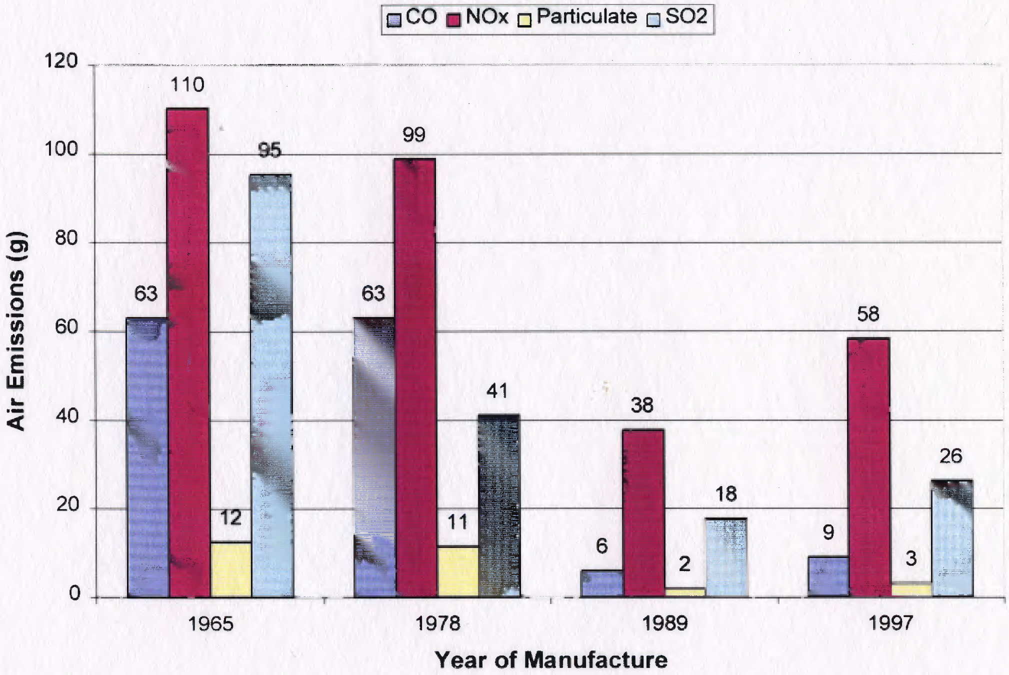


Figure 5.1 Air Emissions Generated from Materials Processing

Table 5.1 displays the extrapolated air emissions for the 1997 telephone, the equations used and the regression coefficient (r^2), for the elements displayed in the figure above. By comparing the actual air emissions from the 1997 telephone to the extrapolated ones, it is obvious that the actual values are higher by more than 40% over the extrapolated values. Moreover, all of these air emissions are higher for the 1997 telephone than for the 1989 telephones. Therefore, it can be concluded that DFE guidelines had no impact on improvements over this metric.

Table 5.1 Extrapolated Values of Air Emissions for Materials

Emissions	CO2 (g)	CO (g)	NOx (g)	SO2 (g)	Particulate (g)
Actual Value (1997)	15814.64	8.94	58.19	26.1	3.05
Extrapolated Value (1997)	8657.66	4.41	31.49	10.26	1.48
Percent Difference	45.3%	50.7%	45.9%	60.7%	51.5%
Equation	Ln y= -0.0429 X+ 10.439	Ln y= -0.0952 X + 4.531	Ln y= -0.0436 X+ 4.845	Ln y= -0.0703x + 4.5782	Ln y= -0.0752 X+ 2.8017
R2	0.7344	0.7076	0.7876	0.9975	0.7432

Carbon dioxide emissions were mainly emitted from the power source required for manufacturing of ABS plastic, which accounts for 60% of total CO_2 emissions, see Table C.10, appendix C. 30% was emitted from the power sources used for processing of metals, mainly aluminum manufacturing, see Table C.12, appendix C. Finally, 20% of the CO_2 emissions was from processing of feedstock metals, mainly steel and then aluminum, see Tables C.4 and C.5 respectively, appendix C. Figure 5.5 illustrates total CO_2 emissions for each stage of the product lifecycle. Appendix C describes the calculation method for the environmental burdens.

- **Production**

Air emissions considered in this stage were those generated from the power sources used during the production stage. The air emissions generated from use of the electric power source during production were calculated based on the MJ of energy used. Figure 5.2 displays some of the air emissions during the production stage. CO_2 had the highest impact on air emissions as shown in Table 5.2, which details the air emissions and solid wastes generated from use of electric power sources. The table also shows the extrapolated values for the 1997 telephone, the equations used and their regression coefficients, r^2. The reduction in CO_2 emissions over the years is mainly attributable to improvements in technology and processes. Despite the reduction over the first three generations, the actual values for the 1997 telephone were 30% more than the extrapolated value, and were essentially unchanged from the 1989 telephone. Therefore, DFE guidelines also had no impact on air emission reductions in this stage.

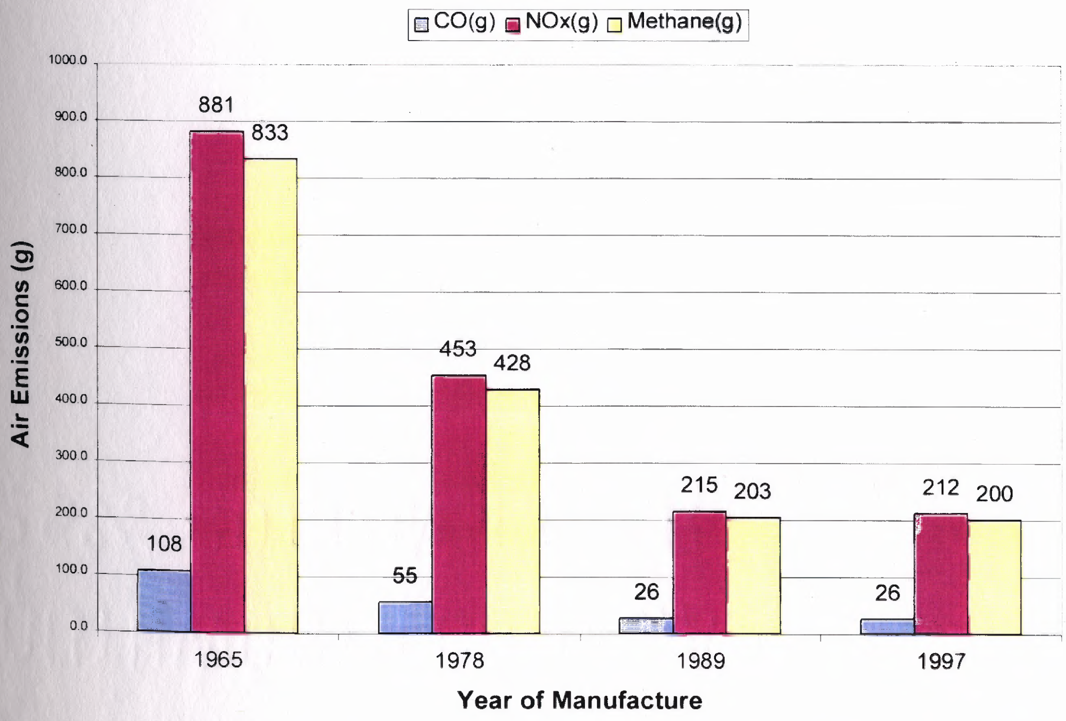


Figure 5.2 Air Emissions Generated from the Production Stage

Table 5.2 Environmental Burdens Generated from Production Stage

		Air Emissions				Solid Wastes
	Energy Electric (MJ)	CO2 (g)	CO(g)	NOx(g)	Methane(g)	(g)
1965	583	310342.2	107.9	881.1	832.9	50135.4
1978	300	159563.6	55.5	453.0	428.2	25777.3
1989	142	75795.7	26.3	215.2	203.4	12244.7
1997	140	74552.5	25.9	211.7	200.1	12043.9
Extrapolated Value (1997)		49168.08	17.054	139.63	132.01	7942.63
Percent Difference		34.0%	34.2%	34.0%	34.0%	34.1%
Equation		Ln y= - 0.0585 X+ 12.675	Ln y= - 0.0586 X+ 4.7116	Ln y= - 0.0585 X + 6.811	Ln y= - 0.0585 X + 6.755	Ln y= - 0.0585 X+ 10.852
R2		0.9935	0.9934	0.9935	0.9935	0.9935

- **Use stage**

Air emissions considered in this stage were those generated from the power sources used during the use stage. The air emissions generated from use of the electric power source during the use stage were calculated based on the MJ of energy consumed. Table 5.3 details the air emissions and solid wastes generated from use of electric power sources. The increase in CO_2 emissions over the years is due to higher energy consumption of the 1989 and 1997 telephones. Figure 5.3 displays the air emissions generated during the use stage for the four telephones. Refer to energy consumption during the use stage calculations on page 146 for more detailed analysis.

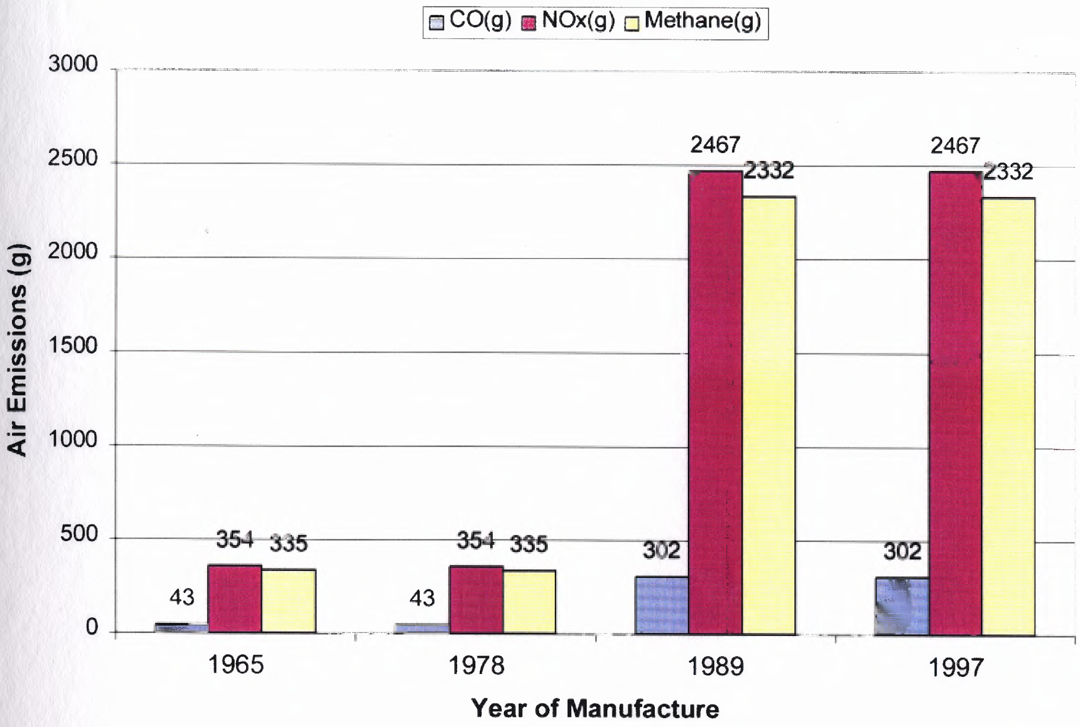


Figure 5.3 Air Emissions Generated from the Use Stage

Table 5.3 Environmental Burdens Generated from Production Stage

		Air Emissions				Solid Wastes
	Energy Electric (MJ)	CO2 (g)	CO(g)	NOx(g)	Methane(g)	(g)
1965	234	124714.55	43.35	354.08	334.70	20147.48
1978	234	124714.55	43.35	354.08	334.70	20147.48
1989	1631	868844.73	302.04	2466.74	2331.75	140360.77
1997	1631	868844.73	302.04	2466.74	2331.75	140360.77

- **Recovery/ Shredder**

Air emissions considered in this stage were those generated from the power sources used during recovery. The air emissions generated from use of the electric power source during the recovery were calculated based on the MJ of energy consumed. Figure 5.4 reflects the reduction in air emissions over the years, which is attributable to the reduction in the weight of the telephones. Table 5.4 displays the air emissions and solid wastes generated during the recovery stage, showing the extrapolated value for the 1997 telephone, the equations used and the regression coefficient for each equation.

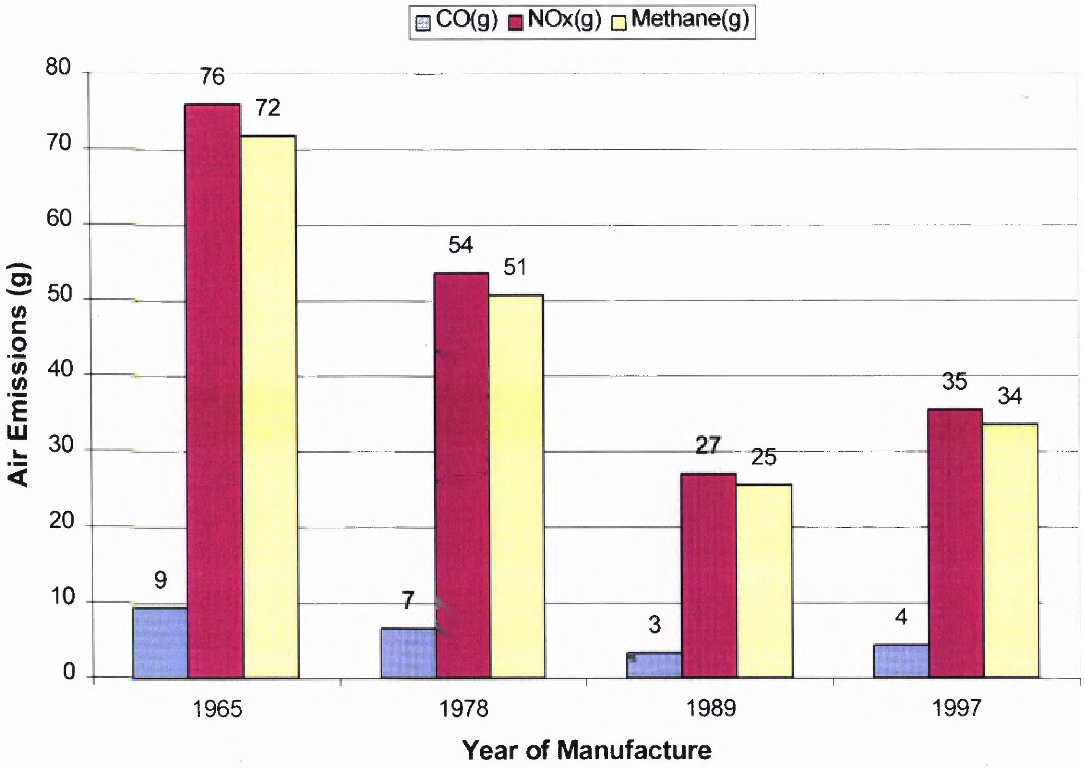
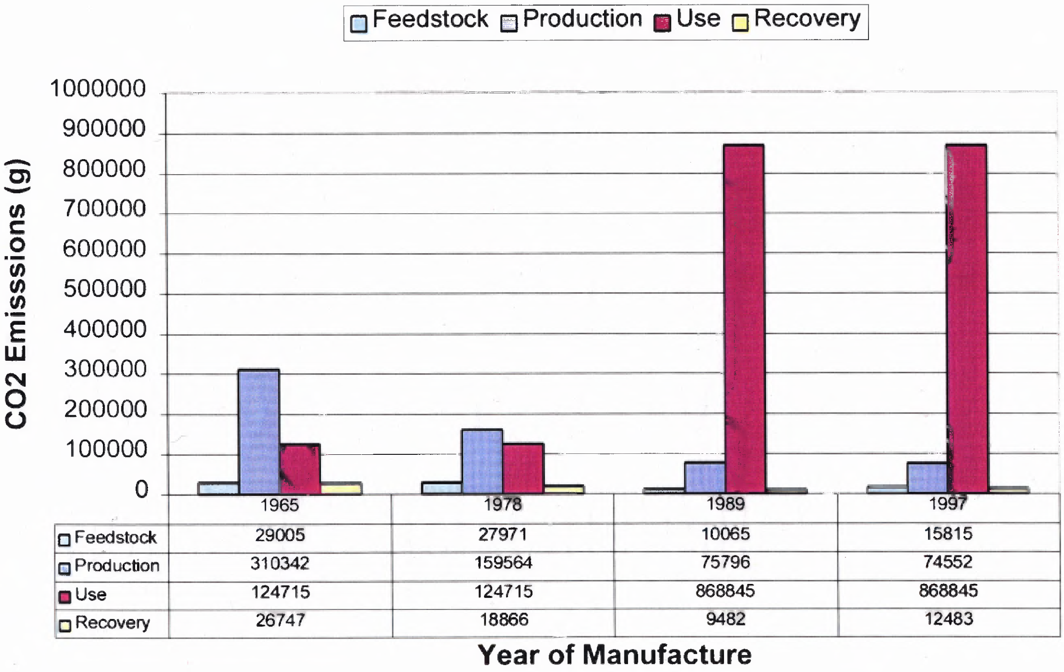


Figure 5.4 Air Emissions Generated during Materials Recovery

Table 5.4 Environmental Burdens Generated during Materials Recovery

	Energy Electric (MJ)	CO2 (g)	CO(g)	NOx(g)	Methane(g)	(g)
1965	50	26747.16	9.30	75.94	71.78	4320.97
1978	35	18866.23	6.56	53.56	50.63	3047.82
1989	18	9481.55	3.30	26.92	25.45	1531.73
1997	23	12483.31	4.34	35.44	33.50	2016.66
Extrapolated Value (1997)		7277.9	2.53	20.66	19.53	1175.8
Percent Difference		41.7%	41.7%	41.7%	41.7%	41.7%
Equation		Ln y= - 0.0427 X + 10.259	Ln y= - 0.0427 X + 2.2947	Ln y= - 0.0427 X + 4.3948	Ln y= - 0.0427x + 4.3384	Ln y= - 0.0427 X+ 8.4361
R2		0.946	0.9461	0.946	0.946	0.946

Figure 5.5 displays the CO_2 emissions throughout the various lifecycle stages of the product. The highest CO_2 emissions was during the use stage of the 1989 and 1997 telephones, followed by emissions during the production stage.



	1965	1978	1989	1997
☐ Feedstock	29005	27971	10065	15815
☐ Production	310342	159564	75796	74552
■ Use	124715	124715	868845	868845
☐ Recovery	26747	18866	9482	12483

Figure 5.5 CO_2 Emissions over the Product Lifecycle

- *DFE Guideline: Has manufacturing solid residue been minimized to the greatest extent possible?*

The following product lifecycle stages were considered:

- **Materials Processing**

The solid wastes generated from processing of feedstock materials composing the telephones were quantified, mainly metals, plastics, and the power source used. Figure 5.6 displays the solid waste graph for the four phones and the extrapolated solid waste value for the 1997 telephone. It also displays the equation, which was derived from the solid waste values of the previous three generations. Manufacturing of copper produces the highest solid waste, 164g / gram of material, when compared to the other materials: steel, aluminum, and ABS. The significant reduction in solid wastes from 1965 to 1978, was due to reduction in the consumption of copper which was reduced from 180g in 1965 to 22g in 1978. The noticeable increase in solid wastes generated from 1989 to 1997 was due to the higher percentage of copper material in the 1997 telephone, and also to the electrical power required to manufacture ABS plastic, where its content was also higher in the 1997 telephone.

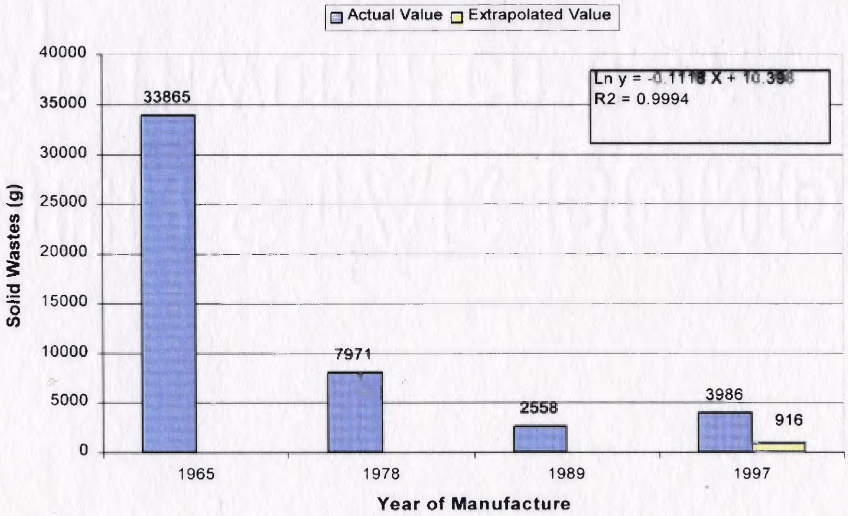


Figure 5.6 Solid Wastes Generated from Materials Processing

- **Production**

Solid wastes considered in this stage were those generated from the power sources used during the production stage. Solid waste generated in this stage was mainly attributable to the energy required to produce ABS and copper. The noticeable reduction in solid wastes in Figure5.7, is mainly due to reduced use of ABS and copper over the first three generations. While the sudden increase in solid waste generation in the 1997 telephone is due to use of more ABS plastics in the unit covers and stand. Figure 5.7 also displays the extrapolated 1997 solid waste being less than the actual solid waste generated in 1997.

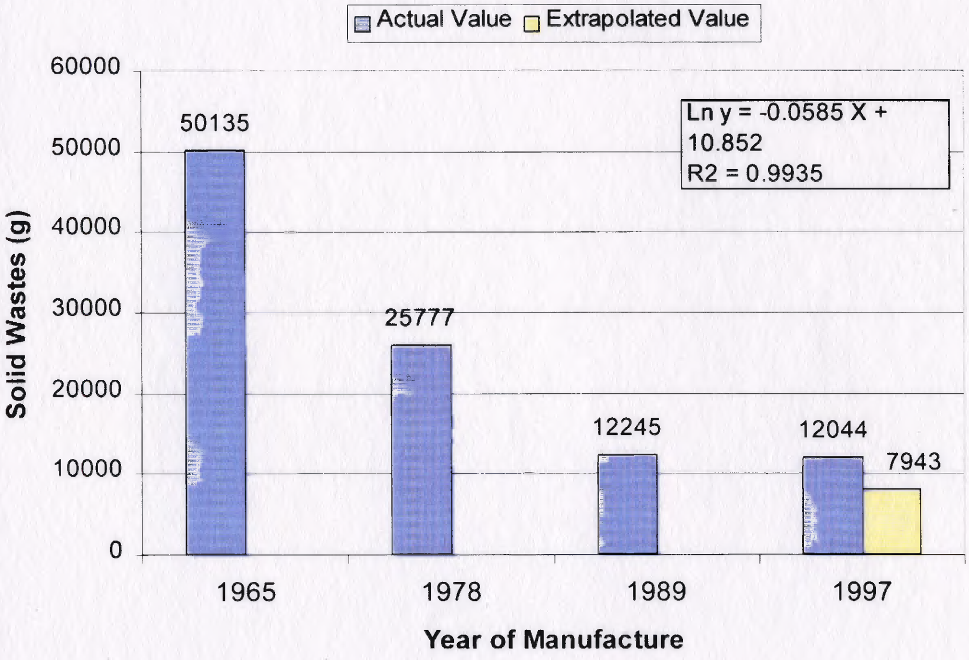


Figure 5.7 Solid Wastes Generated from the Production Stage

- **Use**

Solid wastes considered in this stage were those generated from the power sources used during the use stage. As seen in Figure 5.8, more solid waste was generated during the use phase of the 1989 and 1997 telephone, because of higher energy consumption of those two telephones compared to the older two telephone generations. Refer to the energy consumption analysis of the use stage of the telephones on page 146 for more detailed description.

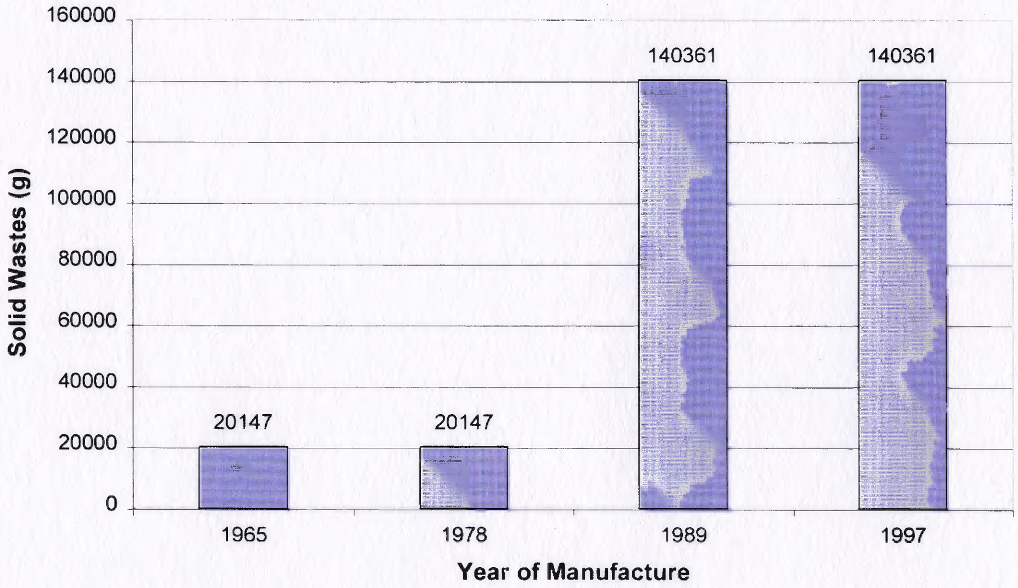


Figure 5.8 Solid Wastes Generated during the Use Stage

- **Recovery**

Solid wastes considered in this stage were those generated from the power sources used during recovery. Solid waste generated during this stage is from the electric energy supplying the recovery process. Figure 5.9 shows that solid wastes generated were reduced over time due to reduction in the mass of the telephones. It also shows the extrapolated solid wastes from the 1997 telephone being less than the actual solid wastes generated from the 1997 telephone, and in fact that more solid waste is generated for the 1997 telephone than for the 1989 telephone.

In conclusion, by comparing the actual solid wastes generated to the extrapolated values over the product lifecycle, it is obvious that actual solid wastes generated are more than the extrapolated values. Therefore, DFE guidelines had no impact on reductions in solid wastes.

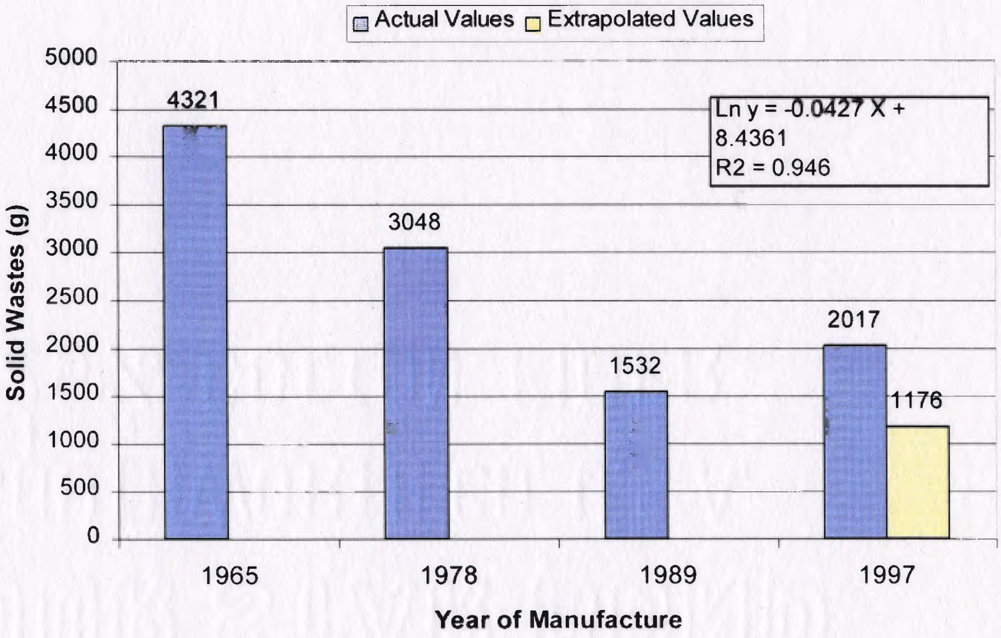


Figure 5.9 Solid Wastes Generated from the Recovery Stage

- *DFE Guideline: Have manufacturing liquid emissions been minimized to the greatest extent possible?*

The following product lifecycle stages were considered:

- **Feedstock Materials**

The waterborne effluents generated from processing of feedstock materials composing the telephones were quantified, mainly metals, plastics, and the power source used. No waterborne effluents were generated from the manufacturing of the metals, all waterborne effluent values are relevant to the production of ABS only. Figure 5.10 displays the waterborne effluents for acids, metal ions, and dissolved solids. Since waterborne effluents are solely dependent on the weight of plastics in the telephones, the shape of the graph is similar to that of the plastic weight graph. Table 5.5 compares the actual waterborne effluents generated in this stage to the extrapolated values. It also shows that the actual waterborne effluents for the 1997 telephone were more than the extrapolated values, and more than the 1989 values. Therefore, DFE guidelines had no impact on reducing waterborne effluents in the 1997 telephone. This extrapolation was based on the equations listed in Table 5.5, which has a low regression coefficient of approximately 0.46.

No water effluents were generated in the other lifecycle stages: production, use, and recovery, since use of electric power sources generates no water effluents.

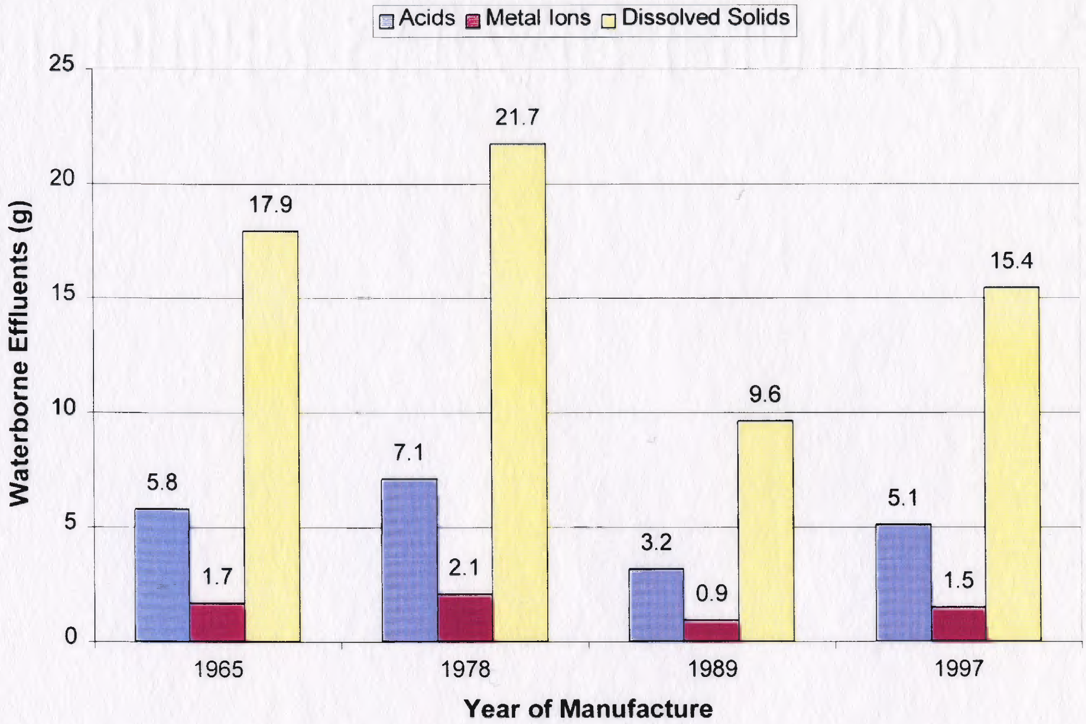


Figure 5.10 Waterborne Effluents from Materials Processing

Table 5.5 Water Effluents Generated during Materials Processing

Emissions	Acids (g)	Metal Ions (g)	Dissolved Solids (g)
Actual Value (1997)	5.1	1.5	15
Extrapolated Value (1997)	3.2	0.91	9.6
Percent Difference	37.3%	39.3%	36.0%
Equation	$\ln y = -0.0236X + 1.9177$	$\ln y = -0.0248X + 0.6982$	$\ln y = -0.0249X + 3.0553$
R2	0.4672	0.4683	0.4797

5.2.2 Material Conservation

- *DFE Guideline: Can materials use be minimized by improved mechanical design?*

This metric reflects the concept of dematerialization. Dematerialization impact is evident throughout the product lifecycle, since the weight reflects the quantity of materials used in the products, and hence the energy consumption and environmental burden associated with the production of the feedstock materials, distribution of the telephones, and end-of-life impacts associated with the product. The materials composing the telephones were divided into three major categories: Plastics, Metals, and Others. The plastic content of the telephones was assumed to be ABS, since ABS is the most widely used polymer in electronic housings and because of the difficulty faced in identifying the different plastics. Metals were divided between steel, aluminum, and copper. Finally, the others category, included mainly circuit boards and wires.

Figure 5.11 compares the total weight of the phones and shows that the extrapolated weight (632.7 g) for the 1997 DFE phone is below the actual weight (1085 g). As can be seen, dematerialization occurred at a rapid ratio due to substitution of electronics for older mechanical components and use of lighter weight plastics for materials. The DFE guidelines have NOT had an impact on material conservation for the telephones. This was also noticed when comparing the copper and steel weights. The extrapolated values generated from the trend lines were all below the actual weights of the materials. It was difficult to extrapolate the values of the plastic and aluminum for the 1997 telephone, by fitting a curve through the values of the previous three generations. But, it is obvious from Figure 5.12 that the weight of plastic material in the 1997 telephone is higher than that of the 1989 telephone. This was due to the design of the telephone unit cover and stand. The weight of the 1997 telephone stand was twice the weight for that of the 1989 telephone, and the weight of the unit covers of the 1997 telephone were also approximately twice that of the 1989 telephone. Table 5.6 shows the weight of the materials in the telephones, the data was obtained from the demanufacturing study conducted on the four telephones. Table 5.7 displays the actual and extrapolated weights for the 1997 telephone, and the equations used for the analysis. Figures 5.12 - 5.15 shows the total weights of plastic, steel, aluminum and copper respectively.

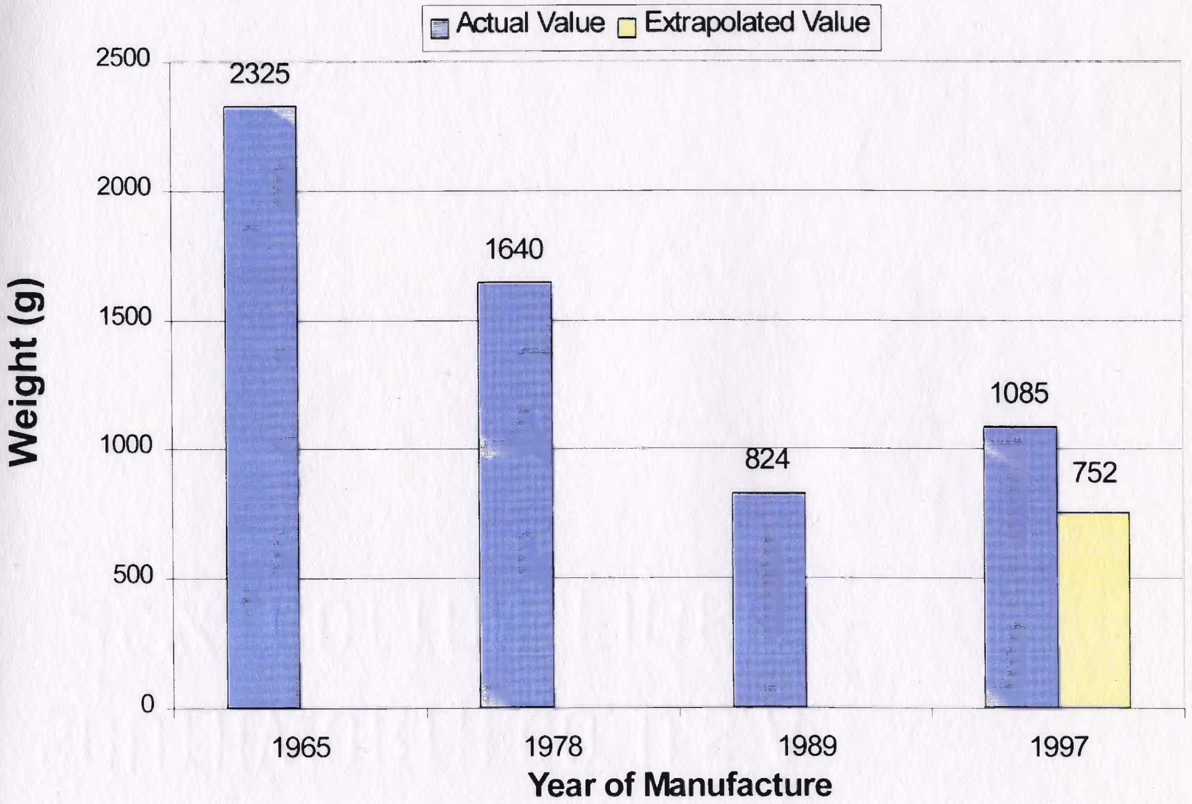


Figure 5.11 Total Weight of the Telephones

Table 5.6 Total Weight of the Telephones

	Plastic			Total Metal Quantity							Other Materials		
	ABS		Total	Steel		Aluminum		Copper		Total			Total Weight
phone	Wt (g)	%Wt	Wt (g)	Wt (g)	%Wt	Wt (g)	%Wt	Wt (g)	%Wt	Wt (g)	Wt (g)	%Wt	Wt (g)
1965	943.55	0.41	943.55	963.06	0.41	62.89	0.03	179.96	0.08	1205.91	175.47	0.08	2325
1978	1175.14	0.72	1175.14	210.32	0.13	62.42	0.04	22.25	0.01	294.99	169.77	0.10	1640
1989	526.06	0.64	526.06	131.75	0.16	0.93	0.00	4.11	0.00	136.79	161.31	0.20	824
1997	845.94	0.78	845.94	120.72	0.11	0.85	0.00	6.14	0.01	127.71	111.43	0.10	1085

Table 5.7 Extrapolated Values of Material Weights for 1997 Telephone

Emissions	ABS (g)	Steel (g)	Aluminum (g)	Copper (g)	Total (g)
Actual Value (1997)	845.94	120.72	0.85	6.14	1085
Extrapolated Value (1997)	530.49	57.4	0.54	1.15	632.7
Percent Difference	37.3%	52.5%	36.5%	81.3%	41.7%
Equation	Ln y= - 0.0231 X + 7.013	Ln y= 0.0839 X + 6.7348	Ln y= - 0.1703 X + 4.8349	Ln y= - 0.1576 X + 5.1795	Ln y= - 0.0427 X + 7.8164
R2	0.4465	0.9394	0.7087	0.9998	0.9459

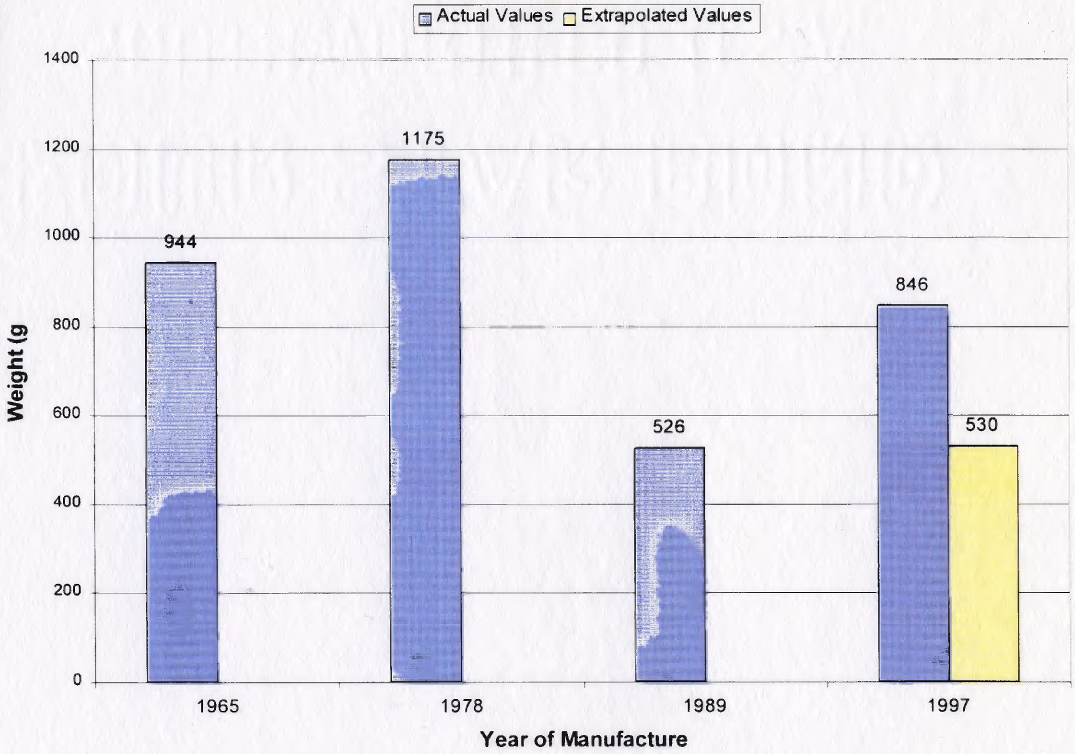


Figure 5.12 Total Weight of Plastics in the Telephones

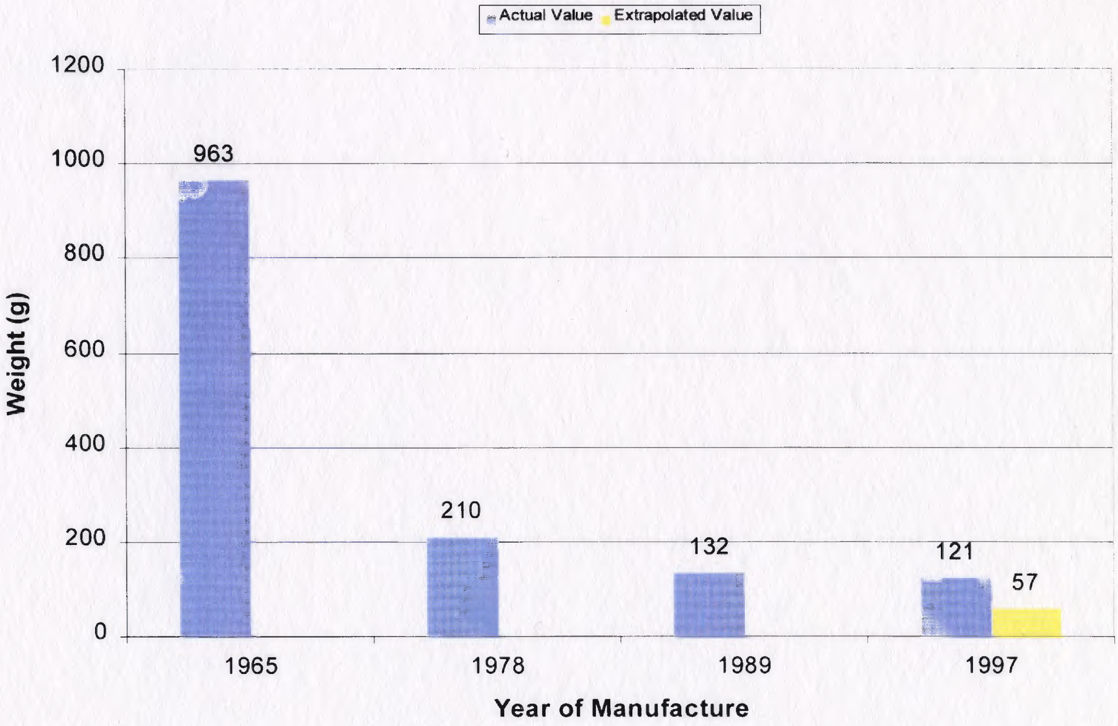


Figure 5.13 Total Weight of Steel in the Telephones

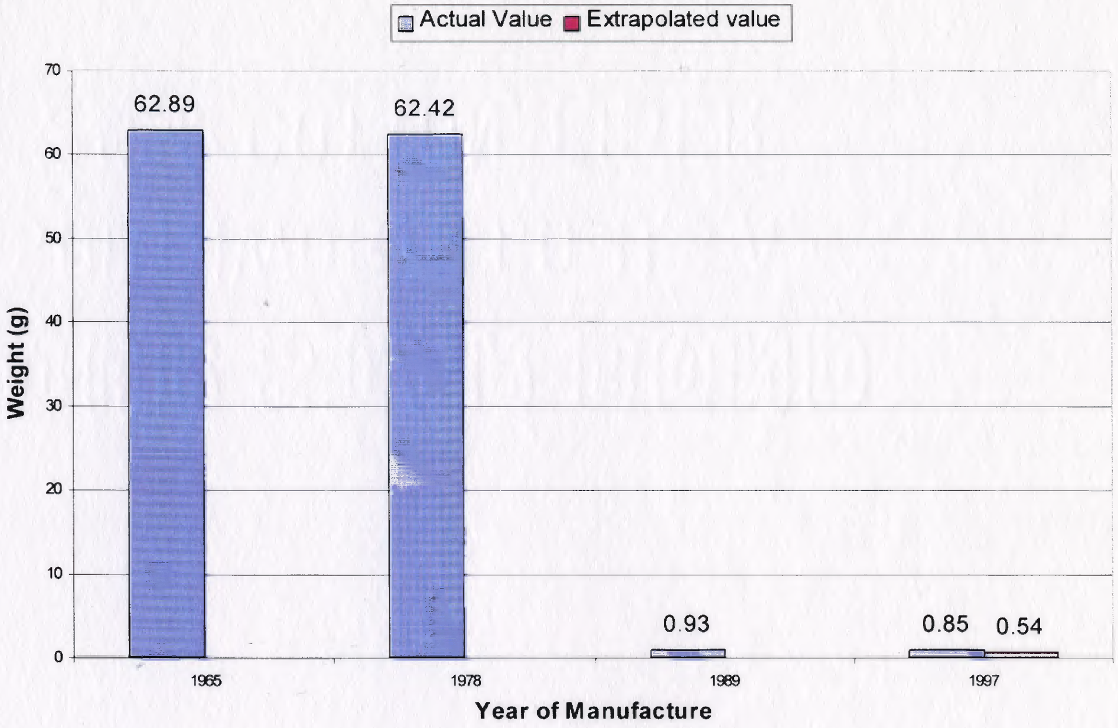


Figure 5.14 Total Weight of Aluminum in the Telephones

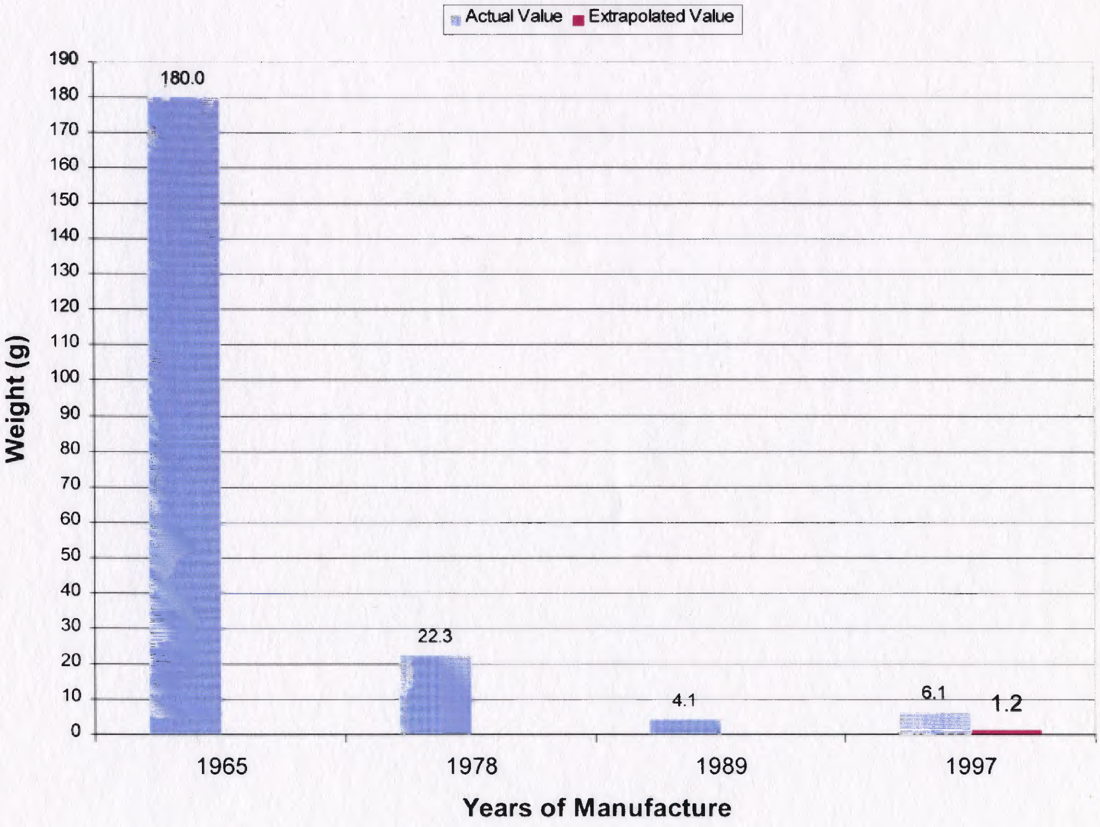


Figure 5.15 Total Weight of Copper in the Telephones

5.2.3 Energy Conservation

The energy consumption of the telephones was measured over its total lifecycle stages. It is expected that more improvements have occurred in energy conservation over time, as more efficient technologies (electronics) have evolved. In order to incorporate the evolution of technology over time, the energy efficiency of production of electronic products was evaluated. Information on energy efficiency during production was based on personal contact with M. Ross [30]. Available data was from the period 1971-1985, where the energy intensity fell an average 3% per year. Figure 5.16 shows the energy efficiency curve for electronics production.

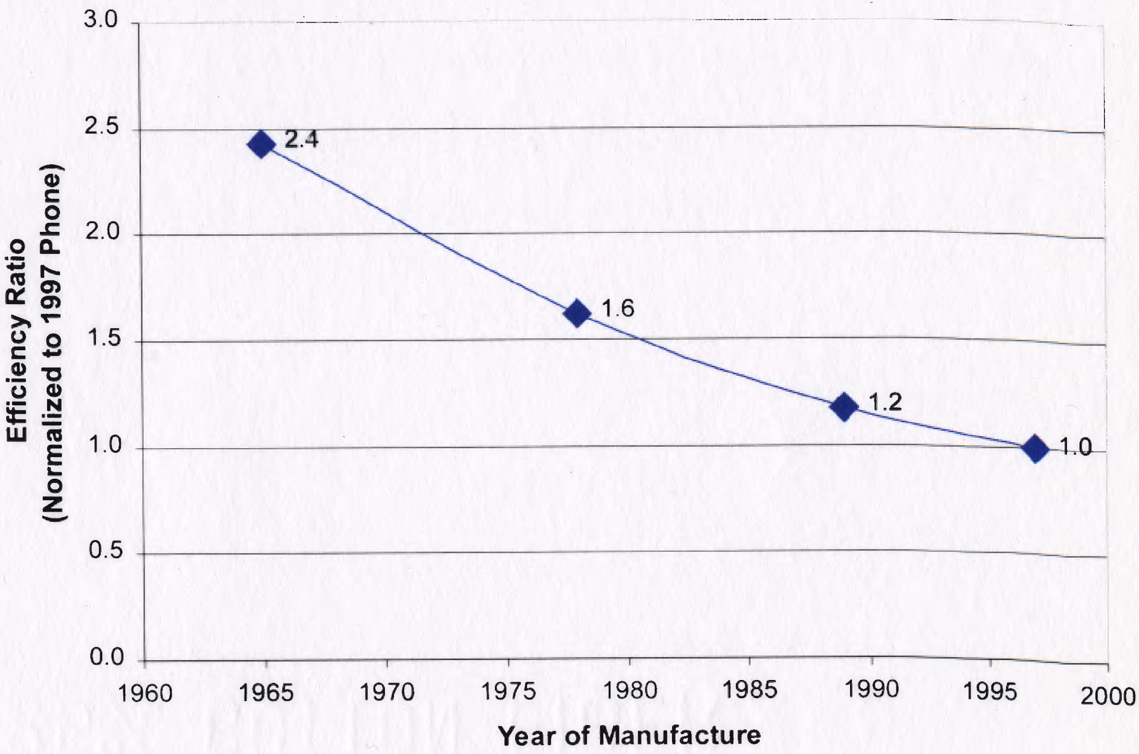


Figure 5.16 Energy Efficiency of Electronic Products in Production

The lifecycle stages quantified in this analysis are: Feedstock materials, Production, Use and Recovery.

- **Feedstock Material**

DFE Guideline: Is the product designed to minimize the use of materials whose extraction is energy intensive?

Data generated for this stage were based on the energy required to produce the various materials used in the four telephones and were calculated based on the weight of each telephone. The source of energy data on the materials was taken from the generic frameworks that were developed and explained in section 3.5. Figure 5.17 shows the total feedstock material energy, which also shows the actual energy value for the DFE-designed phone to be above the extrapolated value, and above the 1989 value. Therefore DFE guidelines did not have a direct impact on feedstock energy conservation for the 1997 phone. The extrapolated energy value for 1997 was calculated using the same uniform equation: LnY= aX+b.

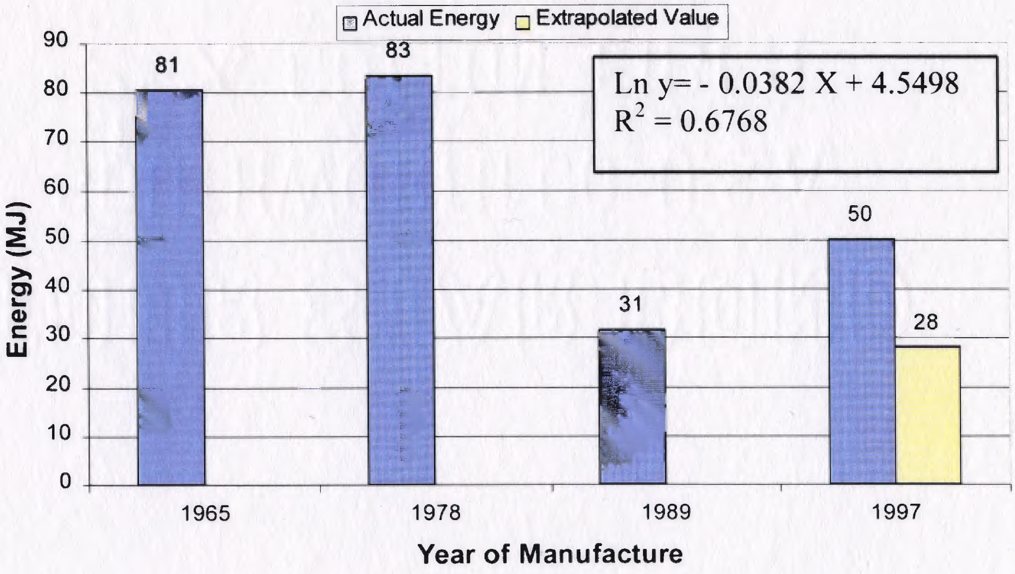


Figure 5.17 Total Feedstock Material Energy

- **Production Stage**

DFE Guideline: Is the product designed to minimize the use of energy-intensive process steps?

The total energy required to produce the telephones is also considered. The production of the circuit board was considered separately from the rest of the telephone production, because of the high energy consumption during its manufacture. The energy required to produce the 1997 telephone was found to be 9.25 kWh or 99.89 MJ, based on personal contact with a research staff at Lucent Technologies [26]. The energy required to manufacture 1 mm^2 of the 21090mm^2 1997 PCB was found to be 0.0019 MJ, this information was based on a study conducted on a telephones lifecycle by J. Young [16]. The efficiency curve for production, Figure 5.16, was applied to both the telephone and the circuit board production. Table 5.8 displays the total production energy for the four telephones. The energy required to produce the telephones (excluding the circuit board) was extrapolated using the following formula:

$$\text{Energy for production of 1997 phone} * \begin{array}{c}\text{Efficiency Ratio}\\ \text{of other Phone}\end{array} * \frac{\text{Wt of Other Phone g}^{*}}{\text{Wt of 1997 Phone g}}$$

* Weight of the telephones does not include the circuit board weight.

Following is the calculation for the production energy of the 1965 Telephone, the same formula was applied to calculate the production energy for the other telephones.

$$99.89 \text{ MJ} * 2.4324 * \frac{2023 \text{ g}}{974 \text{ g}} = 505 \text{ MJ}$$

Following is the calculations for the production energy of the 1965 circuit board, the same formula was applied to calculate the production energy for the other circuit boards.

Energy for production of (MJ /mm^2) * Efficiency Ratio * PCB Area (mm^2)
of PCB for the 1997 phone

= 0.0019 (MJ /mm^2) * 2.4324 * 16900 mm^2 = 78.1 MJ

Table 5.8 Estimated Production Energy for the Telephones

Telephone	**1965**	**1978**	**1989**	**1997**
Energy (MJ) Without PCB	505	236	81	100
PCB Energy (MJ)	78	64	61	40
Total (MJ)	583	300	142	140

- **Use Stage**

DFE Guideline: Has the product been designed to minimize energy use while in service?

The energy consumption of the telephones during the use stage were defined in two categories: The In-Use mode and the Stand-By mode. The utilization factor of the telephones was assumed to be 3%, this percentage was based on an experiment that was conducted on a small sample of users of the 1997 telephone. The results obtained were as follows [26]:

Utilization Factor = 3% of 24 Hours (0.72 hours / day)

Product Lifetime = 7.5 Years

In-Use energy consumption = 5.5 Watts$_e$.

Total energy consumption during In-Use mode:

= No. of Hrs used / day * No. of days / Year * Product Lifetime (Yr) * Energy (Watts$_e$)

= 0.72 hrs / day * 365 days / Yr * 7.5 Yrs * 5.5 Watts$_e$ = 10840 Watt-Hr$_e$

Stand-By energy consumption = 2.2 Watts$_e$

Total energy consumption during Stand-By mode:

= No. of Hrs in Stand-By / day * No. of days / Year * Product Lifetime (Yr) * Energy (Watts$_e$)

No. of Hrs in Stand-By / day = 24 – 0.72 = 23.28

= 23.28 hrs / day * 365 days / Yr * 7.5 Yrs * 2.2 Watts = 140204 Watt-Hr$_e$

Total Energy Consumption during Use Stage:

10840 + 140204 ***= 151044 Watts-Hr = 151.044 kWh$_e$***

Based on the above calculations, it can be concluded that the energy consumption of the 1997 telephone during the Stand-By mode is 14 times greater than the In-Use mode over the telephone's lifetime. Therefore, designers must place more emphasis on reducing the energy consumption of the telephone during the Stand-By mode. For the 1965 telephone, the energy consumed during the In-Use mode was assumed to be 5.5 Watts [31]. During the Stand-By mode, the telephone is assumed NOT to consume energy, since there are no memory cells to store information as the case with the 1989 and 1997 telephones [31]. The same assumption was applied to the 1978 telephone. For the 1989 telephone, it was assumed that there are no significant difference between it and the 1997 telephone, therefore it is assumed to consume 5.5 Watts during the In-Use mode and 2.2 Watts during Stand-By mode. Applying the above assumptions to the previous calculations presented for the 1997 telephone, the energy use of the other telephones can be calculated. The results are shown in Table 5.9, which shows the energy consumption of the four telephones during the use stage.

Table 5.9 Energy Consumption of the Telephones during Use Stage

	Life Time In-Use (Kwh)	Life Time Stand-By (Kwh)	Lifetime Energy Use (Kwh)	Lifetime Energy Use (MJ)
1965	21.7	0.0	22	234
1978	21.7	0.0	22	234
1989	10.8	140.2	151	1631
1997	10.8	140.2	151	1631

Note: Energy consumption is quantified in units MJ in the above table, because all energy calculations and comparisons for the other lifecycle stages are in units of MJ.

- **Recovery**

DFE Guideline: Is the product designed with the aim of minimizing the use of energy-intensive process steps in disassembly? Is the product designed for reuse of materials while retaining their embodied energy?

As mentioned earlier, in chapter 3, section 3.3.1. the metals in the telephones are assumed to be the only materials recovered from the telephones, since the value of recycled plastics is negligible. The materials are recovered by shredding / separation of the telephones. The energy required to perform this operation is estimated to be 2kWh/ 1 Kg (21.6 MJ/ 1Kg) of material, based on the AT&T Reclamation Center, located in West Chicago, IL [15]. The embodied energy of plastics is subtracted from energy consumed during the recovery process. Since all plastic materials in the phone are assumed to be ABS (as imprinted on the 1997 hosing cover), the embodied energy of ABS, which is 30.83 kWh / Kg (332.94 MJ/1Kg) [27], is used for the calculations. Table 5.10 shows the total recovered energy of the telephones. The recovery energy and embodied energy of the telephones was calculated as follows:

1965 Telephone:

Recovery Energy = 2325 g * 0.0216 MJ / g = 50.22 MJ

Embodied Energy = 943.55 g * 0.333 MJ / g = 314 MJ

Table 5.10 Energy Consumed during Recovery of the Telephones

Telephone	**1965**	**1978**	**1989**	**1997**
Shredding Energy (MJ)	50	35	18	23
Embodied Energy (MJ)	314	391	175	282
Total Recovery Energy (MJ)	-264	-356	-157	-258

Figure 5.18 shows the total energy associated with lifecycle stages of the telephones. The energy values represented here are all in MJ units, so that efficiency factor of power sources is all equivalent. This figure shows that energy consumption during the use stage is by far the highest throughout the product lifecycle. Designers must concentrate their efforts on reducing energy consumption of electronic products during use stage. Table 5.11 compares the extrapolated energy consumption of the 1997 telephone to the actual consumption over the telephones lifecycle, showing the equations used for estimation. The results presented in Table 5.11, show that DFE guidelines had no impact on reduction in energy consumption over the product lifecycle.

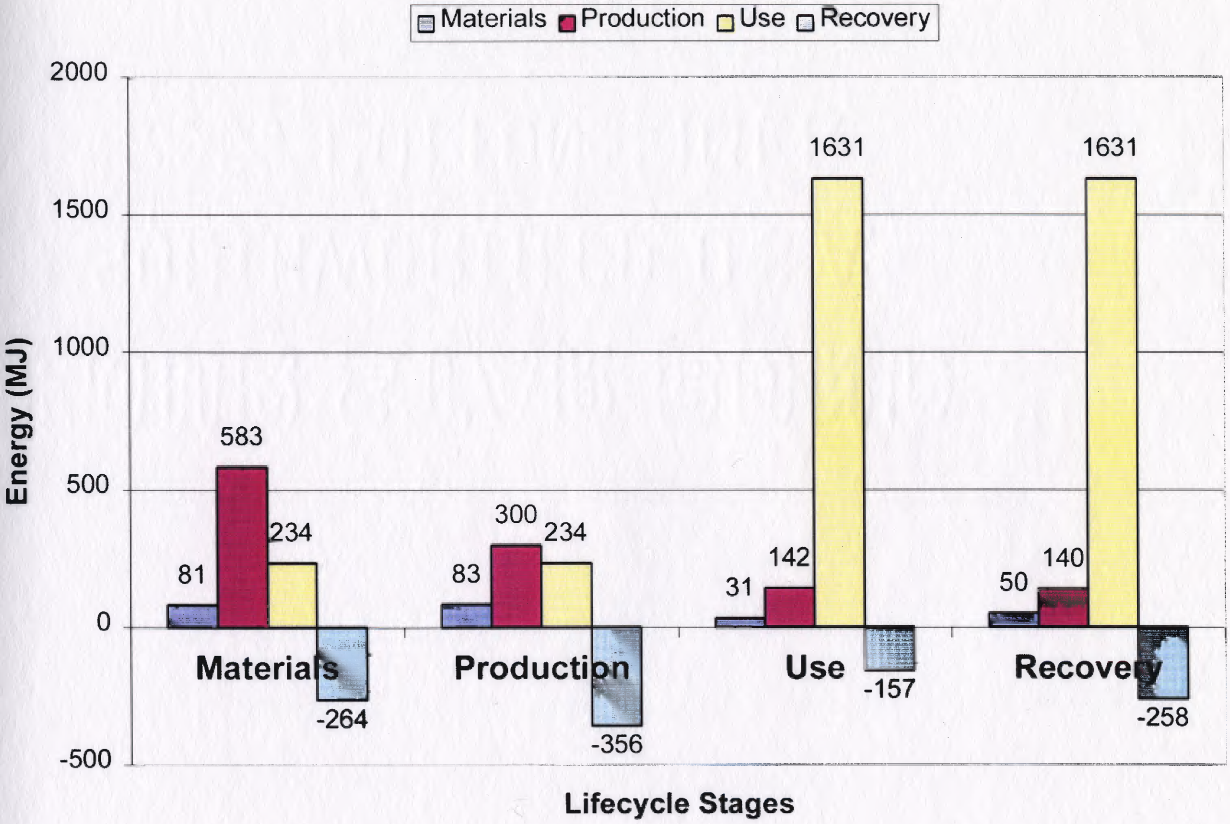


Figure 5.18 Total Energy Consumption over the Product Lifecycle Stages

Table 5.11 Comparison of Energy Consumption over the Product Lifecycle

	Feedstock Material	Production	Use	Recovery
Actual Value (1997)	50	140	1631	-258
Extrapolated Value (1997)	27.87	92.18	N/A	-164.56
Percent Difference	44.3%	34.2%	N/A	36.2%
Equation	Ln y= - 0.0382 X+ 4.5498	Ln y= - 0.0586 X+ 6.3989	N/A	Ln y= -0.0203x + 5.7529
R2	0.6768	0.9939	N/A	0.347

5.2.4 Service Extension

- *DFE Guideline: Are subassemblies designed for ready maintainability rather than solely for disposal after malfunction? Are modules designed for ready removal?*

As mentioned earlier, these guidelines concentrate on service delivery to the product after it has been manufactured and during its use stage. Service extension is one of the six dimensions of the eco-compass tool, mentioned earlier in chapter 2. Three major variables were selected to quantify this dimension: Commonality, Upgradability, and Modularity. Table 5.12 illustrates how each subassembly was defined as common, upgradable, or modular. It also shows for each of the above three variables, the total number of subassemblies that met their criteria. Defining whether a certain subassembly is modular, common or upgradable may differ based on the assumptions made and on the definition of each variable. Table 5.13 shows the final service extension score, which was normalized to a scale of 10, since the number of subassemblies was not uniform for all the telephones. Figure 5.19 presents a chart for the three variables of service extension. This figure shows consistent improvement in the design of the telephones for service extension.

Table 5.12 Defining Subassemblies per Service Extension Variables

	Subassemblies							
1997	Top Cover	Base	Handset	Circuit Board	Key Pad		Total	Total Subassemblies
Upgradebility	Y	Y	N	Y	N		3	5
Commonality	Y	Y	Y	Y	Y		5	
Modularity	Y	Y	Y	Y	Y		5	
	Subassemblies							
1989	Top Cover	Base	Handset	Circuit Board	Key Pad			
Upgradebility	N	Y	Y	Y	N		3	5
Commonality	Y	Y	Y	N	Y		4	
Modularity	Y	Y	Y	Y	N		4	
	Subassemblies							
1978	Top Cover	Base	Handset	Inside Hold	Keypad	Speaker		
Upgradebility	N	N	Y	Y	N	N	2	6
Commonality	N	N	Y	N	N	Y	2	
Modularity	N	N	N	Y	N	N	1	
	Subassemblies							
1965	Top Cover	Base	Handset	Network	Keypad	Ringer		
Upgradebility	N	N	Y	N	Y	N	2	6
Commonality	N	N	Y	N	Y	N	2	
Modularity	N	N	N	N	N	N	0	

Table 5.13 Final Service Extension Scores

	Upgradebility	Commonality	Modularity	Total SA
1965	2	2	0	6
1978	2	2	1	6
1989	3	4	4	5
1997	3	5	5	5

On a Normalized Scale (0- 10), rounded to the nearest digit

	Upgradebility	Commonality	Modularity	Service Extension
1965	3	3	0	6.7
1978	3	3	2	8
1989	6	8	8	22
1997	6	10	10	26

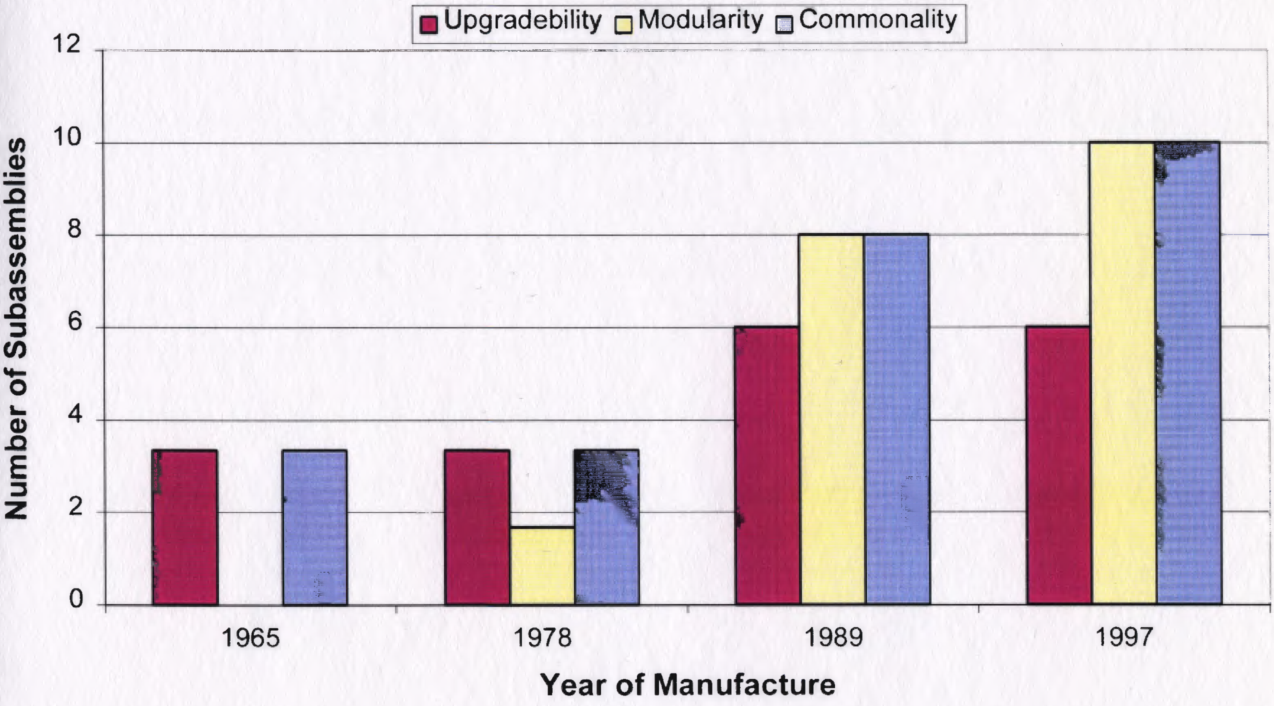


Figure 5.19 Service Extension for the Four Telephones

5.2.5 Demanufacturing

- *DFE Guideline: Are all plastic components identified by ISO markings as to their content?*

Parts must be stamped in a generic way that identifies the type of material its made of. The 1997 telephone was the only telephone stamped with material type identification. The material stamping helps the demanufacturers in identifying the material each part is made from, therefore recognizing the economic value of that part. In many cases, parts that are not identified are thrown into an "unknown materials" bin, which is most probably landfilled, and results in loss of a possible profit for the demanufacturer. Part stamping shows improvement that is directly attributable to DFE guidelines, since no plastic parts were stamped in the previous generations.

- *DFE Guideline: Has the product been assembled with fasteners such as clips or hook-and-loop attachments rather than chemical bonds or welds?*

The number of different fasteners used in the products was counted. Mainly two fasteners were used in all the telephones: slot head screws and snap-fits. As displayed in Figure 5.20, the number of screws used in the telephones was reduced dramatically over the years, while the number of snap fits was variable. Table 5.14 compares the actual values of the snap-fits and screws used in the 1997 telephone to the extrapolated values. It also shows the equations used for estimating the values for 1997, and the regression coefficient for each equation. Since the extrapolated number of screws and snap-fits are both less than the actual one, the conclusion is that the DFE guidelines had no affect on their reduction. This reduction is mainly attributable to design for manufacturability and assembly rather than DFE. Also, the handset of the 1997 DFE designed phone was fastened by using snap-fits and a strong adhesive, which made its disassembly extremely difficult. As a result, DFE guidelines did not have a direct impact on this performance metrics.

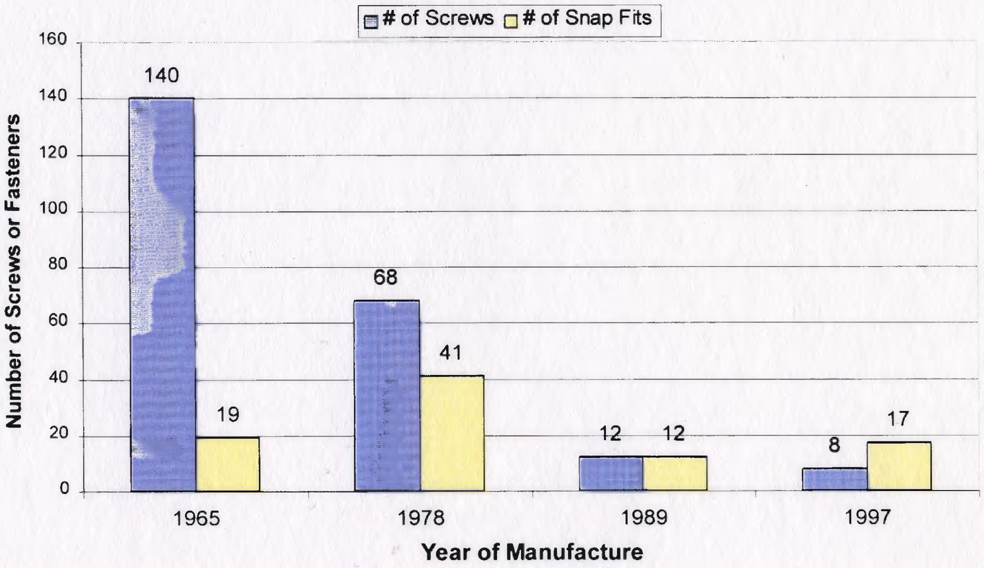


Figure 5.20 Total Number of Fasteners

Table 5.14 Comparison of Actual and Extrapolated Fasteners

	Actual Value (1997)	extrapolated Value (1997)	Percent Change	Equation	R^2
Number of Screws	8	7	12.5%	Ln Y= -0.101 X + 5.1272	0.9227
Number of Snap-Fits	17	15	11.76%	Ln Y= -0.0168 X + 3.2548	0.1057

- **Disassembly Time**

This reflects the time, effort, energy and overhead (in terms of cost and energy consumption) associated with completely disassembling the product. The disassembly time is also expected to decrease over time. DFE guidelines promote the use of fasteners such as clips rather than adhesives, as to minimize the disassembly time of the product. In the case of the 1997 DFE-designed phone, the handset subassembly was joined using a strong adhesive and snap-fits, which caused difficulty in disassembling the subassembly. The time required to disassemble the handset only was 180 sec while the time needed to disassemble the rest of the telephone was 133 sec. Figure 5.21 illustrates the disassembly time of the four telephones, and displays the extrapolated disassembly time and the equation used for estimation. The actual disassembly time is greater than the extrapolated one, therefore, DFE guidelines had no affect on the reduction of the disassembly time.

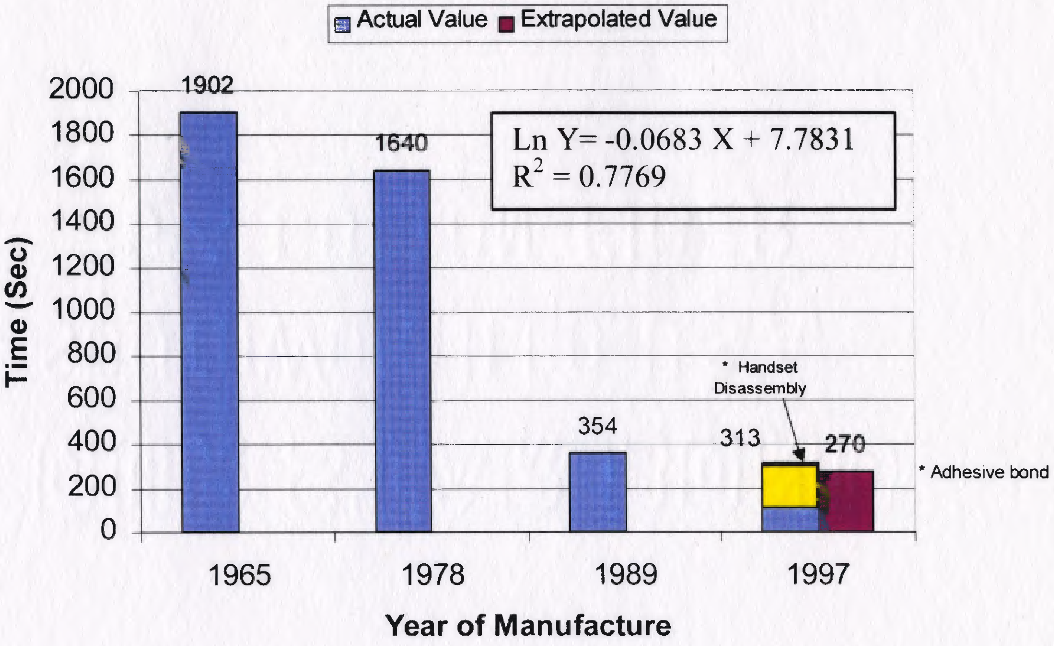


Figure 5.21 Total Disassembly Time for the Telephones

5.3 Other Performance Metrics

- **Number of Parts**

This metric is an essential comparison as the number of parts has an immense impact on the material and energy conservation of the product throughout its lifecycle. It is also a product of the concepts of Design for Manufacturability and Assembly (DFMA), as minimizing the number of parts improves many aspects of the assembly and disassembly processes. Figure 5.22 illustrates a comparison of number of parts for the four telephones and shows that the actual number of parts, 32, for the 1997 DFE phone is lower than the extrapolated value, 36. This value was extrapolated using the following equation: Ln Y= -0.0543 X + 5.328, where the number of parts for the first three generations were used to generate the equation. Since the extrapolated value is slightly higher than actual value, the improvement might be attributable to both DFE and DFMA guidelines.

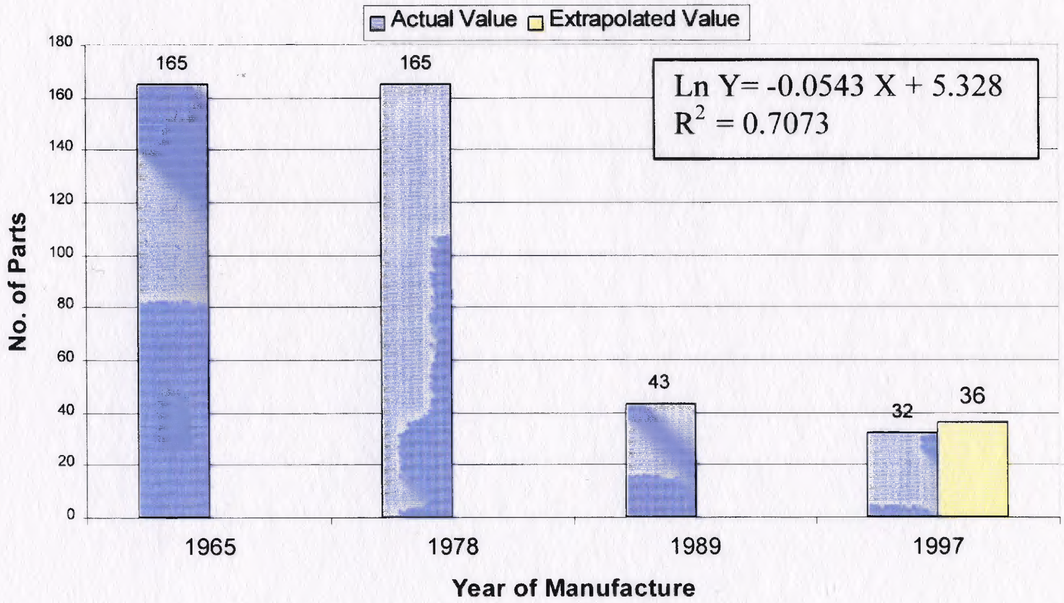


Figure 5.22 Comparison of Number of Parts

- **Subassembly Comparisons**

Instead of concentrating our study on the complete phone only, we decided to expand our evaluation to detect any substantial changes that occurred on the subassemblies. Our analysis covers mechanical, technological, energy consumption and environmental burdens associated with these subassemblies. The major subassemblies under study are the Keypad, Covers, Handset and the PCBs. Figure 5.23 illustrates the weight of the subassemblies for the four telephone generations. It also shows the jump in the weight of the covers for the 1997, compared not only to the 1989 telephone, but also to all the previous generations. As mentioned earlier, this was due to the design of the telephone unit covers which for the 1997 telephone, increased by approximately 70% over the 1989 telephone. Obviously, designers must concentrate efforts on redesigning unit covers with a goal of reducing their materials consumption, since weights of the other subassemblies are much smaller when compared to the unit covers.

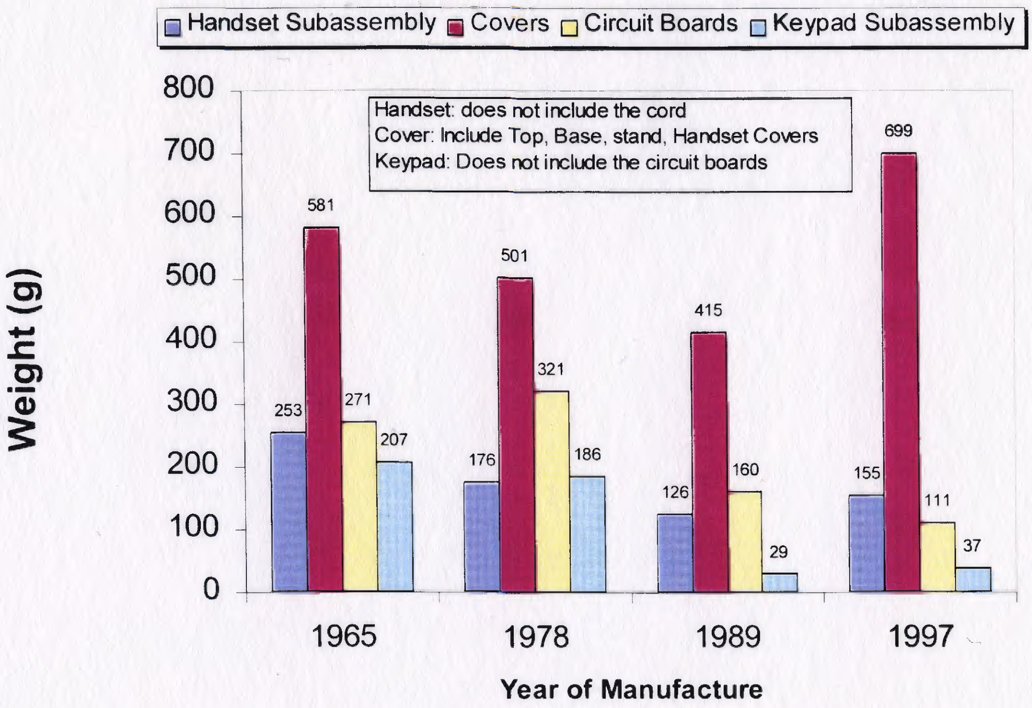


Figure 5.23 Subassembly Comparisons of the Four Telephones

- **Resource Conservation (Integrated Metrics)**

As described earlier in chapter 3, section 3.3.2, this metric aims at measuring material and energy conservation of the telephones. It utilizes the denominator of the resource productivity measure, which was also described in chapter 3, to quantify those variables. The formula for resource conservation is (all values are in monetary value, ($): *(Material Consumed - Recycled) + (Energy Consumed for Production + Recycling – Embodied Energy) + Lifetime Energy Used.* Following is calculation of the resource conservation metric for the 1997 telephone:

$$(\$12.5 + \$0.02) + (\$3.9 + \$0.65 - \$7.8) + \$45 = \$55$$

The values presented in the above formula are taken from resource productivity, Table 5.23 in section 5.4.2. Figure 5.24 displays the resource conservation values for the four telephones.

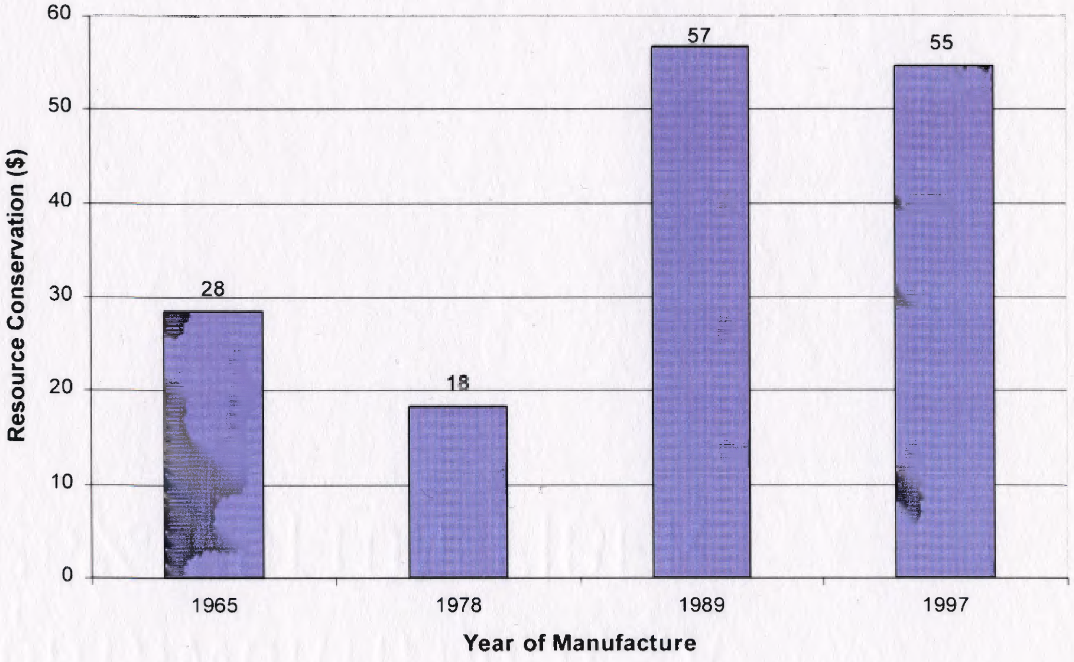


Figure 5.24 Resource Conservation Values for the Four Telephones

- **Keypad Subassembly**

Looking at certain subassemblies and comparing their advancement over time, a significant change was noticed on the keypad subassembly. Table 5.15 shows the number of parts and weight of the four telephones. The number of parts in the keypad subassembly includes the circuit boards, but the circuit boards are not included in the weight values of the keypads. Figure 5.25 shows the tremendous reduction in the number of parts in a keypad subassembly from 43 parts in 1965 to only 3 parts in 1997, it also shows the extrapolated number of parts for the 1997 keypad subassembly, 13. Since the extrapolated number of keypad parts is greater than the actual value for the 1997 keypad subassembly, DFE guidelines may have had an impact on reducing the number of parts used. This reduction may also be attributable to design for manufacturability and assembly, which promote the reduction of parts used. The improvement from 1989 to 1997 was due to integrating all the buttons into one unit rather than being separated. This integrated unit also reduced the disassembly time of the keypad subassembly.

Table 5.15 Keypad Subassembly Comparison

Telephone	**Number of Parts**	**Weight (g)**
1965	43	206.8
1978	40	186.1
1989	15	29.3
1997	3	36.8

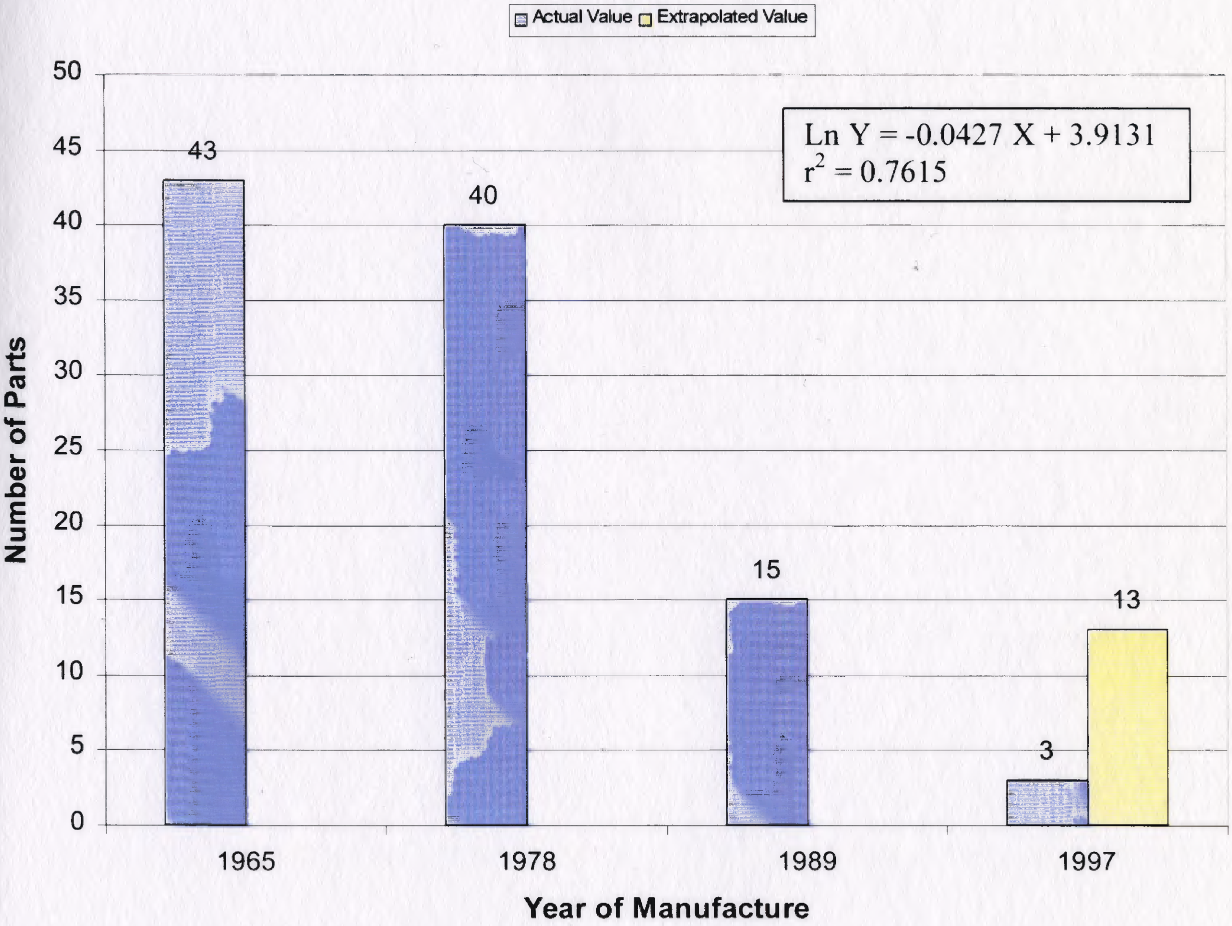


Figure 5.25 Keypad Subassembly Comparison of the Four Telephones

5.4 Performance Attributes

5.4.1 Eco-compass

The methodology applied to the eco-compass tool was described earlier in chapter 3. This tool is utilized to compare and detect the improvement in certain environmental performance attributes. Six dimensions were quantified: Mass Intensity, Energy Intensity, H&E Risk, Revalorization, Service Extension, and Resource Conservation. The 1965 telephone was chosen to be the base case, with a score of 2, where the performance of the other telephones was compared to this base case. The data and information needed was mainly extracted from the results of the demanufacturing study conducted on the telephones. The values of all these dimensions have been quantified earlier in this chapter. Table 5.17 displays the six dimensions of the eco-compass, and the value of each dimension for each telephone. Following is an illustration of a comparison of the 1997 telephone to the base case telephone.

- **Mass Intensity:** The weights of the telephones were compared and plotted on the hexagon scale. The 1965 telephone weighed 2325g, while the 1997 telephone weighed 1085g. Therefore:

  Percent improvement = (2325 g-1085 g) / 2325 g = 0.53 * 100 = 53 % improvement.

  Thus, a score of 4 is assigned to the 1997 telephone for the mass dimension, since the improvement is more than 50 %.

- **Energy Intensity:** The values for this dimension were the result of summing the energy consumption of each telephone at each stage of their lifecycle as described previously in section 5.2.3. For example, energy intensity for the 1997 telephone =

Feedstock material energy (MJ) + Production energy (MJ) + Use energy (MJ) + recovered energy (MJ) (shredding – embodied) =

$$50\text{ MJ} + 140\text{ MJ} + 1631\text{ MJ} + (23\text{ MJ} - 282\text{ MJ}) = 1563\text{ MJ}.$$

By comparing the total lifecycle energy consumption of the 1997 telephone to the 1965 one, it is obvious that the 1997 telephone is less efficient by 140%, because if the high energy consumption during use stage, mainly in the Stand-By mode as mentioned earlier. Therefore a score of 0 is assigned to the 1997 telephone.

- **H&E Risk:** The scores of the health and environmental risk dimension for the eco-compass were calculated from the data presented in section 5.2.1, and in Appendix C. The 1965 telephone was considered the base case and given a score of 2, while the scores for the other three generations were based on comparing their results to the base case only. As discussed earlier in chapter 3, an improvement of more than 50% get a score of 4, while an improvement of more than 75% gets a score of 5, and a decrease by more than 100% gets a score of 0. Table 5.16 presents the scores for the H&E risk dimension of the eco-compass. The total eco-value score for the air emissions was calculated for each telephone by summing the eco-value for air emissions throughout the product lifecycle. The same methodology was applied to waterborne effluents, and to solid wastes. The final eco-value score for each telephone was calculated by averaging the eco-value scores for air emissions, waterborne effluents, and solid wastes. The weighting factors were assumed to be equal for all the environmental burdens, these factors are subject to change based on the assumptions of the users. In the case where the final eco-compass value does not average to a whole number, it is rounded down, as in the case of the 1978 telephone. The final eco-compass score was 2.5, which is an improvement that is less than 50%, therefore it is plotted as a score of 2.

Table 5.16 H&E Risk Calculations for Eco-compass

Final Eco-Value						
AE		WE		SW		
Eco-Value	Weighting Factor	Eco-Value	Weighting Factor	Eco-Value	Weighting Factor	**Eco-Value**
2	1	2	1	2	1	**2**
2.6	1	1.5	1	2.5	1	**2.2**
3.5	1	3.5	1	3.5	1	**3.5**
3.4	1	3	1	3.4	1	**3.3**

Calculations for the other eco-compass dimensions: resource conservation, service extension and revalorization have been presented earlier in the study. Figure 5.26 displays the eco-compass for the 1997 telephone compared to the 1965.

Table 5.17 Eco-compass Values for the Four Telephones

	Mass Intensity (g)	**Energy Intensity (MJ)**	**H & E Potential Risk (g)**	**Revalorization**	**Resource Conservation**	**Service Extension**
1965	2325	633	2	11	27	7
1978	1640	261	2	34	18	8
1989	824	1648	3	52.5	56	22
1997	1085	1563	3	73	54	26
Comparison 1965 - 1997	0.5	-1.5	NA	-5.6	-1.0	-2.9

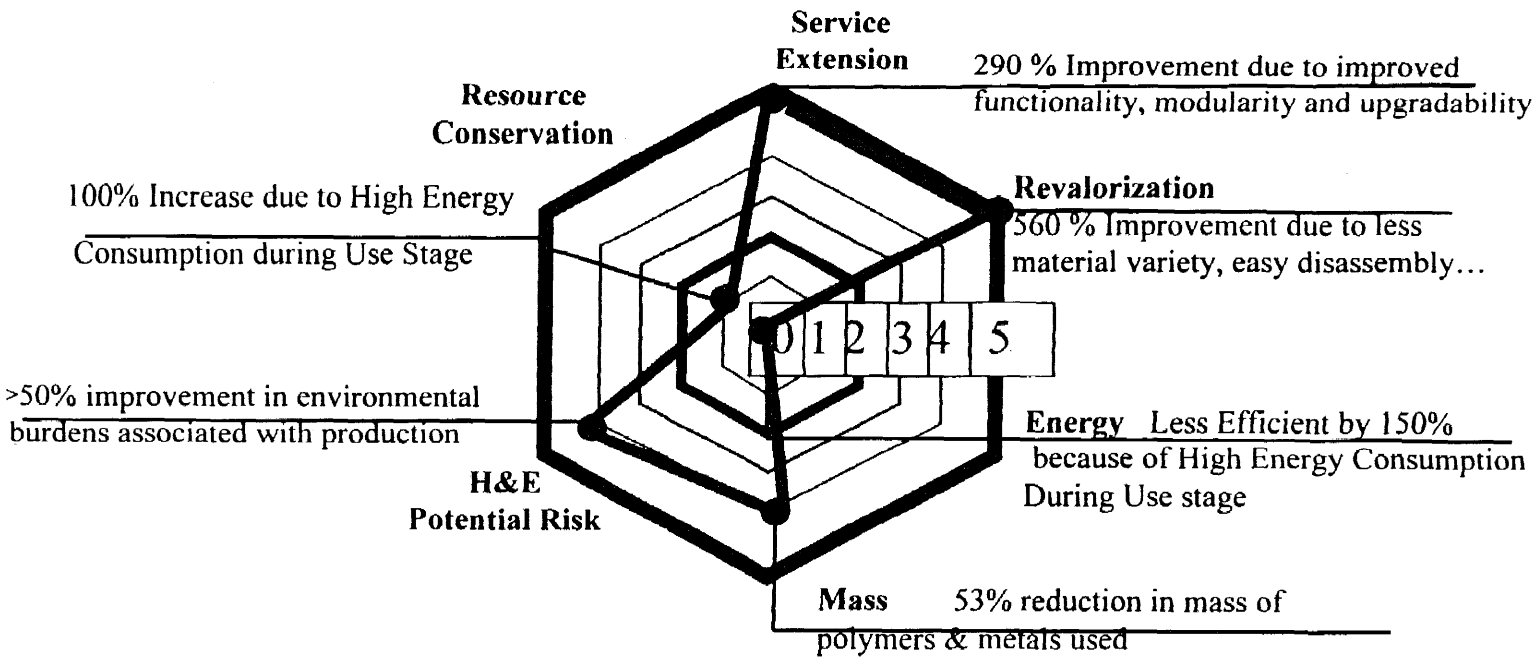


Figure 5.26 Eco-compass Comparison of 1997 Telephone to 1965

5.4.2 Resource Productivity (RP)

The assumptions made and methodology followed for implementing the resource productivity measure was discussed earlier in chapter 3. This section shows the calculations made for the RP and each of its variables.

- **Materials consumed**

Reflects the dollar value for all the feedstock materials in the telephone. Table 5.18 displays the value of each material and the total value for each phone. To calculate the total value of materials consumed incorporating the 95% yield rate assumption, divide the total value by 0.95. For example, for the 1997 telephone = $11.9 / 0.95 = $12.5.

Table 5.18 Dollar Value of Feedstock Material

	Total Plastic Quantity			**Total Metal Quantity**										**Other Materials**				
	ABS			**Steel**			**Aluminum**			**Copper**			**Total**			Total Weight	Total Value	**95 % Yield**
Phon	Wt (g)	**$ / g**	**$**	Wt (g)	**$ / g**	**$**	Wt (g)	**$ / g**	**$**	Wt (g)	**$ / g**	**$**	**Wt (g)**	Wt (g)	**$**	**Wt (g)**	**$**	**$**
1965	944	0.0022	2.08	963	0.0001	0.096	62.89	0.0013	0.08	180	0.0018	0.315	1206	175.47	10	2325	12.6	13.2
1978	1175	0.0022	2.59	210	0.0001	0.021	62.42	0.0013	0.079	22.25	0.0018	0.039	295	169.77	10	1640	12.7	13.4
1989	526	0.0022	1.16	132	0.0001	0.013	0.93	0.0013	0.001	4.11	0.0018	0.007	136.8	161.31	10	824	11.2	11.8
1997	846	0.0022	1.87	121	0.0001	0.012	0.85	0.0013	0.001	6.14	0.0018	0.011	127.7	111.43	10	1085	11.9	12.5

- **Materials Recycled**

Reflects the dollar value for all the recycled material recovered from the telephones. The materials recovered from the telephones are only metals and copper in the circuit boards, which is assumed to be 10% by weight. Table 5.19 displays the value of each material and the total value of recycled material for each phone. To calculate the total value of materials recycled incorporating the 95% yield rate assumption, multiply the total value by 0.95. For example, for the 1997 telephone = $0.0225 * 0.95 = $0.02

Table 5.19 Dollar Value of Recycled Material

	Total Metal Quantity										Other Materials					
	Steel			Aluminum			Copper			Total					Total Value	95 % yield
Phone	Wt (g)	$ / g	$	Wt (g)	$ / g	$	Wt (g)	$ / g	$	Wt (g)	Wt (g)	% of copper Wt (g)	$ / g	$	$	$
1965	963	0.0000937	0.09	62.89	0.000157	0.00987	179.96	0.00064	0.11517	1205.91	175.47	17.547	0.00064	0.0112	0.2265	0.22
1978	210	0.0000937	0.02	62.42	0.000157	0.0098	22.25	0.00064	0.01424	294.99	169.77	16.977	0.00064	0.0109	0.0546	0.05
1989	132	0.0000937	0.01	0.93	0.000157	0.00015	4.11	0.00064	0.00263	136.79	161.31	16.131	0.00064	0.0103	0.0254	0.02
1997	121	0.0000937	0.01	0.85	0.000157	0.00013	6.14	0.00064	0.00393	127.71	111.43	11.143	0.00064	0.0071	0.0225	0.02

- **Energy in Production**

The cost of energy was earlier assumed to be $0.10/kWh, $0.02778 /MJ. To calculate the dollar value of energy during production, the cost of energy ($0.10/kWh, $0.02778 /MJ) is multiplied by the energy during the production stage, which was presented earlier in section 5.2.3 and listed in Table 5.8, The results are displayed in the following Table 5.20:

Table 5.20 Value of Production Energy for the Telephones

Telephone	1965	1978	1989	1997
Energy Value ($)	16.2	8.3	4.0	3.9

- **Energy Consumption During Recovery**

The cost of energy was earlier assumed to be $0.10/kWh, $0.02778 /MJ. To calculate the dollar value of embodied energy and energy during recycling, the cost of energy ($0.10/kWh, $0.02778 /MJ) is multiplied by the calculations made earlier in section 5.2.3 for embodied energy and energy during recycling, which are listed in Table 5.10. The results are displayed in the following Table 5.21:

Table 5.21 Value of Energy Consumed during Recovery of the Telephones

Telephone	**1965**	**1978**	**1989**	**1997**
Shredding Energy ($)	1.39	0.98	0.49	0.65
Embodied Energy ($)	8.7	10.9	4.9	7.8
Total Recovery Energy ($)	-7.31	-9.92	-4.41	-7.15

- **Lifetime Energy Use**

The cost of energy was earlier assumed to be $0.10/kWh. To calculate the dollar value of energy during use, the cost of energy ($0.10/kWh) is multiplied by the calculations made earlier in section 5.2.3 for energy consumption during use, which are listed in Table 5.9. The results are displayed in the following Table 5.22:

Table 5.22 Value of Energy Consumption of the Telephones during Use

Telephone	1965	1978	1989	1997
Energy ($)	7	7	45	45

Using the above calculations and the values assumed for the economic value added and product lifetime for each telephone as mentioned in chapter 3, the following Table 5.23 quantifies the total values of the RP for the four telephones.

Table 5.23 Total RP Values

	Economic Value added ($)	Product Lifetime (Yr)	Material Consumed ($)	Material Recycled ($)	Production Energy ($)	Recycling Energy ($)	Embodied Energy ($)	Lifetime Energy Use ($)	RP
1965	140	15	13.2	0.22	16.2	1.39	8.7	7	74.0
1978	140	15	13.4	0.05	8.3	0.98	10.9	7	114.8
1989	70	7.5	11.8	0.02	4.0	0.49	4.9	45	9.3
1997	70	7.5	12.5	0.02	3.9	0.65	7.8	45	9.6

CHAPTER 6

CONCLUSIONS

6.1 Summary

The aim of this study was to evaluate the true impact and the effectiveness of the DFE guidelines on the 1997-DFE designed phone. Several environmental and non-environmental performance attributes were considered for this evaluation, in which the values of the previous generations were used to forecast and predict values for the 1997 telephone. After studying the various performance metrics considered, and comparing the predicted values of the 1997 telephone to the actual values, the general conclusion is that DFE guidelines did Not have a direct impact on many of those noticed improvements, except for some performance metrics such as the number of parts.

The study also aimed at introducing and developing a methodology that can be followed for assessing DFE guidelines. The methodology followed used the concepts of MLCE for quantifying the material flow, energy consumption, and environmental burdens associated with the telephones throughout their lifecycle. Also the trend analysis was used to evaluate performance attributes by forecasting and predicting ”next generation” values. The MLCA Software was also introduced as a useful tool for evaluating the environmental performance of the telephones, and to simplify the data intensive process of conducting and LCA.

6.2 Demanufacturing Summary

Following is a summary of the major results extracted from the demanufacturing of the four telephones:

- 1965 telephone contained many complex parts and subassemblies that were mostly fastened using screws. Disassembly process was tedious and took approximately 32 minutes.
- 1978 telephone parts and subassemblies became less complex as more circuit boards were integrated into the telephone design. The disassembly time was still high approximately 27 minutes, and so were the number of parts, 165.
- 1989 telephone noticed a dramatic change in design. Telephone became solely dependent on the circuit board. Disassembly time, number of parts, and the weight of the telephone were all reduced by more than 50%.
- 1997 DFE-designed phone noticed only minor improvements over the 1989 telephone, but generally its performance was below that of the 1989 telephone. Materials, energy, and environmental burdens were higher due to the larger weight of the telephone. Disassembly time was less, but the disassembly process of the handset was complex due to use of strong adhesives and snap-fits for fastening the covers.
- As the back covers of the base units were disassembled, it was noticed that the internal components of the four telephones were all flipped.

6.3 DFE Guideline Assessment

The guidelines were divided into 5 major categories: Environmental Burdens, Material Conservation, Energy Conservation, Service Extension, and Demanufacturing. From the analysis conducted on the telephones, and the comparison of the predicted values to the actual values of the 1997 telephone, it is concluded that DFE guidelines had no direct affect on most of the improvements noticed on the "DFE-designed" telephone.

- **Environmental Burdens**

The emissions generated from the manufacturing of the feedstock materials for the 1997-DFE designed telephone, were in general the lowest amongst the other telephone generations. But, those reductions were not attributable to DFE guidelines, since all the actual emissions were more than the extrapolated values. In general, reduction was due to less dependency on metals, where aluminum dropped from 62g in the 1978 to 0.9g in 1997, which had a high impact on reducing carbon monoxide emissions. Copper on the other hand, has the highest impact on solid wastes, was reduced from 180g in the 1965 telephone to 6g in 1997 one.

- **Materials Conservation**

Dematerialization efforts occurred at a rapid ratio due to substitution of electronics for older mechanical components and use of lighter weight plastics for materials. Despite this reduction. the actual value for the weight of the 1997 telephone was more than the extrapolated value. This was due to the design of the covers and stand of the 1997 telephone, which consumed more material, mainly ABS. Once again DFE guidelines had no impact on this metric.

- **Energy Conservation**

The energy consumption during the use stage was considered the highest throughout the product lifecycle. Energy consumption during the Stand-By mode was 13 times more than consumption during the In-Use mode for the 1989 and 1997 generations, while for the 1965 and 1978 generations, the Stand-By energy consumption was negligible. Therefore designers efforts must concentrate on radically reducing energy consumption during the Stand-By mode. Energy consumption during the other lifecycle stages was relatively low compared to the use stage.

- **Service Extension**

This was defined as the modularity, commonality and upgradability of the telephone subassemblies. The modularity of certain subassemblies improved from 1989 to 1997, such as the keypad subassembly, which was reduced from 15 to 3 parts only. In general the 1997-DFE designed telephone noticed improvement in service extension over the previous generations.

- **Demanufacturing**

The metrics quantified under demanufacturing were: disassembly time, number of fasteners and the ISO materials marking. The actual disassembly time was more than the extrapolated value, mainly because of use of adhesive in fastening the 1997 telephone handset. The number of fasteners, whether snap-fits or screw, were reduced but remained larger than the extrapolated values. Therefore DFE guidelines had no affect on reductions over those two metrics. On the other hand, plastics parts of the 1997 telephone were the only ones stamped with ISO material identification.

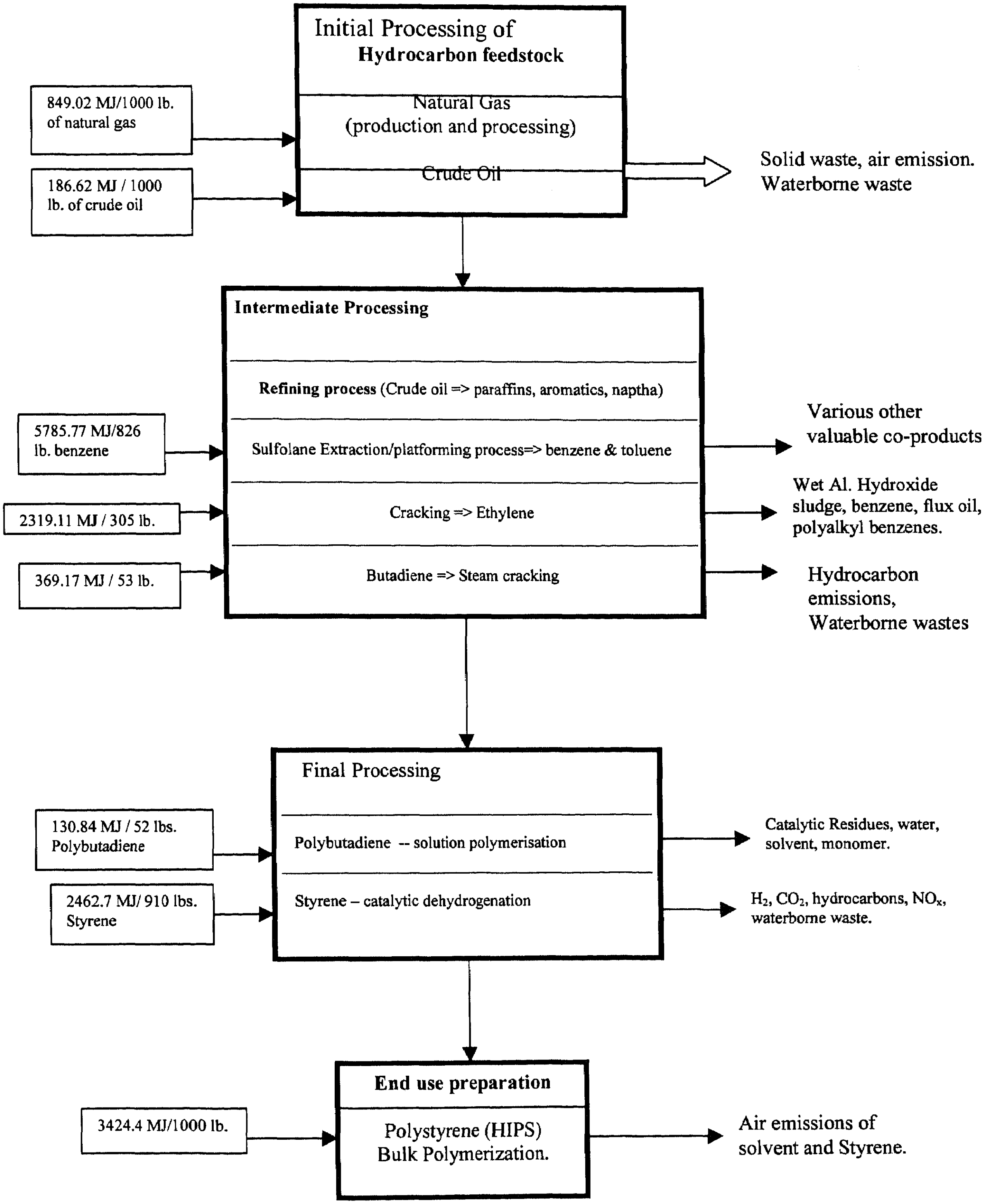
6.4 Future Work

- This thesis study presented a methodology of evaluating performance attributes. In order to obtain a more accurate prediction for new generations of products (telephones), more generations of the same product need to be analyzed and integrated into the study
- Environmental burdens analysis must be expanded to include not only environmental burdens generated from the power source, but also those generated during the production, use and recovery stages of the product lifecycle
- Improvements in processing of primary and secondary feedstock material from 1965 to 1997 were not incorporated in the study, mainly in the environmental burdens calculations, where no improvements in the processes was assumed. Future work must integrate this factor into the analysis
- Develop a standardized set of performance metrics that effectively quantify and evaluate the environmental performance of products
- More dependency on software's such as the MLCA software that focuses on processes that deal with end-of-life options of one product and the beginning of the lifecycle of another product. More emphasis should be concentrated on understanding these processes, and to develop better models for them

APPENDIX A

ENERGY AND ENVIRONMENTAL BURDENS OF FEEDSTOCK MATERIAL

This appendix includes the generic framework for primary and secondary processing of the plastic materials: HIPS, PVC, and PC. It also includes the environmental burdens associated with the manufacturing of those materials, and the references used for all this information. The energy information presented here is all in MJ /1000 LB of material, while the environmental data are in Lb / 1000Lb of material.



Total:15527.63 MJ / 1000 lbs. of HIPS
Total does not include the energy required for transportation.

Figure A.1 Generic Framework for HIPS Processing.

Table A.1 Environmental Burdens Associated with Processing of HIPS.

Processes	**Solid Wastes(LB)**	**Air Emissions LB)**	**Waterborne Wastes(LB)**
Initial Processing (Drilling and processing) 1000 cubic feet	?	Particulate: 0.004 Nitrogen Oxide:0.258 Sodium Dioxide: 0.009 Carbon Monoxide: 0.094 Hydrocarbons: 0.594	Acids: 0.037 Metal ions: 0.011 Dissolved solids:0.22
Natural Gas Production 1000 lbs	?	Hydrocarbons: Methane: 10	Dissolved solids: 3.9 (in the form of brine)
Crude Oil manufacturing 1000 lbs.	0.6	Hydrocarbons: 1.4	Dissolved solids: 11
Intermediate Processing (refining of liquid hydrocarbon, production of ethylene)	?	**Refining of liquid HC fuel: 1000 gal.** Particulate: 3.17 Nitrogen Oxide: 11.3 Sodium Dioxide: 25.6 Carbon Monoxide: 3.17 Aldehydes: 0.34 Other organics: 0.37 Ammonia: 0.39	**Refining of liquid HC fuel: 1000 gal.** BOD: 0.23 COD: 0.78 Suspended solids: 0.46 Dissolved Solids: 1.4 Phenols: 0.06 Sulphides: 0.085 Oil: 0.13 Metal Ions : 1.64 Acids: 5.68
	Ethylene: (284 lb) 0.284	**Ethylene:** Hydrocarbons: 0.28	**Ethylene:** BOD:0.568 COD:1.4768 Oil: 0.5112 Suspended Solids:0.8236
	Butadiene: (71.05 lb) 0.052	**Butadiene: (71.05 lb)** Hydrocarbons: 0.095	**Butadiene: (71.05 lb)** BOD: 0.053 COD:0.23 Oil: 0.003 Suspended solids:0.01
	Benzene: **(792 lb)** 1	**Benzene: (792 lb)** Particulates: 0.27 Hydrocarbons: 2.45 Sulfur Oxides: 2.69 Aldehydes: 0.039 Other organics: 0.039 Ammonia: 0.04	**Benzene: (792 lb)** BOD: 0.027 COD: 0.09 Oil: 0.01 Suspended solids: 0.055 Sulfides: 0.01 Phenols: 0.007
Final processing	**Styrene: (910lb)** .91	**Styrene: (910 lb)** Hydrocarbons: 4.55	**Styrene: (910 lb)** BOD: 2.66 COD: 6.45 Oil: 0.42 Suspended solids: 2.66
	Polybutadiene: **(70 lb)** 0.007	**Polybutadiene:** Hydrocarbons: 2.87	**Polybutadiene:** BOD: 0.0287 COD: 0.0581 Oil: 0.0049 Suspended Solids: 0.0875
End Use Preparation (production of High impact Polystyrene) 1000 lbs.	**HIPS: (1000lb)** 5	**HIPS: (1000lb)** Hydrocarbons: 2.9	**HIPS: (1000lb)** BOD: 0.19 COD: 0.87 Oil: 0.01 Suspended solids: 0.24

All figures are from Reference No. Table A.2

Table A.2 References for Energy and Environemntal Burdens from Processing of HIPS

#	Product	Energy for 1000lb HIPS (MJ)	Source	Assumptions (if any)
1	Polystyrene	3424.4	Hydrocarbon Processing, Nov. '95 [17], Pg. Energy Analyses of 108 Industrial Processes, Sep'85	We use the higher number.
2	Styrene	2462.7	Hydrocarbon Processing, Nov. '85 [16], Pg. 169	
3	Polybutadiene	130.84	Plastics: Resource and Environmental Profile Analyses, 1974 [6], Pg. 87	
4	Butadiene	369.17	Plastics: Resource and Environmental Profile Analyses, 1974 [6], Pg. 84	
5	Ethylene	2319.11	Energy Analyses of 108 Industrial Processes, Sep'85 [17], Pg. 204	
6	Benzene	5785.77	Plastics: Resource and Environmental Profile Analyses, 1974 [6], Pg. 73	
7	Natural gas	849.02	Plastics: Resource and Environmental Profile Analyses, 1974 [6], Pg. 43	
8	Crude oil	186.62	Plastics: Resource and Environmental Profile Analyses, 1974 [6], Pg. 70	
	Total :	**15527.63**		

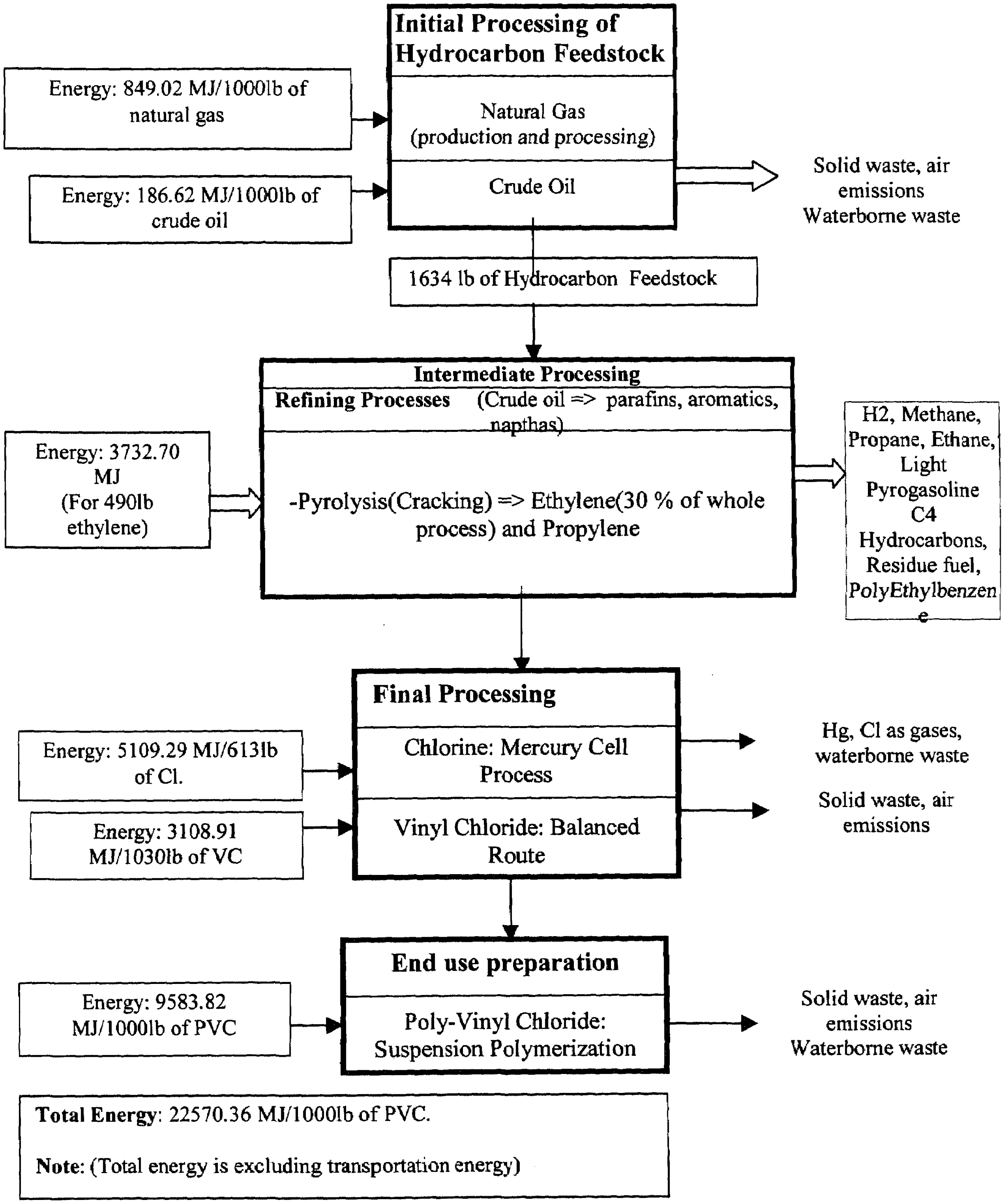


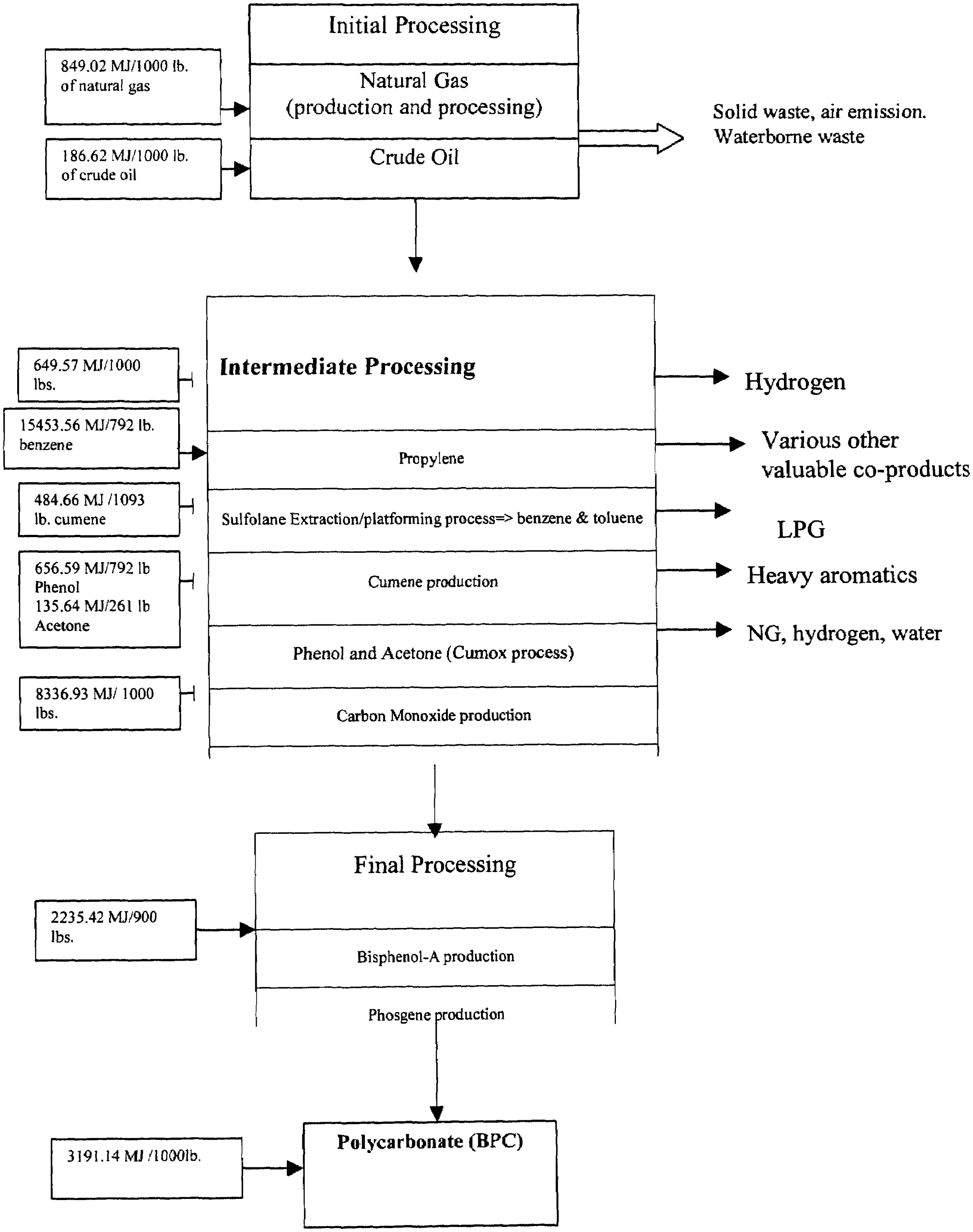
Figure A.2 Generic Framework for PVC Processing.

Table A.2 Environmental Burdens Associated with Processing of PVC.

Processes	**Solid Wastes(lb.)**	**Air Emissions(lb)**	**Waterborne Wastes**
Initial Processing (Drilling and processing)	?	Particulate:0.004 Nitrogen Oxide:0.258 Sodium Dioxide:0.009 Carbon Monoxide:0.094 Hydrocarbons:0.594	Acids:0.037 Metal ions:0.011 Dissolved Solids:0.22
Natural Gas Production	?	Hydrocarbons: Methane: 10	Dissolved solids: 3.9 (inform of brine)
Crude Oil Manufacturing	0.6	Hydrocarbons:1.4	Dissolved solids: 11
Intermediate Processing (refining of liquid hydrocarbon , production of ethylene)	?	**Refining of 1000 gal. Liquid hydrocarbon fuel:** Particulate:3.17 Nitrogen Oxide:11.3 Sodium Dioxide:25.6 Carbon Monoxide:3.17 Aldehydes:0.34 Other Organics:0.37 Ammonia:0.39	**Refining of 1000 gal. Liquid hydrocarbon fuel:** BOD:0.23 COD:0.78 Suspended Solids:0.46 Dissolved Solids:1.4 Phenols:0.06 Sulfides:0.085 Oil:0.13 Metal ions:1.64 Acids:5.68
	Ethylene: 0.49	**Ethylene:** Hydrocarbons:0.49	**Ethylene:** BOD: 0.98 COD: 2.548 Oil: 0.882 Suspended solids:1.421
Final Processing (production of vinyl chloride)	**Cl:** 49.028	**Cl:** Hg Vapour:0.00428 Cl:2.5307	**Cl:** Hg:0.000613 Lead:0.00367 Suspended Solids:0.123
	VC: 1.03	**VC:** Hydrocarbons:16.5418	**VC:** COD:2.1733 BOD:0.8436 Suspended Solids:0.927
End Use Preparation (production of PVC)	3	Hydrocarbons as VCM:30 Particulates:0.34	BOD:0.45 COD:2.25 Suspended Solids:0.45

Note:

- All figures are from Reference No. Tables 3.2 & A.2
- All figures refer to requirements for production of 1000 lb of PVC .



TOTAL ENERGY: 18269.15 MJ / 1000 lbs. PC
Total does not include the energy required for transportation.
NOT COMPLETE—UNDER RESEARCH

Figure A.3 Generic Framework for PC Processing

APPENDIX B

DEMANUFACTURING RESULTS

This appendix includes data extracted from demanufacturing the telephones. For each of the 1989, 1978, and 1965 telephones, it displays the disassembly procedure sheet, inventory tables, reverse fishbone diagrams, and revalorization respectively.

Table B.1 Disassembly Procedure Sheet for the 1989 Telephone

Disassembly Procedure (Black 89 Phone)

Subassembly	Tool	Procedure	Time(sec)
Base Bottom	Hand	Remove handset subassembly, cord.	8
	Hand	Snap off stand	17
	Tool 1	Remove 4 rubber legs	10
	Tool 1	2 screws- separate base from top & handset hook	88
	Tool 1	1 screw- remove weight	17
Handset	Tool 2	2 Screws, Pry off Housings	50
	Hand	Remove circuit board	1
	Hand	Remove Mic, Phone Jack & foam	3
	Hand	Remove Speaker & rubber gasket	20
Base Top	Tool 1	2 screws- lift out circuit board	26
	Tool 1	Pry off face template & translucent (sticky) cover	84
	Hand	Separate: speaker, sticky foam, buttons, Hook.	30
			354
			6 Min 30 Sec

Tools Used:

1- Screw driver, medium size, straight blade

2- Screw driver, medium size, Philips blade

Table B.2 Inventory Table for the 1989 Telephone

Subassembly	Part	Quantity	Function	Color	Weight(g)	Material	No. of Screws	No. of Snap Fits	Market Value
Top Cover									
	Top Cover	1	house internal parts	Black	136.11	plastic	0	0	0.0
	Plastic protector	1	separate keys/ aesthetic quality	Grey	13.89	plastic	0	0	0.0
	Plastic sheet	1	block debris	white	1.39	plastic	0	0	0.0
	Sticky Foam	1	cushions spkr. Phone Mic..	Grey	5.56	foam	0	0	0.0
	Info. Paper	1	display info.	white	1.39	paper	0	0	0.0
	Hook	1	turns phone "on"	Grey	1.68	plastic	0	0	0.0
	hook holder	1	support for handset	Black	2.44	plastic	1	0	0.0
Base									
	Bottom Base	1	house internal parts	Black	125	plastic	2	0	0.0
	Weight	1	"balance" phone	gold	101.39	steel	1	0	9.5E-03
	screws	3	fasteners	silver	3.24	steel	0	0	3.0E-04
	Stand	1	support phone, upright display	Black	77.78	plastic	0	2	0.0

Table B.2 (continued)

Subassembly	Part	Quantity	Function	Color	Weight(g)	Material	No. of Screws	No. of Snap Fits	Market Value
Circuit Board									
	Circuit board	1	electronic functions	green	152.78	circ. Board	0	0	1.3E-02
	Keypad	1	user input	Grey	16.67	plastic	3	0	0.0
	Speaker	1	transmit voice	Grey	18.06	Plastic, Steel	2	0	1.7E-03
	screws	2	fasteners	silver	2.78	steel	0	0	2.6E-04
	Keys (buttons)	12	display #'s, benefit users	Black/white	11.4	plastic	0	0	0.0
	Speaker pad	1	activates spkr. Phone	Grey	0.55	plastic	2	0	0.0
	Screws	2	fasteners	dark Grey	0.59	steel	0	0	5.5E-05
	Speaker key	1	activates spkr. Phone	Black	0.71	plastic	0	0	0.0
Handset									
	outside handset	1	house internal parts/ facilitate use	Black	43.06	plastic	0	8	0.0
	inside handset	1	house internal parts/ facilitate use	Black	33.33	plastic	1	0	0.0
	C.B.	1	transmit voice	mix	7.14	circ. Board	0	0	5.9E-04
	Mic	1	transmits Voice	Grey	0.93	Aluminum	0	0	1.5E-03
	Mic Cover	1	Protects Mic	white	0.79	rubber	0	0	0.0
	Phone Jack	1	Transmits signals	Grey	1.61	plastic/copper	0	0	1.0E-03

Table B.2 (continued)

Subassembly	Part	Quantity	Function	Color	Weight(g)	Material	No. of Screws	No. of Snap Fits	Market Value
Handset (Cont'd)									
	speaker	1	transmits Voice	beige	34.72	plastic/steel	0	0	3.3E-03
	spkr. Gasket	1	block debris	Grey	4.17	rubber	0	0	0.0
	cord	1	transmit signal	Black	25	plastic,copper	0	2	1.9E-02
Total		43			824.16		12	12	$0.05

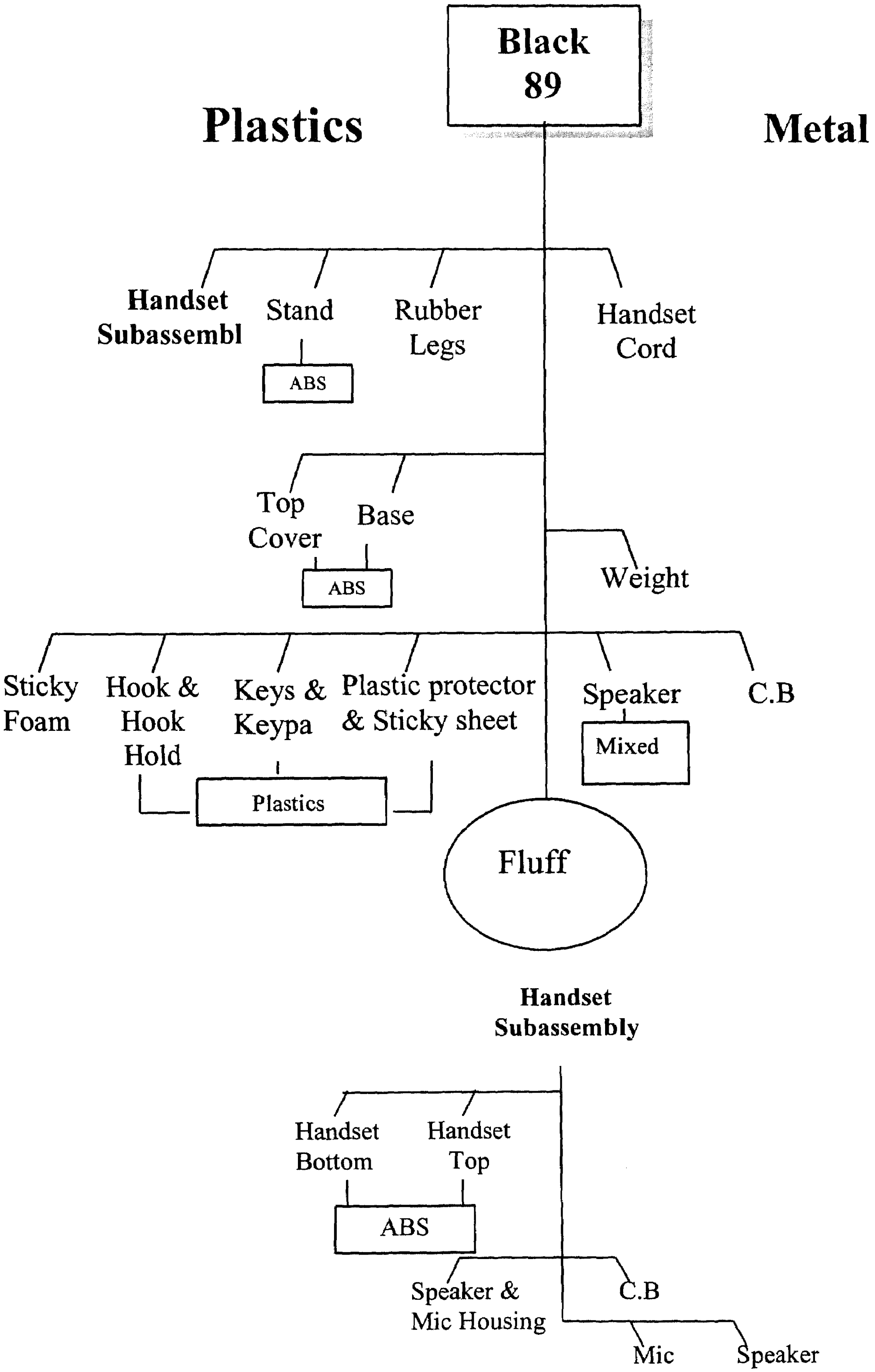


Figure B.1 Reverse Fishbone Diagram for the 1989 Telephone

1) # of different Mat.	<7	6	5	4	3	2	POINTS
POINTS	0	6	12	18	24	30	12
2) # of diff. Fasteners	<6	5	4	3	2	1	POINTS
POINTS	0	5	10	15	20	25	15
3) Mat. Marking	0%	20%	40%	60%	80%	100%	POINTS
POINTS	0	3	6	9	12	15	0
4) Time (MIN)	30	25	20	15	10	5	POINTS
POINTS	1.25	2.5	3.75	5	6.25	7.5	7.25
5) Tools	Unavailable	Special	OEM	Mechanic	Simple	No-Tools	POINTS
POINTS	1	2	3	4	5	6	5
6) Access	(Not-Visible)	Complex-Motion	Dual-Axis	(≥ 4" Deep-Head)	X-Y Axis	Z- Axis	POINTS
POINTS	1	2	3	4	5	6	6
7) Force	Cutting	High-Impact	Low-Impact	Leverage	Torsional	Axial	POINTS
POINTS	0.75	1.5	2.25	3	3.75	4.5	4.5
8)Part -Hold	(Automated ......)		Complex-Fixture	Fixture-Necessary	Two-Hand	No-Hold	POINTS
POINTS	0.5	1	1.5	2	2.5	3	2.5
9)Instruction	Special-Classes	Whole-Day	Half-Day	≤ 5 - 30 min	Simple	None	POINTS
POINTS	0.5	1	1.5	2	2.5	3	3

SCORE : 55.25

Notes:
No of different materials: ABS, Rubber, Aluminum, Copper and Steel.
Fasteners: Snap Fits, Screws and Adhesives.

Figure B.2 Revalorization for the 1989 Telephone

Table B.3 Disassembly Procedure Sheet for the 1978 Telephone

Disassembly Procedure (White78 Phone)

Subassembly	Tool	Procedure	Time(sec)
Handset	Tool 1	1 screw, Pry off cover	60
	Tool 1	5 Screws, Remove bracket	100
	Hand	Remove mic	3
	Hand	Remove rubber gasket	3
	Hand	Remove speaker from bracket	2
	Hand	Remove clear plastic cover & rubber gasket from bracket	3
	Tool 1	4 Screws, Remove wiring from bracket	60
	Tool 3	Pry off 4 connection tabs	32
Base Bottom	Tool 1	Pop out 4 Rubber Legs	24
	Tool 1	4 Screws , separate base from inside hold and top cover.	80
	Tool 1	2 Screws- remove Jack/Cord Holder	30
Base Top	Tool 1	Pry off metal face	10
	Tool 1	Pry out phone # label	10
	Tool 1	4 Screws- Seperate Top cover from inside hold.	105
	Hand	Pop off receiver/hook latch	10
Inside Hold	Tool 1	2 Screws- remove line select board subassembly	35
	Tool 1&2	2 Screws & 2 Wires- "R" button removal	180
	Hand	Slide out dummy button	3
	Tool 1	4 Screws- remove speaker phone	30
	Tool 1	2 Screws- remove hook latch	50
	Tool 1&2	4 Screws & 9 wires cut - remove keypad subassembly	140
	Hand	Circuit board removal	30
	Hand	Remove line jack	30
	Tool 1	2 Screws - remove volume control	23
	Hand	Remove speed dial display Subassembly	5
	Hand	Pop out transformer and board (Sticky Tape) Subassembly	10
Keypad	Tool 1	2 Screws- separate plastic shield	20
	Knife	Cut tape	10
	Hand	Remove clear plastic case	17
	Tool 1	2 Screws- remove mounting bracket	20
	Tool 1&2	7 screws & 1 wire - remove keys & C.B.	180
Speed dial display	Tool 1	3 screws- plastic cover & wiring harness	175
Transformer	Hand	4 clips- remove board	10
line Select	Tool 1	4 screws Separate C.B. from plastic cover and key buttons	70
	Hand	Remove Buttons, and Clear indicators From Plastic Cover	60
	Hand	Remove Gasket from Cover	10
Tools Used:			**1640**
			27 Min 33 Sec

1- Screw driver, medium size, straight blade
2- diagonals
3- Plier

Table B.4 Inventory Table for the 1978 Telephone

Subassembly	Part	Quantity	Function	Color	Weight (g)	Material	No. of Screws	No. of Snap Fits	Market Value
Top Cover									
	Top Cover	1	cover internal parts	white	95.83	Plastic	4	0	0.0
	Top key cover	1	separate keys/ display info.	wood	93.06	Steel	0	3	8.72E-03
	Screws	4	fasteners	silver	11.11	steel	0	0	1.04E-03
	cradle	1	lever - activates phone on and off	clear	12.5	Plastic	0	2	0.0
	support bracket	1	supports plastic strip	White	2.78	Plastic	0	0	0.0
	Plastic Strip	1	Cover paper	Clear	1.2	Plastic	0	0	0.0
Inside Hold									
-	Inside hold (middle)	1	internal support	white	265.28	Plastic	4	0	0.0
	Phone jack	1	Transmits signals to handset	Mixed	3.97	Plastic / copper	0	0	2.5E-03
	Circuit Board	1	circuit board/signal connector	Grey/ green	93.89	Plastic	2	2	0.0
	Screws	2	fasteners	Silver	1.39	steel	0	0	1.3E-04
	Transformer	1	network connector	white	73.61	Plastic	6	4	0.0
	line button housing	1	separates line buttons	white	19.44	Plastic	0	4	0.0
	line button circuit board	1	signals/connection (line board)	green/ black	70.83	Copper, Plastic	8	0	4.53E-02
	line button subassembly								
	Screws	6	fasteners	copper	1.39	copper	0	0	8.90E-04
	lit button display	2	"lit" button display	black/ clear	4.17	Plastic	0	4	0.0

Table B.4 (continued)

Subassembly	Part	Quantity	Function	Color	Weight(g)	Material	No. of Screws	No. of Snap Fits	Market Value
Inside Hold (Cont'd)									
	bracket	1	connector housing for A4	black	1.39	Plastic	0	0	0.0
	line buttons	10	line buttons and hold	white/ clear	13.89	Plastic	0	0	0.0
	line button gasket	1	line button separator	black	2.78	copper	0	0	1.78E-03
	Mech. Actuator	1	activates default line (turns phone "on")	silver	44.44	steel / plastic/ copper	2	0	2.84E-02
	Screws	2	fasteners	silver	0.5	steel	0	0	4.69E-05
	spring	1	redial button tension	silver	0.13	steel	0	0	1.22E-05
	redial button	1	redial button	white	1.26	Plastic	0	0	0.0
	mute button	1	part of button (mute)	white	1.41	Plastic	0	0	0.0
	bracket	1	part of button (redial)	clear	1.31	Plastic	0	0	0.0
	bracket, signal connector	1	make connections	clear	2.31	Plastic/Copper	0	0	1.48E-03
	Plastic sheet	1		brown	0.11	Plastic	0	0	0.0
	c.b.	1	transform and relay signals	green	12.8	c.b.	4	0	1.06E-03
	support bracket	1	bracket support	black	5.56	Plastic	2	0	0.0
	Screws	5	fasteners	silver	3.28	Steel	0	0	3.07E-04
	volume control	1	volume control	black	16.67	plastic, steel	2	0	1.56E-03

Table B.4 (continued)

Subassembly	Part	Quantity	Function	Color	Weight(g)	Material	No. of Screws	No. of Snap Fits	Market Value
Inside Hold (Cont'd)									
	Screws	2	fasteners	silver	1.39	steel	0	0	1.30E-04
	speed dial display								
	c.b.	1	connections for buttons	green	58.33	c.b.	2	0	4.82E-03
	support for info.	1	facilitate connections, absorb pressure	white	16.67	Plastic	1	3	0.0
	bracket	1	facilitate connections, absorb pressure	Black	2.78	Plastic	2	0	0.0
	gasket	1	Block Debris	Black	0.87	Rubber ?	0	0	0.0
	info. display	1	displays information	Black/White	0.64	Paper	0	0	0.0
	support	1	Supports c.b.	Clear	0.3	Plastic	0	0	0.0
	cover	1	Protects Info. Display	Clear	0.15	Plastic	3	2	0.0
	Screws	2	fasteners	silver	0.52	steel	0	0	4.87E-05
BASE									
	Base	1	cover internal parts/ support phone	white	234.72	Plastic	8	0	0.0
	white part for bottom base	1	line in/out (Part of base)	white	5.56	Plastic	0	0	0.0
	rubber legs for bottom base	4	support phone	white	2.78	rubber	0	0	0.0
	Phone jack	1	Receives signal from line	Mixed	11.84	Plastic / copper	0	0	7.58E-03
	Metal bracket	1	Supports phone jack	silver	7.86	Steel	1	0	7.36E-04

Table B.4 (continued)

Subassembly	Part	Quantity	Function	Color	Weight(g)	Material	No. of Screws	No. of Snap Fits	Market Value
Handset									
	inner handle	1	house spkr, microphone	white	37.05	Plastic	1	0	0.0
	outer handle	1	house spkr, microphone	white	40.61	Plastic	0	4	0.0
	inside bracket	1	hold spkr. micro.	black	30.96	Plastic	5	0	0.0
	phone jack wiring	1	transmit signals	multi	2.83	Plastic Copper	0	0	1.81E-03
	Thin black gasket	1	Block Debris	Black	0.68	Rubber ?	0	0	0.0
	Thick black gasket	2	Block Debris	Black	5.04	Rubber ?	0	0	0.0
	Mic.	1	transmits voice	silver/black	16.29	Alum/Plastic	0	0	2.56E-02
	Speaker	1	Transmits Voice	Silver / Grey	32.1	Alum.	0	0	5.04E-02
	white gasket	1	Holds Speaker	White	1.76	Plastic	0	2	0.0
	Connection tabs	4	Connects Speaker & Mic.	Silver	2.48	steel	0	0	2.32E-04
	Big screws	6	fasteners	silver	4.8	Steel	0	0	4.50E-04
	Small Screws	2	fasteners	silver	1.02	steel	0	0	9.56E-05
Speaker									
	Speaker	1	transmits voice	silver	34.03	Alum / Plastic	2	0	5.34E-02
	Wire	1	Transmits signal	mixed	1.3	Copper / Plastic	0	0	8.32E-04
	Speaker holder	1	Supports speaker	grey	9.57	Plastic	4	0	0.0
	Cover	1	Cover plate	grey	4.27	Plastic	0	2	0.0

Table B.4 (continued)

Subassembly	Part	Quantity	Function	Color	Weight(g)	Material	No. of Screws	No. of Snap Fits	Market Value
Speaker (Cont'd)									
	Gasket	1	Block debris	black	0.37	rubber ?	0	0	0.0
	Screw	1	Fastener	silver	0.92	steel	0	0	8.62E-05
Keypad									
	Circuit Board	1	electronic functions	green	98	Circuit board	5	0	8.10E-03
	Key Holder	1	Holds/ Separate keys	white	14.36	Plastic	0	3	0.0
	Inner Housing	1	Houses CB	clear	7.57	Plastic	0	2	0.0
	Housing	1	Houses CB	clear	5.16	Plastic	0	2	0.0
	Gasket Black Debris	1	Block debris	black	0.87	Plastic	0	0	0.0
	Key Separator	1	Separate Keys	Grey	7.16	Plastic	0	2	0.0
	Keys	12	No. Identifier	white	18.36	Plastic	0	0	0.0
	Steel Rods	7	Support	Silver	9.31	steel	0	0	8.72E-04
	Bracket	2	Supports CB	silver	17.32	steel	0	0	1.62E-03
	Spring	12	Tension	silver	1.2	spring steel	0	0	1.12E-04
	Support Bracket	1	Supports CB	silver	1.51	steel	0	0	1.41E-04
	Screws	8	fasteners	silver	5.29	steel	0	0	4.96E-04
Miscellaneous									
	cover	4	facilitate connections, absorb pressure	clear	13.89	Plastic	0	0	0.0
	Screws	12	fasteners	silver	11.12	steel	0	0	1.04E-03
		165			1639.9		68	41	$0.25

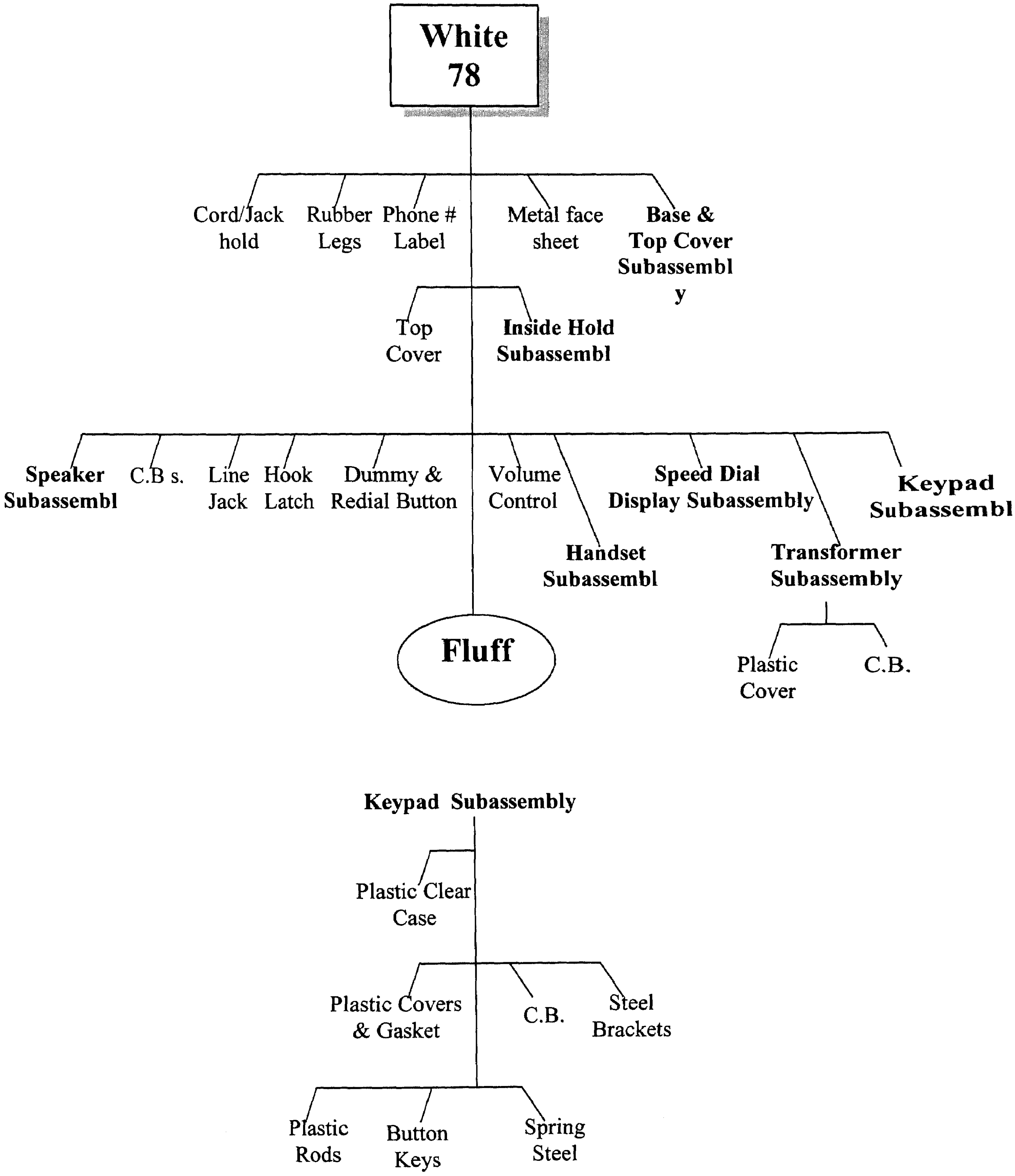


Figure B.3 Reverse Fishbone Diagram for the 1978 Telephone

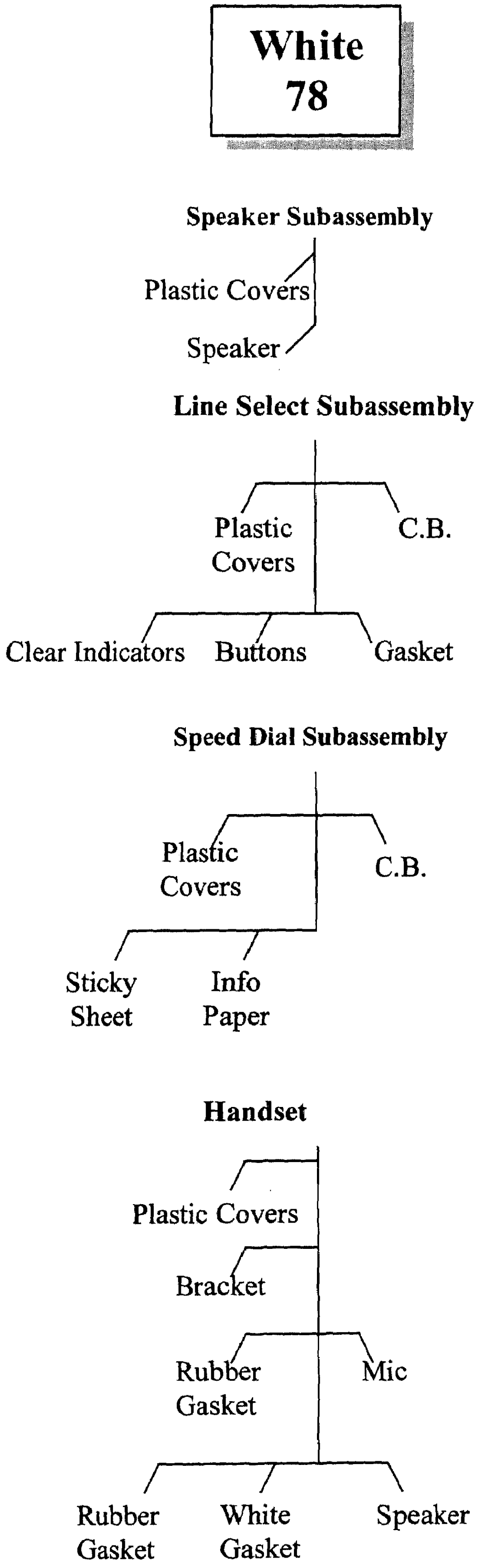


Figure B.3 Continued

1) # of different Mat.	<7	6	5	4	3	2	POINTS
POINTS	0	6	12	18	24	30	12
2) # of diff. Fasteners	<6	5	4	3	2	1	POINTS
POINTS	0	5	10	15	20	25	10
3) Mat. Marking	0%	20%	40%	60%	80%	100%	POINTS
POINTS	0	3	6	9	12	15	0
4) Time (MIN)	30	25	20	15	10	5	POINTS
POINTS	1.25	2.5	3.75	5	6.25	7.5	2.75
5) Tools	Unavailable	Special	OEM	Mechanic	Simple	No-Tools	POINTS
POINTS	1	2	3	4	5	6	5
6) Access	(Not-Visible)	Complex-Motion	Dual-Axis	(≥ 4" Deep-Head)	X-Y Axis	Z- Axis	POINTS
POINTS	1	2	3	4	5	6	5.4
7) Force	Cutting	High-Impact	Low-Impact	Leverage	Torsional	Axial	POINTS
POINTS	0.75	1.5	2.25	3	3.75	4.5	4.5
8)Part -Hold	(Automated ......)		Complex-Fixture	Fixture-Necessary	Two-Hand	No-Hold	POINTS
POINTS	0.5	1	1.5	2	2.5	3	2.5
9)Instruction	Special-Classes	Whole-Day	Half-Day	≤ 5 - 30 min	Simple	None	POINTS
POINTS	0.5	1	1.5	2	2.5	3	2.5

SCORE : 44.65

Notes:
No of different materials: ABS, Rubber, Aluminum, Copper and Steel.
Fasteners: Snap Fits, Screws, Tape and Adhesives.

Figure B.4 Revalorization for the 1978 Telephone

Table B.5 Disassembly Procedure Sheet for the 1965 Telephone

Disassembly Procedure (Green-65 Phone)

Subassembly	Tool	Procedure	Time(sec)
Handset			
	Hand	Remove Cord	6
	Hand	Twist off Covers	25
	Tool 1	2 Screws- Remove microphone & Speaker	10
Housing			
	Tool 1	Remove keypad cover	10
	Tool 1	2 Screws- Remove cover	10
	Tool 1	Remove screw & screw anchor	10
	Tool 1	Remove keyapd holder tab	8
	Tool 1	4 Screws-Remove bell subassembly	40
	Tool 1	2 Screws- Remove Line select subassembly	20
	Tool 1	9 Screws- Loose keypad assembly	85
	Tool 1	2 Screws- Remove latch/hook assembly	90
Key Pad			
	Hand	Remove Plastic covers	28
	Tool 1	7 Screws, remove grey keypad casings	85
	Hand	Remove buttons and linkage, and transformer	60
Bell			
	Tool 1	2 screws- remove solenoid	30
	Hand	remove steel supports from solenoid	10
	Tool 1	1 Screw- remove bell	12
	Tool 1	1 Screw- remove striker	10
	Hand	Separate base from magnet	22
	Tool 1	Remove Relay	15
Line Select			
	Tool 1	48 Screws- Remove Leads, wiring harness	226
	Tool 2	Cut 1 lead	5
	Hand	Light Bulbs	20
	Hand	Remove 6 push buttons, from metal front	20
	Hand	Remove plastic push button from Aluminum holder	5
	Tool 1	2 Screws- Remove metal front	33
	Tool 1	5 Screws, 4 clips, Remove plastic cover off transform	70
	Tool 2	Cut 22 solder joints	190
	Tool 2	Cut 24 Wire Connections	102
	Tool 3	Drill 3 Rivets	240
Base			
	Tool 3	3 Rivets, remove support bracket	240
	Tool 1	Remove rubber legs	15
	Tool 3	Drill 11 places- remove components	150
Tools Used:			**1902** 32 Min 15 Sec

1- Screw driver, medium size, straight blade
2- diagonals
3- drill with # 18 bit

Table B.6 Inventory Table for the 1965 Telephone

Subassembly	Part	Quantity	Function	Color	Weight(g)	Material	No. of Screws	No. of Snap Fits	Market Value
Handset									
	Cord handset	1	carries signals	green	34	Plastic, Copper	0	2	2 18E-02
	Handset	1	house speaker/microphone	green	92.56	Plastic	0	0	0 00
	Microphone Cap (talk in)	1	covers microphone	green	18.88	Plastic	0	0	0.00
	Speaker cap (hear)	1	covers speaker	green	20.04	Plastic	0	0	0.00
	Microphone	1	transmit voice	silver	75.05	Alum., Copper, Plastic	0	0	1.18E-01
	Speaker	1	transmit voice	silver	31.48	Alum., Plastic	2	0	4.94E-02
	Speaker Housing	1	Houses speaker/ makes connec	Grey	14.66	Plastic/steel/copper	2	0	9.38E-03
	Cotton Ball	1	muffle sound	white	0.6	Cotton	0	0	0.00
Top cover									
	Housing	1	house internal parts	green	202.87	Plastic	2	0	0.00
	Keypad cover	1	separate keys/# display	green	28.29	Plastic	0	2	0.00
	Screw	1	Fastener	silver	0.42	steel	0	0	3.94E-05
	Screw Anchor	1	Screw anchor	gold	1.58	brass	0	0	1.01E-03
	Keypad holder tab	1	Keypad holder tab	silver	0.44	steel	0	1	4 12E-05
Base									
	Bottom Plate	1	base/weight stabilizer	silver	218.11	Steel	4	0	2.04E-02
	Rubber Legs	4	support phone	red/silver	8	rubber	4	0	0.00
	bracket	1	internal support bracket for bell	brass color	48.51	Steel , rubber	4	0	4.55E-03
	Screws	4	Fastener	Silver	4	Steel	0	0	3.75E-04

Table B.6 (continued)

Subassembly	Part	Quantity	Function	Color	Weight(g)	Material	No. of Screws	No. of Snap Fits	Market Value
Network									
	Wiring Harness	1	house wiring/carry signals	Grey	302.21	Copper, Steel, Plastic	3	1	1.93E-01
	Transformer	1	transforms signals	white/red/ blue/silver	141.04	Copper, Silicon Steel, Plas	14	0	9.03E-02
	Wiring	1	carries signals	silver/ brown	31.86	Copper, Steel, Plastic	0	0	2.04E-02
	circuit connector	1	makes signal connections	Grey/silver	85.61	Plastic / Steel	53	6	8.02E-03
	line button support	1	weight balance/supports extension line buttons	Grey/silver	103.03	Steel, Pot metal	4	0	9.65E-03
	Bulbs	5	identifies "lit" extensions	red/silver/ clear	6.1	Glass, Steel	0	0	5.72E-04
	Linkages (buttons)	6	makes signal contact for line board	white/Grey	12.8	Plastic, Steel	0	0	1.20E-03
	Functions button board	1	identifies function and makes connections	white/red/ silver/clear	20	Plastic	0	0	0.00
	Functions button board Holder	1	Supports Function button board	silver	8.3	Aluminum	0	0	1.30E-02
	transformer connection board	1	Covers & connects transformer A1	Grey	6.92	Plastic	5	3	0.00
	Plate	1	support line buttons (extensions)	silver	59.65	Steel	3	0	5.59E-03
	Bracket	1	supports hook	silver/ brass	18.12	Steel	1	0	1.70E-03
	Plate	1	line board switch holder	copper	13.58	Copper	0	0	8.69E-03
	Plate	1	internal support	brass	17.27	Steel	3	0	1.62E-03
	Copper tabs	12	facilitate signal connections	copper	10.85	Copper	0	0	6.94E-03
Keypad									
	Keypad Circuit Board	1	transforms signals	tan/multi	153.45	Copper, Steel, Plastic	12	0	1.27E-02
	Keys	12	# identifier, used by operator	Grey/ white	19.32	Plastic	0	0	0.00
	Key Spring	12	Key Tension	Silver	1.26	Spring Steel	0	0	1.18E-04
	cover	1	house cb	clear	7.47	Plastic	0	0	0.00
	Keypad Casing (2)	1	separates buttons	Grey	7.47	Plastic	0	1	0.00
	cover (see A7)	1	house cb	clear	3	Plastic	0	0	0.00
	key Gasket	1	block debris	clear	0.1	Plastic	0	0	0.00
	Keypad casing(1)	1	separates buttons	Grey	14.75	Plastic	5	0	0.00

Table B.6 (continued)

Subassembly	Part	Quantity	Function	Color	Weight(g)	Material	No. of Screws	No. of Snap Fits	Market Value
Bell									
	Bell	1	sounds bell for call	brass	27.9	Brass	4	0	1 79E-02
	Bell Striker	1	Hits against bell to make sound	Multi	14.51	Brass/steel/copper.	0	0	9 29E-03
	Bracket, volume control	1	volume control for bell	Grey	148.87	Plastic/ Pot metal	8	0	1.39E-02
	Relay	1	relay signal-activates solenoid	silver	13.38	Steel, Plastic	0	0	1.25E-03
	Steel Brackets	4	Support brackets	Silver	6.9	Steel	0	0	6.47E-04
	Solenoid	1	Generates electricity	Yellow/Brown	55.5	Copper/ Plastic	0	0	3.55E-02
	Steel Supports	16	Supports solenoid & creates magnetic field	Black	15.86	Steel	0	0	1.49E-03
	Bracket	1	Support for solenoid	Silver	50.47	Steel/copper	0	0	3.23E-02
	bell sound enhancer	1	alter bell sound	white	1.83	Plastic	0	0	0.00
Miscellaneous									
	Telephone cord	1	carries signals	Grey	54.47	Plastic, Copper	0	2	3 49E-02
	Screws and springs	16	fasteners/used w/buttons	silver	14.84	Steel , spring steel	0	0	1.39E-03
	Brackets	4	internal support brackets	silver	29.69	Steel	7	0	2 78E-03
	Broken Pieces	1	cushioning, internal supports	brown/Grey	18.42	Steel, Plastic	0	0	1.73E-03
	Phone Jack Wiring	1	transmit signals	Grey	4.59	Copper, Plastic	0	1	2.94E-03
	Wires	11	transmits signals	red	3.71	Copper / plastic	0	0	2.37E-03
	Broken plastic pieces	6	support	Green / white	10.65	Plastic	0	0	0.00
	Plastic cover	1	Cover	Light blue	2.22	Plastic	0	0	0.00
	Phone Jack	1	transmits signals	Grey/ multi	2.83	Plastic/ copper	0	0	1.81E-03
	Screws	8	Fasteners	Silver	4.64	Steel	0	0	4 35E-04
	Total	165			2324.93		140	19	$0.76

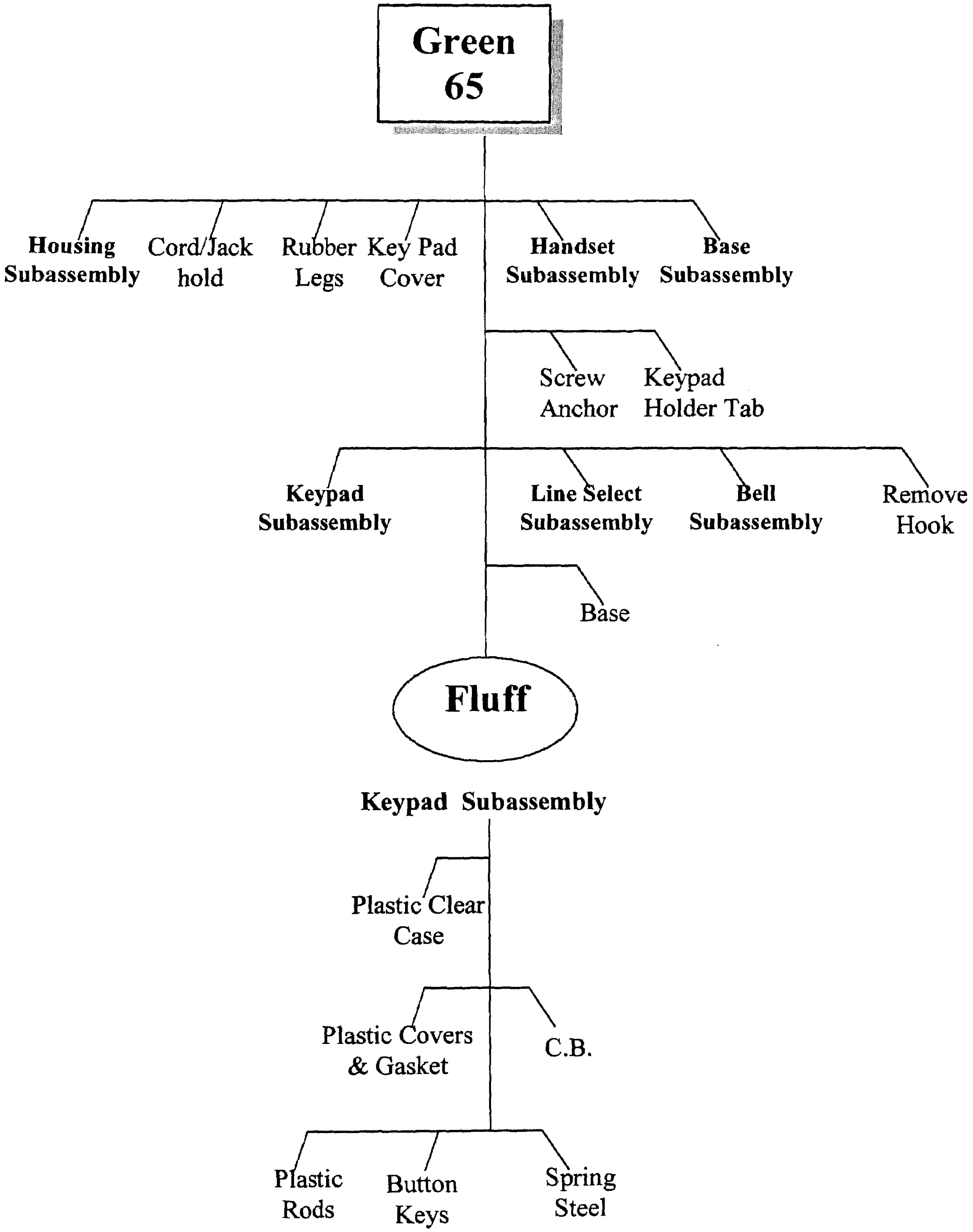
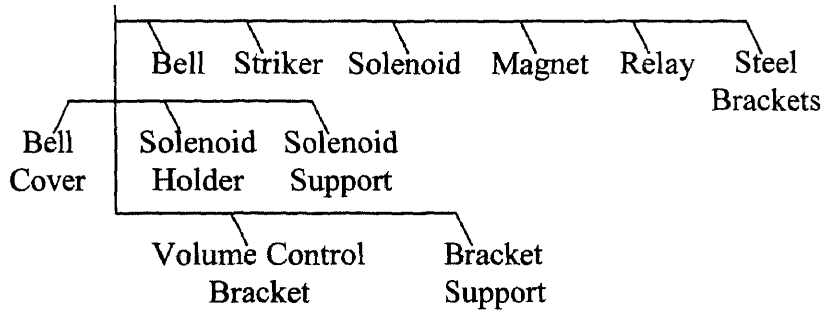


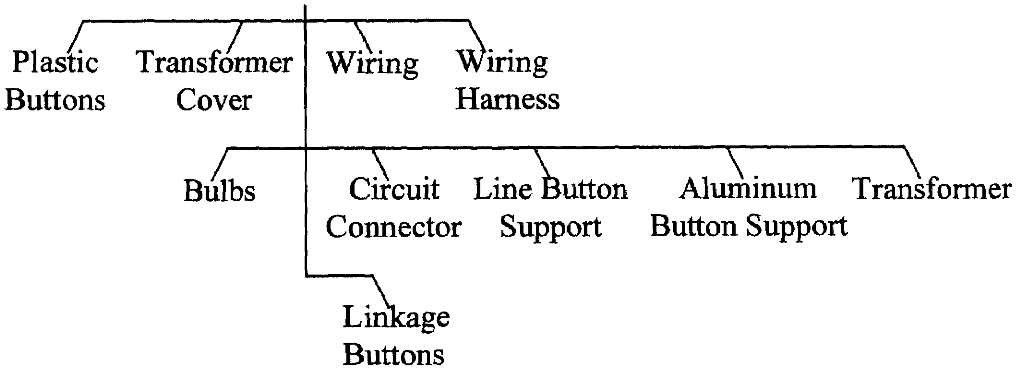
Figure B.5 Reverse Fishbone Diagram for the 1965 Telephone

Green 65

Bell Subassembly



Line Select Subassembly



Handset

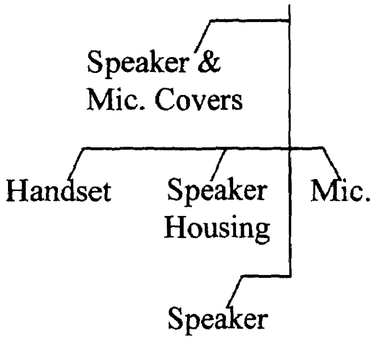


Figure B.5 Continued

1) # of different Mat.	<7	6	5	4	3	2	POINTS
POINTS	0	6	12	18	24	30	0
2) # of diff. Fasteners	<6	5	4	3	2	1	POINTS
POINTS	0	5	10	15	20	25	5
3) Mat. Marking	0%	20%	40%	60%	80%	100%	POINTS
POINTS	0	3	6	9	12	15	0
4) Time (MIN)	30	25	20	15	10	5	POINTS
POINTS	1.25	2.5	3.75	5	6.25	7.5	1.75
5) Tools	Unavailable	Special	OEM	Mechanic	Simple	No-Tools	POINTS
POINTS	1	2	3	4	5	6	5
6) Access	(Not-Visible)	Complex-Motion	Dual-Axis	(≥ 4" Deep-Head)	X-Y Axis	Z- Axis	POINTS
POINTS	1	2	3	4	5	6	5
7) Force	Cutting	High-Impact	Low-Impact	Leverage	Torsional	Axial	POINTS
POINTS	0.75	1.5	2.25	3	3.75	4.5	3.75
8)Part -Hold	(Automated ......)		Complex-Fixture	Fixture-Necessary	Two-Hand	No-Hold	POINTS
POINTS	0.5	1	1.5	2	2.5	3	2.5
9)Instruction	Special-Classes	Whole-Day	Half-Day	≤ 5 - 30 min	Simple	None	POINTS
POINTS	0.5	1	1.5	2	2.5	3	2.5

SCORE : 25.5

Notes:
No of different materials: ABS, Rubber, Aluminum, Copper, Steel, Brass and Pot metal.
Fasteners: Snap Fits, Screws, Rivets, Tape and Adhesives.

Figure B.6 Revalorization for the 1965 Telephone

APPENDIX C

ENVIRONMENTAL BURDENS GENERATED FROM THE TELEPHONES

This appendix contains the air emissions, waterborne effluents, and solid wastes generated from the manufacturing of the feedstock materials used in the telephones, mainly metals and plastics, including the environmental burdens from generated from power source use. It also includes the environmental burdens generated from using the power source during the production, use and recovery stages of the product lifecycle. The environmental burdens generated from the feedstock materials and power sources, multiplied by the quantity of each material in the telephones, produced the environmental burdens associated with the four telephones over their lifecycle. Since the elements under air emissions and water effluents can not be added together, each element was quantified separately.

Due to the vast number of elements quantified whether energy or environmental burdens, it becomes difficult to manage and calculate these values. Linking spreadsheets in a software such as, MS Excel, would reduce calculation time and provides more accurate and reliable results, once the links and formulas entered are validated.

Table C.1 Environmental Burdens Generated from Production of Plastics

Environmental Burdens		ABS	PVC	HIPS
Air Emissions		g/g	g/g	g/g
	Particulate	0.003379	0.003514	0.003444
	Nitrogen Oxide	0.011558	0.011558	0.011558
	Sulfur Dioxide	0.025609	0.025609	0.025609
	Carbon Monoxide	0.003264	0.003264	0.003264
	Hydrocarbons	0.01480428	0.049026	0.015139
	Methane	0.01	0.01	0.01
	Aldehydes	0.000369	0.00034	0.000379
	Ammonia	0.0006286	0.00039	0.00043
	Sulfur Oxides	0.0019929	0	0.00269
	Other Organics	0.000399	0.00037	0.000409
	Carbon Dioxide	0	0	0
	BOG	0	0	0
	Fluoride	0	0	0
	Gas, Dust	0	0	0
	Hg Vapour	0	4.28E-06	0
	Cl	0	0.002531	0
Waterborne Effluents				
	Acids	0.005717	0.005717	0.005717
	Metal Ions	0.001651	0.001651	0.001651
	Dissolved Solids	0.01652	0.01652	0.01652
	BOD	0.0047804	0.002504	0.003757
	COD	0.0133064	0.007751	0.009955
	Suspended Solids	0.0051366	0.003381	0.004336
	Oil	0.00163613	0.001012	0.001089
	Phenols	0.000065	0.00006	0.000067
	Sulfides	0.000092	0.000085	0.000095
	Ammonia	0.0000509	0	0
	Cyanide	9.896E-07	0	0
	Hg	0	6.13E-07	0
	Lead	0	3.67E-06	0
	Iron	0.000016	0	0
	Aluminum	0.000016	0	0
	Nickel	0.000008	0	0
	Chromium	0.0000016	0	0
Solid Wastes		0.0037991	0.054148	0.007253

Table C.2 Environmental Burdens Generated from Production of Metals [Source 14]

		Steel	Aluminum	Copper
Air Emissions		g/g	g/g	g/g
	Particulate	0	0.115	0.011
	Nitrogen Oxide	0.022	0	0
	Sulfur Dioxide	0.022	0	0.2765
	Carbon Monoxide	0.001	0.79	0
	Carbon Dioxide	2.549	0.65	0
	BOG	3	0	0
	Fluoride	0	0.02	0
	Gas, Dust	0	0	0.334
Solid Wastes		0.41	1.9153	163.927

Table C.3 Environmental Burdens Generated from Power Sources Used during Production of Feedstock Material

	ABS	Steel	Aluminum	Copper
Air Emissions	g/g	g/g	g/g	g/g
CO2	1.8E+01	7.8E-01	9.1E+01	1.7E+01
CO	6.3E-03	2.7E-04	3.2E-02	5.8E-03
NOx	5.3E-02	2.4E-03	2.6E-01	5.0E-02
Methane	4.8E-02	2.1E-03	2.4E-01	4.5E-02
Hydrocarbons	4.6E-03	4.7E-04	1.0E-02	4.7E-03
Particulate	3.1E-05	3.2E-06	6.9E-05	3.2E-05
SO2	7.0E-05	7.2E-06	1.6E-04	7.1E-05
Monoxide	7.3E-04	7.5E-05	1.6E-03	7.5E-04
Solid Wastes	2.9E+00	1.3E-01	1.5E+01	2.7E+00
Waterborne Effluents				
Dissolved Solids	1.7E-03	1.8E-04	3.8E-03	1.7E-03
Acids	2.9E-04	3.0E-05	6.4E-04	2.9E-04
Metal Ion	8.5E-05	8.8E-06	1.9E-04	8.7E-05

Table C.4 Air Emissions and Solid Wastes Generated from Steel Production for the Four Telephones

	Steel Material									
		Air Emissions (g)								Solid Wastes (g)
Telephone	Weight (g)	Particulate	Nitrogen Oxide	Sulfur Dioxide	Carbon Monoxide	Carbon Dioxide	BOG	Fluoride	Gas, Dust	
1965	963.06	0.0E+00	2.1E+01	2.1E+01	9.6E-01	2.5E+03	2.9E+03	0	0	394.855
Eco Value			2	2	2	2	2			2
1978	210.32	0.0E+00	4.6E+00	4.6E+00	2.1E-01	5.4E+02	6.3E+02	0	0	86.2312
Eco Value			5	5	5	5	5			5
1989	131.75	0.0E+00	2.9E+00	2.9E+00	1.3E-01	3.4E+02	4.0E+02	0	0	54.0175
Eco Value			5	5	5	5	5			5
1997	120.72	0.0E+00	2.7E+00	2.7E+00	1.2E-01	3.1E+02	3.6E+02	0	0	49.4952
Eco Value			5	5	5	5	5			5

Table C.5 Air Emissions and Solid Wastes Generated from Aluminum Production for the Four Telephones

Aluminum Material										
		Air Emissions (g)								**Solid Wastes (g)**
Telephone	Weight (g)	Particulate	Nitrogen Oxide	Sulfur Dioxide	Carbon Monoxide	Carbon Dioxide	BOG	Fluoride	Gas, Dust	
1965	62.89	7.2E+00	0.0E+00	0.0E+00	5.0E+01	4.1E+01	0.0E+00	1.3E+00	0.0E+00	1.2E+02
Eco Value		2			2	2		2		2
1978	62.42	7.2E+00	0.0E+00	0.0E+00	4.9E+01	4.1E+01	0.0E+00	1.2E+00	0.0E+00	1.2E+02
Eco Value		3			3	3		3		1
1989	0.93	1.1E-01	0.0E+00	0.0E+00	7.3E-01	6.0E-01	0.0E+00	1.9E-02	0.0E+00	1.8E+00
Eco Value		5			5	5		5		5
1997	0.85	9.8E-02	0.0E+00	0.0E+00	6.7E-01	5.5E-01	0.0E+00	1.7E-02	0.0E+00	1.6E+00
Eco Value		5			5	5		5		5

Table C.6 Air Emissions and Solid Wastes Generated from Copper Production for the Four Telephones

Copper Material										
		Air Emissions (g)								Solid Wastes (g)
Telephone	Weight (g)	Particulate	Nitrogen Oxide	Sulfur Dioxide	Carbon Monoxide	Carbon Dioxide	BOG	Fluoride	Gas, Dust	
1965	179.96	2.0E+00	0.0E+00	5.0E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	6.0E+01	3.0E+04
Eco Value		2		2					2	2
1978	22.25	2.4E-01	0.0E+00	6.2E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	7.4E+00	3.6E+03
Eco Value		5		5					5	5
1989	4.11	4.5E-02	0.0E+00	1.1E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.4E+00	6.7E+02
Eco Value		5		5					5	5
1997	6.14	6.8E-02	0.0E+00	1.7E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.1E+00	1.0E+03
Eco Value		5		5					5	5

Table C.7 Environmental Burdens Generated from Production of all the Metals in the Four Telephones

Total Metals Material										
	Air Emissions (g)									**Solid Wastes(g)**
Telephone	Particulate	Nitrogen Oxide	Sulfur Dioxide	Carbon Monoxide	Carbon Dioxide	BOG	Fluoride	Gas, Dust	AE Average Eco-tool	
1965	9.2E+00	2.1E+01	7.1E+01	5.1E+01	2.5E+03	2.9E+03	1.3E+00	6.0E+01		3.0E+04
Eco Value	2	2	2	2	2	2	2	2	2	2
1978	7.4E+00	4.6E+00	1.1E+01	5.0E+01	5.8E+02	6.3E+02	1.2E+00	7.4E+00		3.9E+03
Eco Value	4	5	5	4	4	5	3	5	4.375	3.67
1989	1.5E-01	2.9E+00	4.0E+00	8.7E-01	3.4E+02	4.0E+02	1.9E-02	1.4E+00		7.3E+02
Eco Value	5	5	5	5	5	5	5	5	5	5
1997	1.7E-01	2.7E+00	4.4E+00	7.9E-01	3.1E+02	3.6E+02	1.7E-02	2.1E+00		1.1E+03
Eco Value	5	5	5	5	5	5	5	5	5	5

Table C.8 Air Emissions and Solid Wastes Generated from ABS Production for the Four Telephones

	Plastics (Material)												
		Air Emissions (g)											Solid Waste (g)
Telephone	Weight (g)	Particulate	Nitrogen Oxide	Sulfur Dioxide	Carbon Monoxide	Hydrocarbons	Methane	Aldehydes	Ammonia	Sulfur Oxides	Other Organics	Carbon Dioxide	
1965	943.55	3.2E+00	1.1E+01	2.4E+01	3.1E+00	1.4E+01	9.4E+00	3.5E-01	5.9E-01	1.9E+00	3.8E-01	0.0E+00	3.6E+00
Eco Value		2	2	2	2	2	2	2	2	2	2	2	2
1978	1175.1	4.0E+00	1.4E+01	3.0E+01	3.8E+00	1.7E+01	1.2E+01	4.3E-01	7.4E-01	2.3E+00	4.7E-01	0.0E+00	4.5E+00
Eco Value		1	1	1	1	1	1	1	1	1	1	1	1
1989	526.06	1.8E+00	6.1E+00	1.3E+01	1.7E+00	7.8E+00	5.3E+00	1.9E-01	3.3E-01	1.0E+00	2.1E-01	0.0E+00	2.0E+00
Eco Value		3	3	3	3	3	3	3	3	3	3	3	3
1997	845.94	2.9E+00	9.8E+00	2.2E+01	2.8E+00	1.3E+01	8.5E+00	3.1E-01	5.3E-01	1.7E+00	3.4E-01	0.0E+00	3.2E+00
Eco Value		3	3	3	3	3	3	3	3	3	3	3	3

Table C.9 Waterborne Effluents Generated from ABS Production for the Four Telephones

		Water Effluents(g)														
Telephone	Weight (g)	Acids	Metal Ions	Dissolved Solids	BOD	COD	Suspended Solids	Oil	Phenols	Sulfides	Ammonia	Cyanide	Iron	Aluminum	Nickel	Chromium
1965	943.55	5.4E+00	1.6E+00	1.6E+01	4.5E+00	1.3E+01	4.8E+00	1.5E+00	6.1E-02	8.7E-02	4.8E-02	9.3E-04	1.5E-02	1.5E-02	7.5E-03	1.5E-03
Eco Value		2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
1978	1175.1	6.7E+00	1.9E+00	1.9E+01	5.6E+00	1.6E+01	6.0E+00	1.9E+00	7.6E-02	1.1E-01	6.0E-02	1.2E-03	1.9E-02	1.9E-02	9.4E-03	1.9E-03
Eco Value		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1989	526.06	3.0E+00	8.7E-01	8.7E+00	2.5E+00	7.0E+00	2.7E+00	8.6E-01	3.4E-02	4.8E-02	2.7E-02	5.2E-04	8.4E-03	8.4E-03	4.2E-03	8.4E-04
Eco Value		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
1997	845.94	4.8E+00	1.4E+00	1.4E+01	4.0E+00	1.1E+01	4.3E+00	1.4E+00	5.5E-02	7.8E-02	4.3E-02	8.4E-04	1.4E-02	1.4E-02	6.8E-03	1.4E-03
Eco Value		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

Table C.10 Environmental Burdens Generated from Power Sources during ABS Production for the Four Telephones

		Feedstock Material (Plastics)											
		Air Emissions								Waterborne Effluents			Solid Wastes
	Weight (g)	CO2	CO	NOx	Methane	Hydrocarbons	Particulate	SO2	Monoxide	Dissolved	Acids	Metal Ion	
1965	943.55	16989	5.9E+00	5.0E+01	4.6E+01	4.3E+00	2.9E-02	6.6E-02	6.9E-01	1.6E+00	2.7E-01	8.0E-02	2744
1978	1175.14	21158	7.4E+00	6.2E+01	5.7E+01	5.4E+00	3.6E-02	8.2E-02	8.5E-01	2.0E+00	3.4E-01	1.0E-01	3418
1989	526.06	9471.7	3.3E+00	2.8E+01	2.5E+01	2.4E+00	1.6E-02	3.7E-02	3.8E-01	8.9E-01	1.5E-01	4.5E-02	1530
1997	845.94	15231	5.3E+00	4.5E+01	4.1E+01	3.9E+00	2.6E-02	5.9E-02	6.1E-01	1.4E+00	2.4E-01	7.2E-02	2461

Table C.11 Environmental Burdens Generated from Power Sources during Steel Production for the Four Telephones

	Steel												
		Air Emissions (g)								Waterborne Effluents(g)			Solid Wastes (g)
Telephone	Weight (g)	CO2	CO	NOx	Methane	ydrocarbo	Particulat	SO2	Monoxide	solved So	Acids	Metal Ion	
1965	963.06	753.4218516	2.6E-01	2.3E+00	2.0E+00	4.6E-01	3.1E-03	6.9E-03	7.2E-02	1.7E-01	2.8E-02	8.5E-03	122
Eco Value													
1978	210.32	164.5377067	5.7E-02	5.1E-01	4.4E-01	1.0E-01	6.7E-04	1.5E-03	1.6E-02	3.7E-02	6.2E-03	1.8E-03	27
Eco Value													
1989	131.75	103.0707629	3.6E-02	3.2E-01	2.8E-01	6.2E-02	4.2E-04	9.5E-04	9.9E-03	2.3E-02	3.9E-03	1.2E-03	17
Eco Value													
1997	120.72	94.44176471	3.3E-02	2.9E-01	2.5E-01	5.7E-02	3.9E-04	8.7E-04	9.1E-03	2.1E-02	3.6E-03	1.1E-03	15
Eco Value													

Table C.12 Environmental Burdens Generated from Power Sources during Aluminum Production for the Four Telephones

Aluminum													
		Air Emissions (g)								Waterborne Effluents(g)			Solid Wastes (g)
Telephone	Weight (g)	CO2	CO	NOx	Methane	ydrocarbo	Particulat	SO2	Monoxide	solved So	Acids	Metal Ion	
1965	62.89	5740.393	2.0E+00	1.7E+01	1.5E+01	6.5E-01	4.3E-03	9.8E-03	1.0E-01	2.4E-01	4.0E-02	1.2E-02	8
Eco Value													
1978	62.42	5697.493	2.0E+00	1.6E+01	1.5E+01	6.4E-01	4.3E-03	9.7E-03	1.0E-01	2.4E-01	4.0E-02	1.2E-02	8
Eco Value													
1989	0.93	84.88735	3.0E-02	2.5E-01	2.3E-01	9.5E-03	6.4E-05	1.4E-04	1.5E-03	3.5E-03	5.9E-04	1.8E-04	0
Eco Value													
1997	0.85	77.58521	2.7E-02	2.2E-01	2.1E-01	8.7E-03	5.9E-05	1.3E-04	1.4E-03	3.2E-03	5.4E-04	1.6E-04	0
Eco Value													

Table C.13 Environmental Burdens Generated from Power Sources during Copper Production for the Four Telephones

Copper													
		Air Emissions (g)								Waterborne Effluents(g)			Solid Wastes (g)
Telephone	Weight (g)	CO2	CO	NOx	Methane	ydrocarbo	Particulate	SO2	Monoxide	solved Sc	Acids	Metal Ion	
1965	179.96	3026.852	1.1E+00	9.0E+00	8.1E+00	8.5E-01	5.7E-03	1.3E-02	1.3E-01	3.1E-01	5.3E-02	1.6E-02	489
Eco Value													
1978	22.25	374.2357	1.3E-01	1.1E+00	1.0E+00	1.0E-01	7.1E-04	1.6E-03	1.7E-02	3.9E-02	6.5E-03	1.9E-03	60
Eco Value													
1989	4.11	69.12848	2.4E-02	2.0E-01	1.9E-01	1.9E-02	1.3E-04	2.9E-04	3.1E-03	7.2E-03	1.2E-03	3.6E-04	11
Eco Value													
1997	6.14	103.2722	3.6E-02	3.1E-01	2.8E-01	2.9E-02	1.9E-04	4.4E-04	4.6E-03	1.1E-02	1.8E-03	5.4E-04	17
Eco Value													

Table C.14 Environmental Burdens Generated from Power Sources during Metals Production for the Four Telephones [Summation of Tables C.10-C.12]

Total Metals											
Air Emissions (g)									Waterborne Effluents(g)		Solid Wastes(g)
Telephone	CO2	CO	NOx	Methane	ydrocarbo	Particulate	SO2	Monoxide	solved So	Acids	Metal Ion	
1965	9.5E+03	3.3E+00	2.8E+01	2.6E+01	1.9E+00	1.3E-02	3.0E-02	3.1E-01	7.2E-01	1.2E-01	3.6E-02	6.2E+02
Eco Value												
1978	6.2E+03	2.2E+00	1.8E+01	1.7E+01	8.4E-01	5.7E-03	1.3E-02	1.3E-01	3.1E-01	5.3E-02	1.6E-02	9.5E+01
Eco Value												
1989	2.6E+02	8.9E-02	7.7E-01	6.9E-01	9.1E-02	6.2E-04	1.4E-03	1.4E-02	3.4E-02	5.7E-03	1.7E-03	2.8E+01
Eco Value												
1997	2.8E+02	9.6E-02	8.2E-01	7.4E-01	9.5E-02	6.4E-04	1.4E-03	1.5E-02	3.5E-02	5.9E-03	1.8E-03	3.2E+01
Eco Value												

Table C.15 Total Environmental Burdens Generated from Power Sources during Materials Production for the Four Telephones

	Air Emissions (g)								Waterborne Effluents(g)			Solid Wastes (g)
Telephone	CO2	CO	NOx	Methane	Hydrocarbons	Particulate	SO2	Monoxide	Dissolved Solids	Acids	Metal Ion	
1965	26509.2	9.215441	77.99143	71.143692	6.282864	0.042309	0.095195	0.99425796	2.326986719	0.391357	0.116349	3363.12354
Eco Value	2	2	2	2	2	2	2	2	2	2	2	2
1978	27394.56	9.523219	80.48698	73.519758	6.24124	0.042029	0.094564	0.98767098	2.311570376	0.388764	0.115579	3513.02303
Eco Value	1	1	1	1	2	2	2	2	2	2	2	1
1989	9728.752	3.382023	28.70993	26.109397	2.507102	0.016883	0.037986	0.39674671	0.928556141	0.156166	0.046428	1558.07176
Eco Value	4	4	4	4	4	4	4	4	4	4	4	4
1997	15506.38	5.390509	45.75278	41.615014	3.979544	0.026798	0.060296	0.6297595	1.473905212	0.247884	0.073695	2492.60931
Eco Value	3	3	3	3	3	3	3	3	3	3	3	3

Table C.16 Total Air Emissions and Solid Wastes Generated from Feedstock Material Production for the Four Telephones (Summation of Plastics, Metals, and Power Source)

Total	Air Emissions (g)											Solid Wastes (g)
Telephone	CO2	CO	NOx	Methane	Hydrocarbons	Particulate	SO2	Monoxide	BOG	Fluoride	Gas, Dust	
1965	29005	62.94135	110.0843	80.579192	20.25144	12.44247	95.20483	0.994258	2889.18	1.2578	60.10664	33382.319
Eco Value												
1978	27971	62.881	98.69629	85.271158	23.63834	11.43588	40.96789	0.987671	630.96	1.2484	7.4315	7370.6475
Eco Value												
1989	10065	5.965533	37.68863	31.369997	10.29504	1.9466	17.54477	0.396747	395.25	0.0186	1.37274	2289.609
Eco Value												
1997	15815	8.943877	58.18599	50.074414	16.50308	3.05052	26.07752	0.629759	362.16	0.017	2.05076	3553.4581
Eco Value												

Table C.17 Total Waterborne Effluents Generated from Feedstock Material Production for the Four Telephones (Summation of Plastics, Metals, and Power Source)

Total	Water Effluents(g)														
Telephone	Acids	Metal Ions	Dissolved Solids	BOD	COD	Suspended Solids	Oil	Phenols	Sulfides	Ammonia	Cyanide	Iron	Aluminum	Nickel	Chromium
1965	5.8E+00	1.7E+00	1.8E+01	4.5E+00	1.3E+01	4.8E+00	1.5E+00	6.1E-02	8.7E-02	4.8E-02	9.3E-04	1.5E-02	1.5E-02	7.5E-03	1.5E-03
Eco Value															
1978	7.1E+00	2.1E+00	2.2E+01	5.6E+00	1.6E+01	6.0E+00	1.9E+00	7.6E-02	1.1E-01	6.0E-02	1.2E-03	1.9E-02	1.9E-02	9.4E-03	1.9E-03
Eco Value															
1989	3.2E+00	9.1E-01	9.6E+00	2.5E+00	7.0E+00	2.7E+00	8.6E-01	3.4E-02	4.8E-02	2.7E-02	5.2E-04	8.4E-03	8.4E-03	4.2E-03	8.4E-04
Eco Value															
1997	5.1E+00	1.5E+00	1.5E+01	4.0E+00	1.1E+01	4.3E+00	1.4E+00	5.5E-02	7.8E-02	4.3E-02	8.4E-04	1.4E-02	1.4E-02	6.8E-03	1.4E-03
Eco Value															

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