ABSTRACT

MULTI-LIFECYCLE ASSESSMENT DESIGN TOOLS
AND
SOFTWARE DEVELOPMENT

by
Ji Jin

This thesis introduces the concept of Multi-lifecycles and a Multi-lifecycle assessment (MLCA) methodology for evaluating the energy consumption and environmental emissions of a product. MLCA quantifies materials, energy, and environmental burdens associated with end-of-life options, as well as obtains the value of returning parts and materials back to use, through demanufacturing, reengineering and remanufacturing.

A Multi-lifecycle Assessment software is developed as a tool to implement MLCA methodologies. By this software, one can practice a full life-cycle analysis on a product, or compare the environmental impacts of different products. Detailed designs on MLCA software including the databases, user interfaces, and algorithm designs are presented in this thesis. The initial prototype version of the multi-lifecycle assessment software tool has been completed with three major components: Product Description, Lifecycle stages, and Analysis and Results.

This thesis also applies the MLCA software tool to four generations of business telephones. Relevant characteristics such as raw materials, energy consumption, and environmental burdens were used to analyze the environmental performance of the telephones based on lifecycle data stored in MLCA software databases.

MULTI -LIFECYCLE ASSESSMENT DESIGN TOOLS
AND
SOFTWARE DEVELOPMENT

by
Ji Jin

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Computer Engineering

Department of Electrical and Computer Engineering

May 1999

MULTI-LIFECYCLE ASSESSMENT DESIGN TOOLS
AND
SOFTWARE DEVELOPMENT

Ji Jin

Dr. MengChu Zhou, Thesis Advisor   Date
Associate Professor of Electrical and Computer Engineering, NJIT

Dr. Reggie J. Caudill, Committee Member   Date
Professor of Mechanical Engineering and Executive Director of Multi-Lifecycle
Engineering Research Center, NJIT

Dr. Edwin Hou, Committee Member   Date
Associate Professor of Electrical and Computer Engineering, NJIT

BIOGRAPHICAL SKETCH

Author: Ji Jin

Degree: Masters of Science in Computer Engineering

Date: May 1999

Undergraduate and Graduate Education:

- Master of Science in Computer Engineering,
  New Jersey Institute of Technology, Newark, NJ, 1999

- Bachelor of Science in Electrical Engineering,
  Luoyang Institute of Technology, Luoyang, P.R.China, 1994

Major: Computer Engineering

To my beloved family

ACKNOWLEDGMENT

I would like to express my sincere gratitude to Dr. MengChu Zhou, who not only helped me as my thesis advisor, by providing valuable resources and insights, but also gave me support and encouragement.

Special thanks to Dr. Reggie Caudill for his invaluable support.

Thanks to Dr. Edwin Hou for actively participating in my committee and for his constructive comments and recommendations.

I would like to take this opportunity to thank Ms. Elizabeth McDonnell, Ms. Toia Moore and the staff at the Multi-Lifecycle Engineering Research Center (MERC) for their continuous motivation and suggestions.

Finally, I thank my friends and individuals not specifically delineated here who assisted me in this research.

TABLE OF CONTENT

TABLE OF CONTANTS
(Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES
(Continued)

CHAPTER 1

INTRODUCTION

1.1 Background

Increasing public concern and statutory regulations are making environmental protection

an important issue for industry. Both environmental concerns and rising product disposal

costs have pressured both manufactures and customers for more environmentally friendly

products. A large number of products related environmental laws and regulations are

rapidly increasing throughout the world. Topics such as product takeback and energy

efficiency are receiving a great deal of attention by the European Union and individual

countries throughout the world. Monitoring, evaluating and complying with these

numerous and complex laws and regulations present a major challenge for manufacturers

[Thomas 95]. As a result of these economic and legislative restrictions, a firm's

competitiveness in future world markets depends upon making environmental issues a

central concern.

Electronic products are playing an evermore-significant role in our lives. As those

products become obsolete at an increasing rate, recycling processes are needed to reclaim

value from the materials in the waste stream and divert them from landfills. Recycling to

date has largely been dismantling assemblies to salvage valuable components and

incineration to obtain precious metals. The bulk of the material is thus landfilled.

Government and industry officials have recognized the need for recycling methods to

reclaim value from all the materials in the electronic scrap stream [Nissen 97].

Based on EPA's municipal solid waste (MSW) characterization and the durable

goods fraction of MSW, the scrap electronics waste stream may be as high as 5 to 10

million tons per year. In 1993, approximately one billion tons of plastics resin was sold to electronics markets, which represented about 3% of the total plastics sold. Multiplying that 3% to 19.3 million tons, the total plastics waste generated in MSW in 1993, yields approximately 580,000 tons per year of plastic waste in scrap electronics [Allred 97]. With increasing product complexity, sophistication of manufacturing processes, range of environmental concerns, and other pressures on industry over time, environmental evaluation is likely to become increasingly difficult and a key issue in industrial ecology.

In response to increasing pressure by organizational stakeholders, environment management is at the top of the list of environmental design objectives. There are a number of different systems-based approaches to integrating environmental issues into industry, such as Life-cycle assessment (LCA), design for the environment (DFE), total quality environmental management (TQEM), ecofusion, green supply chain management, and a number of national and international environmental standards [Marion 98]. DFE focuses primarily on a design process, whereas TQEM focuses on the management and elimination of wastes and the continuous improvement of processes and systems. Green supply chain management is linked to the external relations of manufacturing firms and involves logistic planning.

1.2 Multi-Lifecycle Engineering

Over the last decade, efforts to reduce process wastes and design green products were initiated and practised in American's manufacturing industry. The need to increase the pace for more environmentally friendly products is also felt by many companies. Consumer electronics, computers, and household appliances contribute significantly to

the environmental burden placed on the municipalities across the nation. If discarded products and waste streams such as those mentioned could be recovered and reengineered into valuable feed streams, then we can break this trend and achieve sustainability.

To do these, Multi-Lifecycle Engineering (MLCE), a new approach in today's environmental area was proposed [Caudill 97]. It is based on the principle of sustainable economy where competitiveness is balanced with environmental responsibility. MLCE 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 designs for the environmental, but rather a complex, next generation engineered system that transcends traditional discipline boundaries in search of scientific knowledge, new methodologies and technologies. The main thrusts of Multi-Lifecycle Engineering (MLCE) are:

- Incorporating full multi-lifecycle consequences into the product with particular emphasis on material and form substitution in design, lifecycle assessment, next-generation use, material recovery and value analysis.

- Characterizing materials from waste streams, reengineered material systems, structure/property relationships, and predictive models for mixtures based on fundamental characterization of component elements.

- Focusing on separation processes for material reclamation and purification and processing of gaseous, liquid and solid waste streams.

- Developing methodologies and technologies with demanufacturing, systematic disassembly, mechanical sortation, and part cleaning and reliability test of discarded products, components and materials.

- Creating methodological and theoretical frameworks and database for examining product lifecycle assessment.

1.3 Aims and Objectives

Multi-lifecycle Assessment (MLCA) systematically considers and quantifies the consumption of resources and the environmental impacts associated with a product or process. By considering the entire life-cycle and the associated environmental burdens, MLCA identifies opportunities to improve environmental performance, and reduce resource depletion.

Software and public databases can facilitate defining the system under investigation, supporting the identification and collection of data of appropriate quality, and performing the extensive computations. Software takes a position between formalized methodology and accessible to the data. 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.

This thesis aims to develop an MLCA software as a tool for analyzing and comparing the environmental impacts of different products. By this software, one can practice a full life-cycle analysis on products by considering all the affects and options. Specific objectives include:

1) Reviewing the state of the art in area of life cycle assessment tools.

2) Introducing LCA methodologies and multi-lifecycle assessment tools.

3) Designing MLCA software database, user interface, and algorithm.

4) Applying the developed tool to four generations of business telephones.

1.4 Organization

This thesis presents a review of existing life-cycle assessment (LCA) tools in Chapter 2. LCA methodologies are introduced, and the multi-lifecycle assessment tool is presented in Chapter 3. As a new methodology, MLCA methodology focuses on multi-lifecycle of a product with the idea of disassembling an old product and passing different subassemblies and parts of the product into different ways to make them reusable. Detailed designs of MLCA software databases, user interfaces and algorithms are presented in Chapter 4. The multi-lifecycle assessment software design and implementation are discussed in Chapter 5. In Chapter 6, a case study on telephone 1989 is presented to illustrate the software application, including the project information, product description, and seven lifecycle stages, i.e., material process, production process, packaging, use, reengineering, demanufacturing, and remanufacturing. Conclusions and further research directions are presented in Chapter 7. Finally, the detailed inventory table of telephone 1989 is displayed in Appendix A. Energy consumption and environmental burdens generated from plastics and some metals are listed in Appendix B.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Increasing environmental awareness in the general public, concerns over the disposal of used products, and corporate efforts to buy "green" products are resulting in new challenges for manufacturers to develop cleaner technologies, environmentally friendly products and industrial production methodologies [Brinkley 97]. Currently, to stay competitive in the marketplace, manufacturers become more aware of the environmental impacts of their products, in order to control or avoid the environmental impacts they may cause. They have undertaken environmental audits or assessments to measure the environmental performance of their products. Thus they can reduce their environmental impacts through better designs, manufacturing processes, etc.

The first attempt to look at extended product systems can be traced back to as early as the 1960s, which mainly focused on calculating energy requirements. In the mid-1970s, landmark studies which focused on environmental issues were performed by Arthur D. Little and Midwest Research Institute (MRI) [Mary 96]. Activities in the United States on environmental LCAs, however, continued at a low pace in the last decades. Meanwhile, extended system studies were conducted in Europe during this period. They looked mainly at packaging systems, such as beverage containers. To the 1980s, a renewed interest in LCA as the Green Movement in Europe brought the subject to public attention on issues related to recycling, where environmental releases were routinely added to energy, raw materials, and solid waste considerations. In 1990s, the interest in LCA led to an increase in research activity by government, academia, and

private industry. This was followed by increased interest by companies to assess the life cycle impacts of their products and processes. The Society of Environmental Toxicology and Chemistry (SETAC) [SETAC 91], as the first international organization that paid its more attentions on LCAs, conducted its first technical workshop on LCAs in 1990, where the basic four components of an LCA were developed: Definition of Scope and Boundaries, Inventory Analysis, Impact Analysis and Improvement Analysis. The developed components and methods laid the framework for the LCA today.

2.2 Life Cycle Assessment (LCA)

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. The concepts of Design for Environment (DFE) and Life Cycle Assessment (LCA) are proposed to fulfill the aim [Marion 98]. DFE is a systematic process by which firms design products and processes in an environmentally conscious way. It requires environmental considerations over a complete product life cycle in the design process. Closely linking to DFE output, Life Cycle Assessment (LCA), is a family of methods for examining and selecting materials, products, processes, and technologies of a product through every step of its life. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation, and distribution; use, reuse, maintenance; recycling; and final disposal. It is a large and complex analysis, and there are many variations. LCA is targeted at analysis of the design, and involves an examination of all aspects of product design from the preparation of input materials to end-use. This includes evaluation of the

types and quantities of both input materials, such as energy, raw materials, and water and product outputs, including atmospheric emissions, solid and aqueous waste, and the end product as well as identification and evaluation of opportunities for reduction of the environmental impacts of processes and products. An LCA methodology has four interrelated components: definition of scope and boundaries, inventory analysis, impact analysis and improvement analysis. The concept of a life-cycle methodology is pictured Figure 2.1. First, the scope of the LCA is defined. An inventory analysis and an impact analysis are then performed, the result being an environmentally responsible product rating (Rerp). This rating guides an analysis of potential improvements (which may feed back to influence the inventory analysis). Finally, the improved product is released for manufacturing. A full life cycle assessment includes each of these four components.
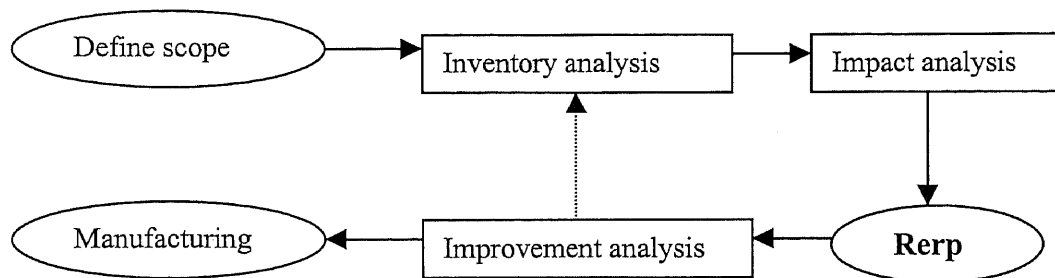
Figure 2.1 Steps in the Life-Cycle Assessment of a Product [Graedel 95]

An environmental LCA evaluates the environmental effects associated with any given activity from the initial gathering of raw materials from the earth (petroleum, crops, ores, etc.) to the point at which all materials return to the earth. This evaluation includes all side-stream releases to the air, water, and soil. LCA is an attempt to comprehensively describe all these activities and the resulting environmental releases and impacts.

2.2.1 Definition of Scope and Boundaries

Before an LCA is begun, we must define the purpose of the product system under study. We need also identify all the assumptions and thresholds. The purpose of studies could be a performance for an LCA of a new product, or a comparison of a new product to that of an older model or an alternative product, or to investigate the impact of new guidelines and policies introduced in an organization. After defining the purpose of the study, we need to set the boundaries and depth level of the system under study as well.

2.2.2 Inventory Analysis

The goal of the inventory analysis stage is to obtain quantitative and qualitative information that fully describes all life cycle stages to establish the levels and types of energy and materials inputs to an industrial system and the environmental release that result, as shown schematically in Figure 2.2. The approach can be based on the idea of a family of materials budgets, measuring the inputs of energy and resources that are supplied and the resulting products, including those with value and those with potential liabilities. The assessment is performed over the entire life cycle including materials extraction, manufacture, distribution, use and disposal.

2.2.3 Impact Analysis

Environmental life cycle inventories produce large quantities of complex information on natural resource use and releases to the environment. Usually, in the areas of atmospheric and waterborne emissions, a typical result consists of long lists of 20 to 30 different chemicals for each product, process, or packaging scenario. These data are difficult to

interpret. The development of measures of actual impact on human health, ecological quality, and natural resource depletion enables impact analysis. Impact analysis converts the results from inventory analysis to a set of common impact measures such as excess mortality, habitat disruption, and others.
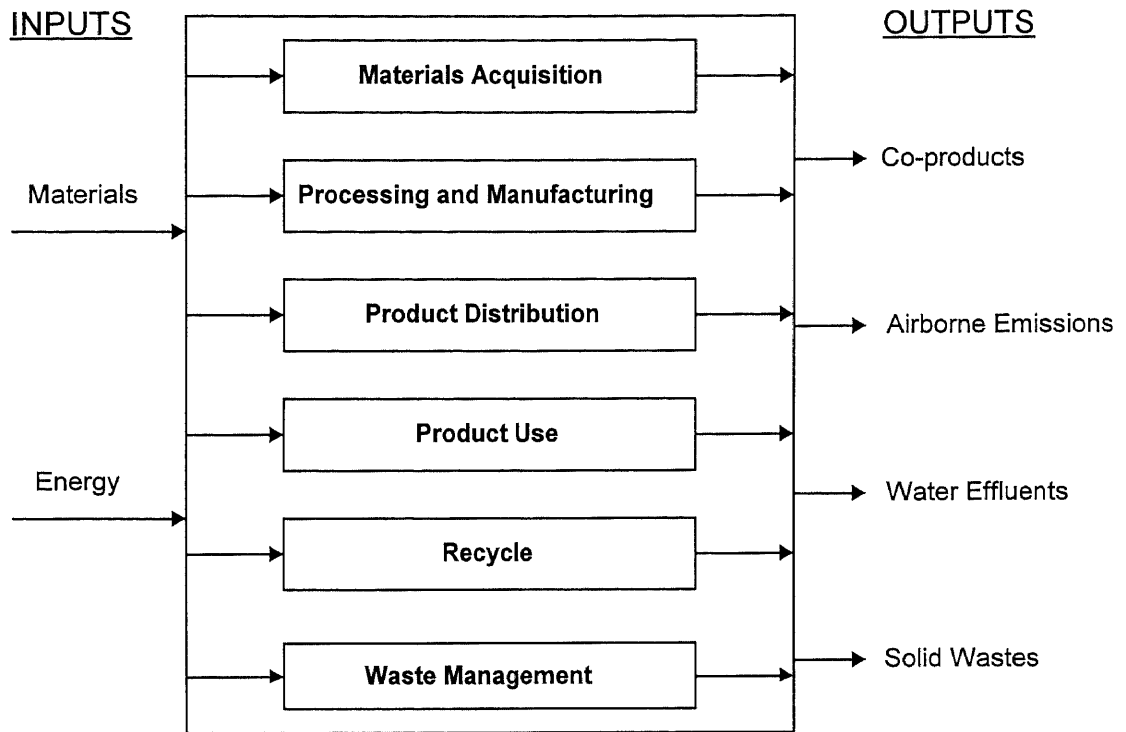
Figure 2.2 The Elements of a Life-Cycle Inventory Analysis [SETAC 91]

2.2.4 Improvement Analysis

The forth stage, improvement analysis, is the component of an LCA in which options for reducing the environmental impacts or burdens of the products under study are identified and evaluated. This analysis is necessary in identifying and discovering new opportunities to reduce environmental emissions, energy and material consumption of products and processes. The inventory analysis may be used to reveal aspects that can be improved. Improved efficiency inputs include smaller electricity demand. Improved

efficiency outputs include greater production yield and environmental outputs such as less resource use and fewer emissions. They offer opportunities with respect to environmental improvement. One can conduct a comparison to evaluate the environmental performance of the product as different materials are substituted can be conducted and a sensitivity analysis to an evaluate the variations in data inputs and their effect on the final result. There is not a commonly accepted approach to improvement assessment. More research, development and industrial practices are still needed.

2.3 LCA Software

The conduct of life-cycle assessments demands considerable effort on methodology development and data collection. The development for life cycle assessment (LCA) can be highly theoretical, where as the collection of data often has a direct connection with practice. To practice LCA, we need to combine them together. What is the easy way to apply theoretical methodologies to the data from real world [Guinee 93]? Software brings the opportunity to do so. It acts as a bridge between theory and practice, which 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 a methodology and the suitability of the data within the theoretical framework. Software and public databases can facilitate defining a system under investigation, supporting the identification and collection of data of appropriate quality, and performing the extensive computations.

2.3.1 General Structure of LCA Software

Stand-alone LCA software has evolved rapidly over the past several years from largely spreadsheet-based systems to graphically oriented systems employing standard Windows features and appearance. The most common type of LCA software model, as is distinguished from design or engineering LCA modeling tools, is referred to as an *input-output model* [Mary 96]. The typical structure of integrated LCA software is shown in Figure 2.3, which consists of a user interface, database, computational engine, and report processor. At first, product data and information are stored into LCA databases through user interfaces, then, data processing is going on with the computational engine, and calculation results are treated in report processor to give a direct and clear reports to the user.
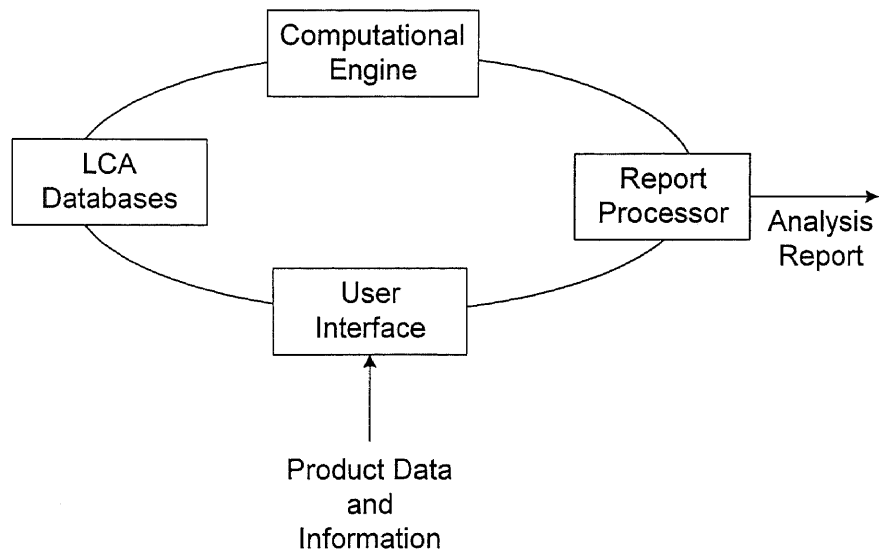
Figure 2.3 Typical Structure of Integrated LCA Software

LCA software products developed for users that may or not an expert in environmental issues typically results that provide recommendations on materials and process choices based on life-cycle considerations. 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.

2.3.2 Inventory Analysis Software

Inventory analysis is basic to all LCAs and uses quantitative data to establish types of energy and materials inputs to a product system, and measure the outputs, i.e., co-products, airborne emissions, water effluents, and solid wastes, that occur at each stage of a product's life.

Commercial spreadsheet programs such as Microsoft Excel and Lotus 1-2-3 are the more popular systems of first generation inventory software [Mary 96]. The most basic execution of LCA inventory software uses the unadorned spreadsheet as the input data template, computational engine, and output form. The spreadsheet may also include a simple database on materials and processes, so those users are not required to input anything more than basic functional units and product descriptions. 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.

Advanced features of spreadsheets in recent softwares include a multi-sheet capability so that input, intermediate calculation, and output sections can be separated. Separation of certain common operational elements, as transportation systems, is also facilitated. Many of the internal computational tools of practitioners as well as industry commodity data sets are maintained in a spreadsheet format. Graphical capabilities of spreadsheets have been improving to present the results in a meaningful manner.

A step beyond the basic inventory models is models that have been developed with extended interfaces between the program and the user. Input screens are designed to input some basic information about the product or package. This usually entails providing a unique product name and description, specifying the calculation unit for presentation of the results, and describing the components comprising the product or package. Users will generally be able to select these options from a list.

Users can also exercise limited control over how the calculations are handled. This is normally associated with allocation or non-serial types of systems, such as those involving recycling loops. Different software treats the recycling issue in different ways, with the user specifying a recycling percentage or determining the type of recycling (open- or closed-loop). The software then applies a predetermined set of decision rules to complete the calculations. Typically, several formats for tabular or graphical data are offered, and some flexibility on how the results are shown is afforded.

Embedded databases, often incorporating a commercial database software system in the model, are preferred to support a greater variety of data. Popular choices for embedded database software are dBase IV, FoxPro, Access, and Oracle. When the permanent database lacks certain information, the software allows for augmentation of

the permanent database records. The user is presented with input data templates for materials or processes, and when the information is inserted, the new information can be linked to describe a system in the same manner as that resident in the permanent database.

The ultimate in user-controlled data capability is embodied in models that can import information from external databases, either those created expressly for LCA or more general-purpose data in public domain databases. To ensure compatibility among data sets, it is necessary to define a certain format to report of external data sets, and to incorporate in the software the ability to translate the specification to process or segment definitions.

2.3.3 LCA Tools

Many LCA tools have been available for implementing a full LCA analysis. Since it is unlikely that one single LCA methodology can be optimal for all LCA analysis, differences can be found in these tools, depending on the boundaries set by the tool and the specific problems it is designed to solve. Some software deals with energy at just one life-cycle stage rather than the total lifecycle. Some varies in the type of databases of materials it uses. Some of the available LCA databases and software are introduced in the following sections. There are also some other LCA softwares available on the market, due to the unavailable information, they are not introduced in this thesis.

2.3.3.1 Eco-it: ECO-it shown in Figure 2.4 is a LCA tool developed by PRé Consultants, which helps designers to measure and optimize the environmental performance of a product in its design phase. It specify a product with its life cycle by inputting the materials and processes information of that product, calculating its environmental load, and showing the product contribute result for environment.

The Eco-it values are computed using the experimental Eco-indicator methodology that is based on the Life Cycle Assessment (LCA) principle. This methodology was developed for the Dutch government NOH programme and VROM byPRé on request of Philips, Océ, NedCar and Schuurink [Eco-it]. ECO-it databases displayed in Figure 2.5 have over 100 indicator values for commonly used materials such as metals, plastics, paper, board and glass, as well as production, transport, energy and waste treatment processes.
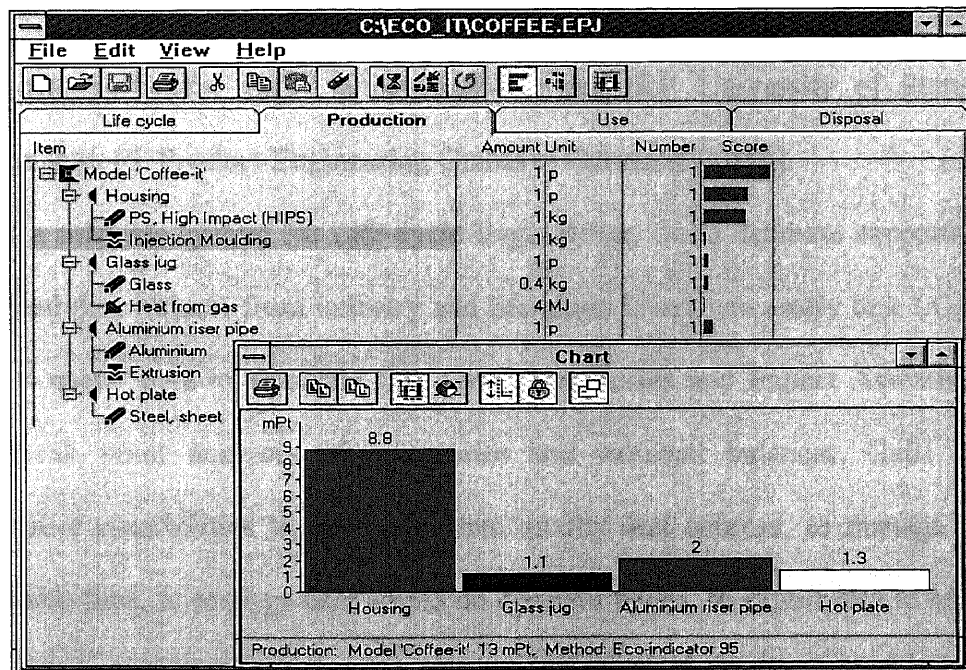
Figure 2.4 Eco-it Software [Eco-it]
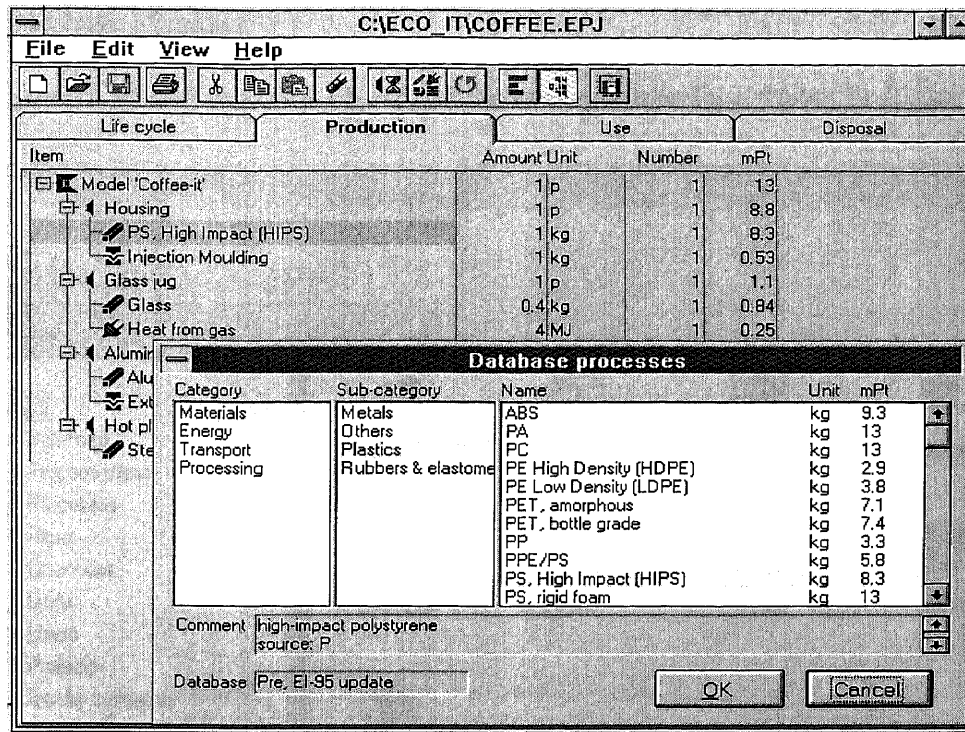
Figure 2.5 ECO-it Database Screen [Eco-it]

2.3.3.2 GaBi Software: GaBi is developed at the IKP University of Stuttgart in cooperation with PE Product Engineering GmbH in Germany [GaBi].

As a software system for Life-cycle Engineering, GaBi database supports plenty of predefined data objects from industry and literature. Users can easily link LCA GaBi data sets to users' data to calculate Life Cycle Inventories and Impact Assessments. It supplies weak point analyses of inventories and valuated balances. GaBi features comprehensive possibilities to document data quality and sources, to manage various projects at one time, to manage user access on different levels, to export data to Microsoft Excel, and to maintain the database content. Main features of GaBi version 3 are as follows:

- The Database Manager

GaBi supplies a Windows compatible database manager interface shown in Figure 2.6.
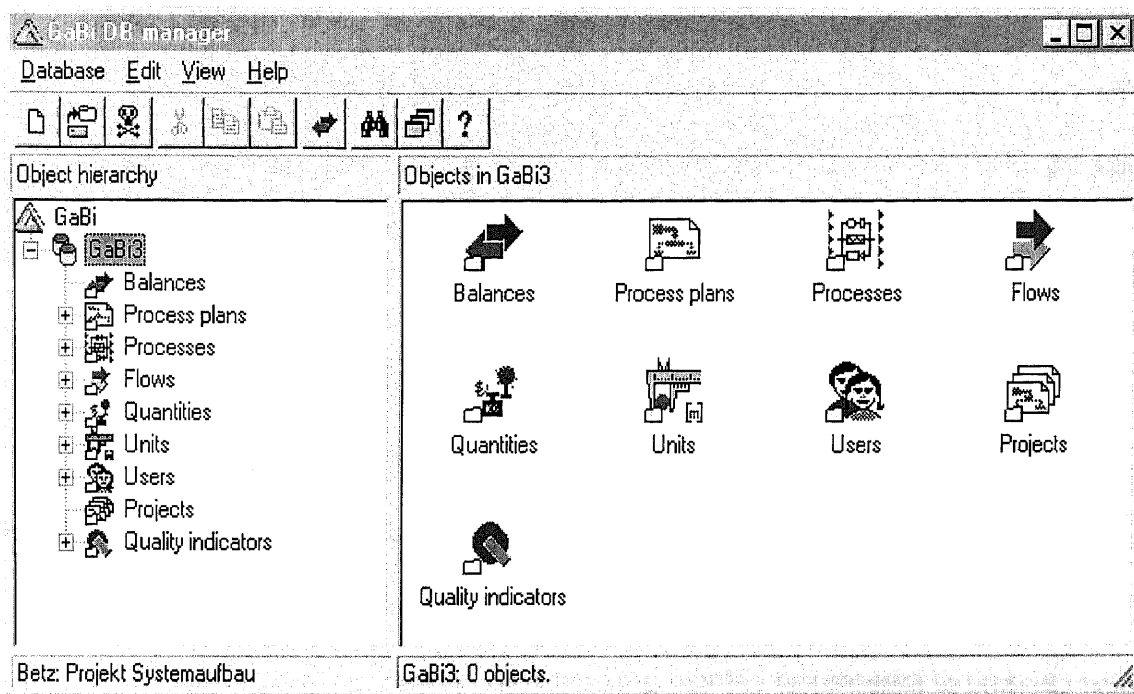
Figure 2.6 Database Manager of GaBi [GaBi]

All GaBi databases installed are shown in the left-hand part of the manager window, and can be extended step-by-step as the Windows Explorer does. A GaBi database includes a set of database objects needed for a product's life-cycle assessment, i.e., Balances, Processes plans, Processes, Units, Quantities, Projects, and tools for user administration and project management.

- Process Modeling

GaBi allows accurate and flexible modelling of real world processes. Process modules within the GaBi database are divided into different classes to ensure easy and quick

access: acquisition, production, transportation, use, service, auxiliary processes, recycling, and deposit. One of the process-modeling screens is displayed in Figure 2.7.

Each process mask contains a header comprising process name, geographic details and time statement along with indicators for allocated processes and linked process. Parameter table accepts parameters, equations and parameter values, and input and output flows are entered into the tables Inputs and Outputs tables.

• Computing and Analyzing

GaBi sets up inventory (or balance) sheets with any degree of depicted detail. An inventory in GaBi is similar to separate processes made up of input and output tables. Inventories are computed automatically on the basis of process plans that define the life cycle, it's boundaries and references. By supplying flexible instruments to present results, GaBi particularly supports weak point analysis of complex life cycles. This means to identify prominent sources of environmental burdens and to point out possibilities for reducing them.

Figure 2.7 Process Modeling in GaBi Software [GaBi]

2.3.3.3 TEAM: TEAM is a professional LCA software program tool for Environmental Analysis and Management [TEAM]. It allows the user to build and use a large database and to model any system representing the operations associated with products, processes and activities It is designed to describe and model complex industrial systems and to calculate the associated: Life cycle inventories, Life cycle potential environmental impacts, and Process-oriented life cycle costs.

By offering powerful calculation capabilities, linked to a comprehensive process and material database, TEAM™ dramatically speeds up the process of carrying out LCA without compromising the LCA methodology Main Features of TEAM are [TEAM]:

- Model any kind of system directly from the graphical user interface.

- Compile life cycle inventories using Ecobilan Group data, your own data, or any combination thereof.

- Import data from other sources (e.g. Excel spreadsheets / ASCII format) directly into TEAM™.

- Perform sensitivity analyses in an automated fashion to identify 'data hot spots'. Investigate 'what if' scenarios via user friendly 'Control Panels'

- Conduct life cycle impact assessment determinations using any one of the protocols incorporated within the software.

- Report your findings in a variety of different ways making use of the tabular / graphical display options.

2.4 Review of SimaPro 4.0 Software

SimaPro is the most widely used tool for the environmental assessment of products which is developed by the product ecology consultants in Netherlands [SimaPro]. SimaPro 4.0 is the latest fourth generation of the Simapro software. It is a full-featured Life Cycle Assessment software tool. We have an opportunity to view this software from its 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. 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 following section provides a detailed description on life-cycle analyses and databases of SimaPro.

2.4.1 Inventory Analysis

SimaPro uses the concept of *assemblies* to describe a product. A process tree for the assembly, shown in Figure 2.8, is used to display the assembly elements, processes and materials of a product.
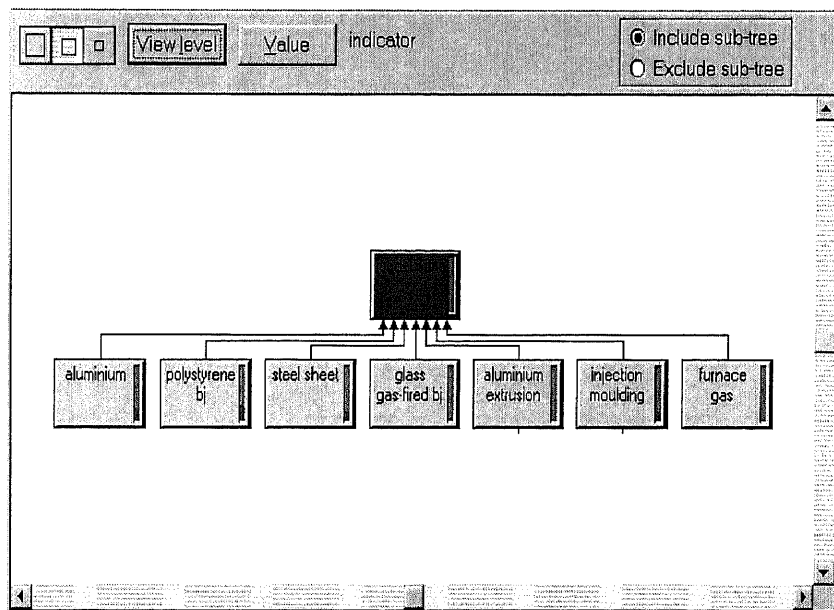
Figure 2.8 Process Tree for Model Sima [SimaPro]

Once a product assembly has been put together, SimaPro can perform the inventory phase and calculations to produce the so-called inventory table. It is a long list of all raw material extractions and emissions involved with the system assembly being studied. The inventory table is very useful if you want to see where specific substances come from in the manufacture of an assembly. Figure 2.9 shows the inventory table in detail.

No	Substance	Category	Unit	Total	Aluminium (block) bj	PS (GPPS) b
1	1,2-dichloroethane	Air	µg	15.1	0.00232	x
2	acetaldehyde	Air	µg	419	0.21	x
3	acetic acid	Air	µg	1.92E3	0.964	x
4	acetone	Air	µg	417	0.21	x
5	Acid as H+	Water	µg	73.2	0.0365	x
6	acrolein	Air	ng	104	0.0471	x
7	Ag	Water	ng	1.65E3	0.828	x
8	air	Raw	kg	0.0317	x	x
9	Al	Water	mg	346	0.174	x
10	Al	Air	mg	13.3	0.00667	x

Figure 2.9 Inventory Table for Model Sima [SimaPro]

2.4.2 Impact Analysis

In order to get more insight into the relative contribution of the different items in the assembly to the overall environmental impact, we can use one of SimaPro's evaluation methods to calculate their contributions to a number of specific environmental impacts. They can be presented with a histogram showing a number of environmental effects calculated on the basis of the impact table in three different ways named Characterisation,

Normalisation, and Evaluation. In Figure 2.10, the *Simapro3.0 Eco Ind.* method is used as the evaluation method that calculates environmental effects in Eco indicator points.
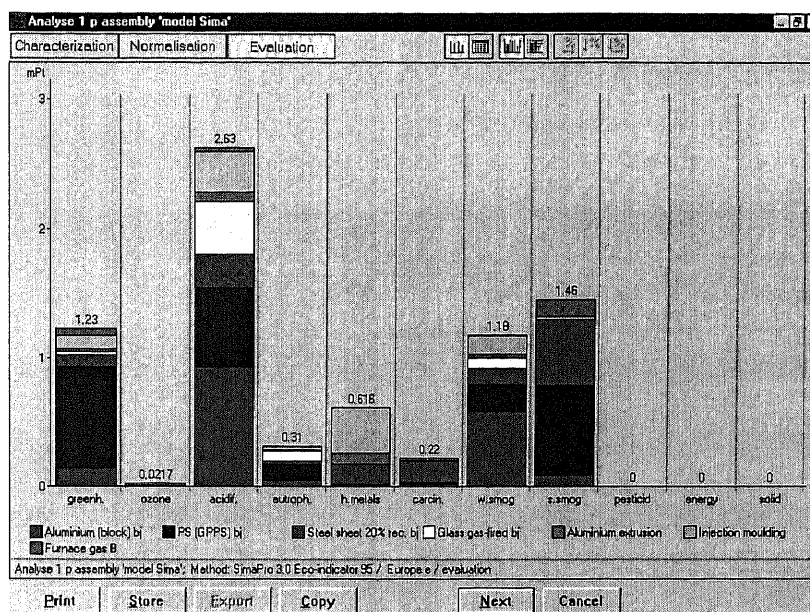
Figure 2.10 Evaluation Graph for Model Sima [SimaPro]

2.4.3 Comparing Products and Other Abilities

Other than analyzing the product lifecycle of a single product, SimaPro also has the ability to compare the performance of two, or more different products. It also offers a range of options for modeling the complex end-of-life scenarios that will occur when products are disposed of, recycled, or disassembled and partly reused.

SimaPro makes a distinction between:

• Disposal of product assemblies, using a disposal scenario box, a disassembly box or a reuse box;

• Waste treatment of materials, using a waste scenario or a waste treatment process.

2.4.4 The SimaPro Databases

Databases are important portions for the product life cycle assessments. They store the detailed information on products, processes, analysis methods, energy consumption and environmental burdens. Four main data sources come with SimaPro 4.0 [SimaPro]:

A) Franklin LCI database

The Franklin Associates US LCI Database has a great deal of Life Cycle Inventory (LCI) data reflecting industrial operations in the United States of America. An important aspect of this database is that it contains LCI data for commodity fuels and electricity, as well as a variety of product systems and materials, with varying degrees of recycled content.

The database includes data for 22 energy, fuel and transportation processes. It also includes life cycle inventory data for roughly 40 materials. For 13 of the materials, the database includes data for both 100% virgin-based and 100% recycled content, so that the user is able to interpolate between the virgin and the recycled tables to analyze any percentage of recycling or recycled content. Some of these 13 materials are unbleached kraft paperboard, paper towels, newsprint, glass, and aluminum.

B) FEFCO database and scripts for the corrugated board industry

Since 1994 FEFCO, Groupement Ondulé and Kraft Institute have been working together to provide the industry and its customers up-to-date knowledge, based on facts, concerning the impact of the industry on the environment. This knowledge helps to integrate environmental affairs into decision making. It is the basis for product and process improvements, thus enabling a responsible and pro-active industry attitude towards the environment.

Each association regularly collects environmental data from its members. The weighted averages of the collected data are published together in a report "European Database for Corrugated Life Cycle Studies". The LCA software tool is based on the data and methodology as described below:

- descriptions of the production systems

- methodology questions

- data for consumption of raw materials, additives and water

- data for emissions to air and water and waste

C) Dutch concrete database and scripts

This database and scripts have been made especially for the Concrete and Building industry in the Netherlands on behalf of the "Betonplatform". Over 50 companies have already used this database in combination with SimaPro Light.

D) The updated IVAM database

A complete update of the IVAM ER LCA database will appear soon. Features of this new version of the database are:

- Land use impacts on biodiversity and life support for all processes

- New category agriculture products

- Switches between ETH and Dutch energy systems

- Other switches for sensitivity analyses

- Updated impact assessment methods, including new normalisation data

- Including APME and BUWAL data for comparisons

- Including many new process data

2.5 LCA Limitations

As the popular tools used for evaluating the environmental performance of products, LCAs still has many problems in its utilization. LCA is a time-consuming and data intensive procedure that requires expert knowledge in materials, manufacturing, use and disposal. The main concerns in LCA are:

- How to draw system boundaries, what are the assumptions made, and how to ensure consistency throughout the life cycle stages.

- The availability of environmental data and energy information. Data gaps are created in LCA studies whether it was in materials or production processes or any other stage of the product life cycle.

- The LCA methodology is another problem, since it is not standardized so far. Problems encountered in the methodology such as uncertainty and quality of data, difficulties to compare old products to new products, no standardized method for calculating the impact of products or processes on the health and environment, the different units by which system inputs and outputs are measured, and no uniform unit by which costs and benefits can be converted into impact analysis.

CHAPTER 3

LCA and MLCA METHODOLOGIES

3.1 Introduction

It is well known that life cycle assessment (LCA) of a Product can reveal whether a design is environmentally responsible and help designers identify changes that can make it more so. Another advantage is that over time, LCA can aid in the design and manufacture of products with a commonality of responsible choices in materials, processes, and resource conservation across the life cycle of products.

LCA methodologies [EPA 93] concentrate on material and energy balances for each operation within the system and for the whole life cycle system itself. There are a number of variations. It is very important to review and present some well-established methodologies before we introduced Multi-lifecycle assessment methodology. Among them are Graedel's matrix based method and Mary's step-by-step appoarch. They are discussed in sufficient detail in section 3.2 and 3.3. These two approaches are also the basic of many other approaches including the MLCA methodology we will present in section3.4.

3.2 Graedel's Methodology

How should a product inventory be performed? Graedel Methodology proposed to use an industrial ecology matrix template to perform and present a material and process analysis. The typical matrix template is a matrix system graphically and qualitatively summarizing the status of a particular design option across the product life cycle [Graedel 95].

To perform a product inventory, we use the matrix concept to deal with all materials over a single product line. In this approach to industry ecology, individual products are assessed as they reach the design and development stage. A typical matrix is illustrated in Figure 3.1. A matrix of this type has rows labeled as the different life cycle stages and columns labeled by different environmental impacts, which are divided into five classes: materials choice, energy use, solid residues, liquid residues, and gaseous residues.

Life stage	aterials choice	Energy use	Solid residues	Liquid residues	Gaseous residues
Resource extraction					
Product manufacture					
Product packaging					
Product use					
Recycling, disposal					

Figure 3.1 Basic Matrix of Environmental Concerns of a Product [Graedel 95]

Each element in the product audit matrix shows the extent of the impact of one life cycle stage in one particular area as well as the degree of reliability of this information. The graphical nature of this representation makes it relatively easy to compare the total impacts of the different life cycle stages or obtain the total impact of each life cycle stage by summation across rows. If we preform the matrix on several products or on the different designs of a product, we can determine their relative level of merit by comparing several products or responsible designs.

Four generation telephones are used as an example to show the idea of the matrix assessment concept. They are shown in Figure 3.2. We use the telephone 1989 as an example to present all the details using this approach.
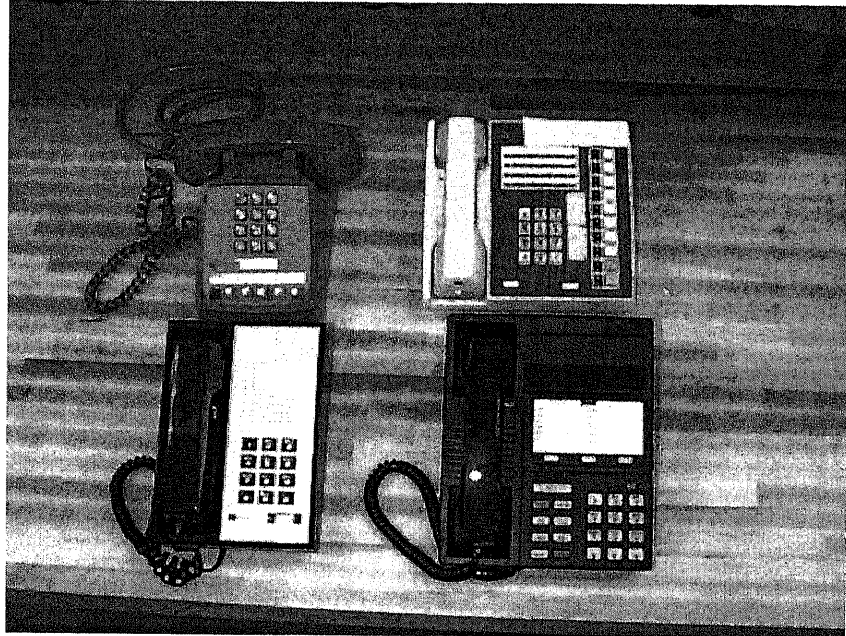
Figure 3.2 Four Generations of Business Telephones:
Top Row (Left to Right):   1965   1978
Bottom Row (Left to Right):   1989   1997

In order to evaluate the environmental concerns of a telephone, we present the material inventory for 1989 AT&T telephone in Appendix A. We can begin our evaluation from the first life cycle stage, materials extraction, to the last stage. Since we have the material information of 1989 telephone in Appendix A, the evaluation can be made by considering a series design rules of material selection. For instance, we need to think over questions: Are any proposed materials in restricted supply or are any proposed materials toxics? If the answer is yes, we need further consider if any material

substitution is thoroughly considered? After answering all the questions, we should

choose an ellipse filled to indicate the degree of confidence in evaluation. The detailed

rules are shown in Appendix A in [Graedel 95]. The result is summarized in Figure 3.3.

Life stage	Materials choice	Energy use	Solid residues	Liquid residues	Gaseous residues
Resource extraction	●	●	●	●	●
Product manufacture	●	●	●	●	○
Product packaging	●	●	●	●	○
Product use	○	●	○	○	○
Recycling, disposal	●	●	○	●	●

● 100%   ● 75%

○ 50%   ○ 0%

Degree of Certainty in Assessment

Figure 3.3 Matrix Study on Telephone1989

We can use the matrix concept and derive all the assessment results for four

generations of telephones. From the summary matrix options, we can draw the conclusion

that one is the best in terms of environmental burdens and what we should improve in

certain fields of a telephone product.

3.3 Mary's Methodology

Mary's Methodology [Mary 96] is an inventory methodology based on five basic steps of an LCI study. Following is a detailed discussion of each step.

- **Define the Scope and Boundaries**

This is a continuation of the goal definition and scoping stage of the LCA. In addition to the activity set in the goal definition and scoping stage, more specific information on the product is incorporated. It is important to define specifically the product, process, or activity for which an LCA is to be performed. The definition needs to be made in measurable terms, such as the weight of each component and material that make up a product, specific amount of associated packaging used for the system, and the functional units.

- **Gather Data**

Identifying all the process steps within the system being studied is the first step in gathering data for an LCA. Beyond this, a large amount of process data is necessary to complete a typical LCA. Raw materials use, energy use, the ratio of product to coproducts, and environmental releases must all be quantified for each process step of the system. This is necessary for all the LCA stages from raw material production and continues through product use and disposal. Once data is collected for each step in the system being analyzed, certain calculations are necessary to put the data into the desired format for entry into a computer model.

- **Create a Computer-Based Tool**

A large number of complex calculations in LCA make the use of a computer model ideal for LCA studies. Computer modeling can be done by using simple spreadsheets or sophisticated database softwares. The goal of a computer tool is to allow users to define and describe their product's structure, and then compile all the input and output data for each step of the system. Also, results can be displayed in varying detail based on the need of the user.

- **Analyze and Report the Study Results**

Results obtained from the life-cycle inventory must be analyzed and reported in a meaningful way that conveys all the LCI information. The presentation of the results in the inventory stage is important to help product designers make their decisions. The complete LCA report conclusions are extracted from this analysis stage. Tools such as eco-compass, resource productivity, and various trend and graphs are used to help present the extensive LCA data. More details on the use of these tools will be presented in the Chapter 4.

- **Interpret Results and Draw Conclusions**

After the results of the LCA are generated, they can be interpreted, and conclusions can be drawn based on the purpose of the study. Conclusions for LCA studies are specific to the product, process, or activity being analyzed. LCA results list resource use, energy use, and environmental releases to the air, water and land. At this stage of the LCA, no attempt is made to determine the relative impact of each of these on the environment or

on human health. Therefore, conclusions and improvement analysis are limited to seeking less resource, less energy use, and lower levels of emissions to the environment. The value of tradeoffs within result categories is a question left for the impact stage of the LCA. We will give an example in Chapter 6, since this methodology is one part of the Multi-Lifecycle Methodology (MLCA) which is the main part in this thesis.

3.4 Multi-lifecycle Assessment Methodology

As mentioned in the previous chapters, life cycle assessment (LCA) is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases on the environment, and to evaluate and implement opportunities to effect environmental improvements [Caudill 99]. Traditional LCA is a cradle-to-grave analysis whereas multi-lifecycle assessment emphasizes a cradle-to-cradle perspective. We extend the structure of traditional LCA's to include explicit consideration of demanufacturing, remanufacturing, reengineering and reuse-extending LCA's to the realm of multi-lifecycle engineering. These end-of-life recovery processes have been modeled to account for material flows, energy usage and environmental burdens associated with recovery and reprocessing of components and basic materials. The total life-cycle engineering framework is presented in Figure 3.4.
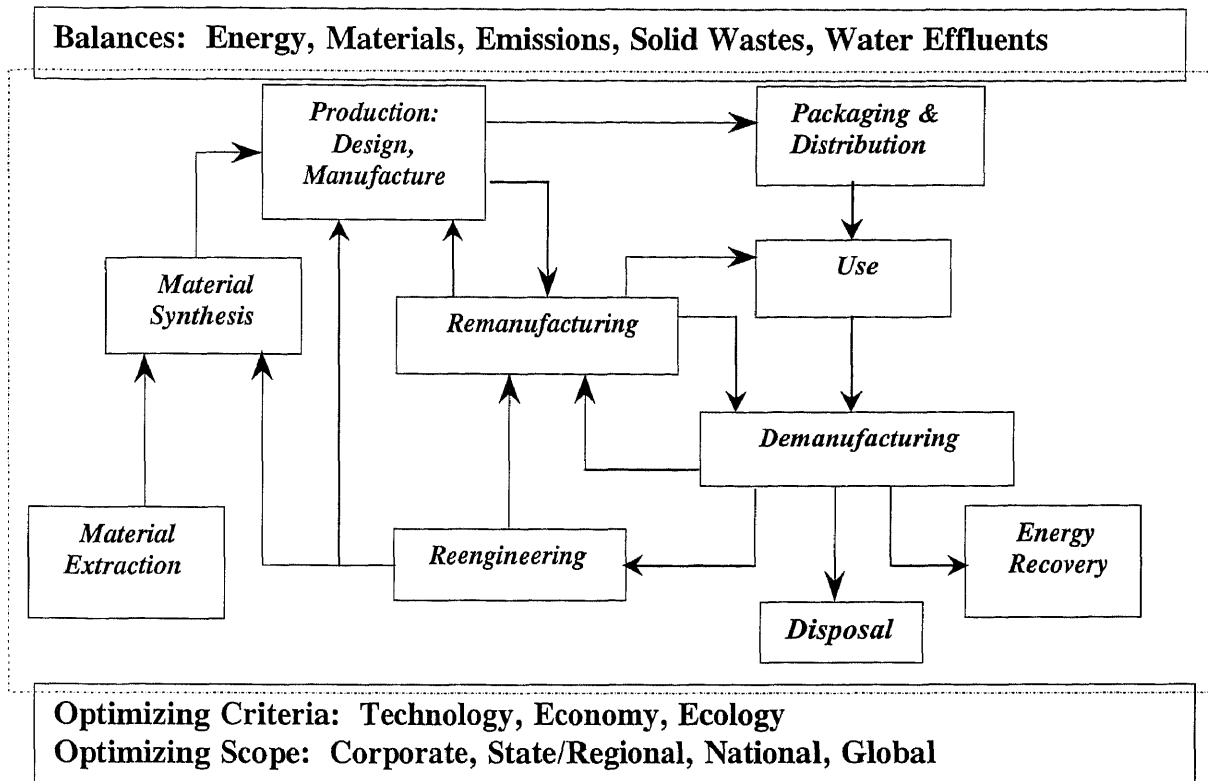
Figure 3.4 Total Life-Cycle Consideration for Analysis and Modeling

Comparing to the tradition life-cycle model, which consists of four life-cycle stages: material manufacturing, product manufacturing, product use, and recovery, there are some additional definitions to Multi-lifecycle structure: 1) Materials production includes two stages, materials extraction and materials synthesis. 2) To quantify the materials used in a packaging process, methods of transportation, distance traveled, and energy and emissions associated with these processes, a packaging and distribution stage is separated from the production stage as an independent stage. 3) The recovery and new life options of a product is the main point where MLCA differs from LCA. LCA specifies two types of recycling processes, open loop recycling and closed-loop recycling. MLCA merges these two recycling options into one, and throughout its life from raw material

extraction to final disposal. MLCA calls this stage of a product life-cycle as Demanufacturing. 4) The reengineering stages acts as a link that closes the lifecycle loop. 5) Remanufacturing stage is where the parts and subassemblies are reused. Those parts can be reused in new products at production stage or as replacements at the use stage or can be sent back to demanufacturing. An important aspect of multi-lifecycle assessment is balance flows of energy and materials and quantifies emissions, solid wastes and water effluents throughout the product life. Generic frameworks of each multi-lifecycle are discussed in Hussam's Master thesis [Hussam 99].

CHAPTER 4

MULTI-LIFECYCLE ASSESSMENT SOFTWARE DESIGN

4.1 System Platform

The MLCA software tool is written for a personal computer Windows environment using Visual Basic 5.0 with Microsoft Access 97 as the database package. Visual Basic is one of the popular languages nowadays because of its friendly interface supply and easy communication with databases. We also select Access 97 as the database package instead of Microsoft Excel and Lotus 1-2-3. The reason is that by using a Microsoft Excel worksheet to maintain data of products, a list of repeating data can grow too large and become very difficult to maintain in Microsoft Excel. But we can make it easier to manage our product list by Microsoft Access, so that when we update information in one place, it's updated everywhere in the database. Microsoft Access also makes it possible for several users to work in the database at the same time.

4.2 Database Design

MLCA, as a life cycle analysis tool, requires a large amount of data and information on product materials, manufacturing processes, energy and environmental issues, demanufacturing, etc. It allows designers to enter different types of materials they anticipate using in their product, and can automatically generate a list of energy consumption and environmental burdens associated with these materials. A set of databases coupled with MLCA software are designed to store all the data and information, which relate to each other in a complex way. The database design is the most important one in the whole MLCA software design.

37

MLCA databases are divided into two fields, one is standard database with the verified data, and another is a user-defined database where users can distribute their own databases of different products. Some utilize custom databases that address specific products and processes, while others may include large databases that describe generic processes and their emissions and other effects. The data can be checked and transferred to the standard database using as a standard if the data is accurate for a product.

4.2.1 Product Description Databases

There are three main databases designed for the overall information of a product: The *project information database* stores the general information about a project, including the project name, description, user name, and the corresponding information about the user, such as the phone number, address of the user, etc. *Production description database* and *production material database* store the material inventory data of a specific product. Usually, the software has some existing databases on certain products. Also, users can input their own data from the software project information and product description interfaces, which we will discuss in detail later. We also need to design a *relationship database* for the tree structure display of a product's assembly. The relationships between basic product information databases are shown in Figure 4.1. The relation schemas of those tables in MLCA database are displayed in Table 4.1 to Table 4.9.

Component name
Component description
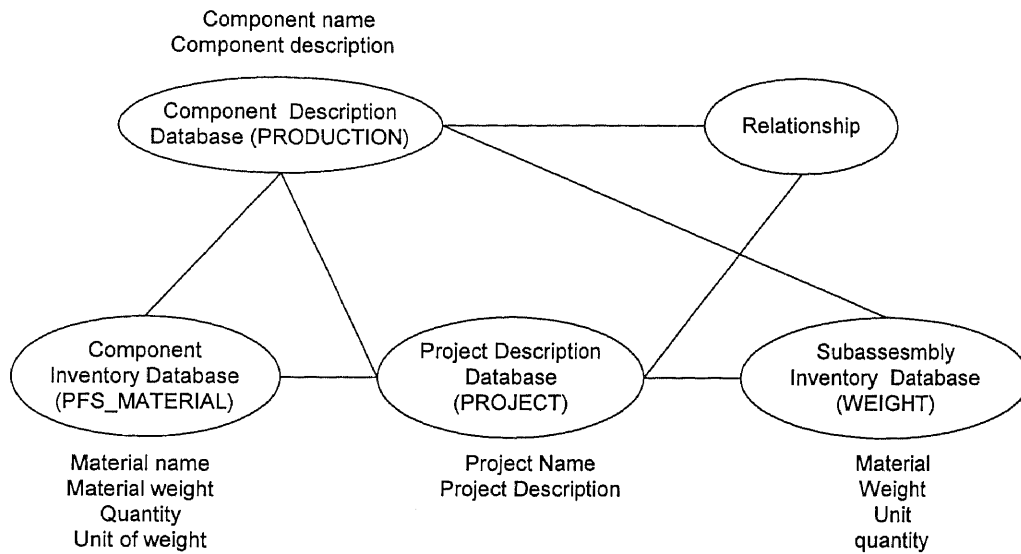
Figure 4.1 Relationships between Basic Product Information Databases

Table 4.1 Project Relation

Project_ID	Project_Name	Project_Description	User_Name	Company	Address	Telephone

Project_ID: the prime key to distinguish different projects. Different products have

different Project_ID.

Project_Name: the name of a product.

Project_Description: brief explanation on a product.

User_Name: the user who creates the project information.

Company: user's work place.

Address: user's company address.

Telephone: user's phone number.

Table 4.2 Production Relation

Project_ID	PFS_ID	Name	Description	Root_ID	Identify

Project_ID: the foreign key to distinguish different projects. Different products have

different Project_ID.

PFS_ID: the primary key to distinguish different components of a product. Each

component including subassembly with part, final subassembly, and final part

has its own ID to avoid name conflicting.

Name: the name of a component that constitutes a product.

Description: brief explanation on each component of a product

Root_ID: the identification number is used to present first level nodes in a product tree

structure. If a node is a root in a product tree, the corresponding field is filled

with "R".

Identify: to specify a component in a product to be a subassembly with part or final

subassembly or a final part. We use "S" as a subassembly with its own part

children, "P" as a part with its subassembly parent, "FS" as a final subassembly

without any subassembly or part, and "FP" as a final part without any

subassembly parent. The classification of the component of a product is

explained in Chapter 4.3.

Table 4.3 PFS_Material Relation

Project_ID	PFS_ID	ID	Material_Name	Weight	Quantity	Unit

Project_ID: the foreign key to distinguish different projects. Materials with same

Project_ID belong to the same product.

PFS_ID: the foreign key to specify the relationship between a material and a component. Materials with the same PFS_ID means that the component is made up of more than one material.

ID: the primary key of the PFS_Material relation.

Material_Name: specify material types in a product

Weight: the weight of a material used to build up a component.

Quantity: the quantity of a component used in a product.

Unit: unit of the material weight. Default one is gram.

MLCA software links these tables with Jet engine by setting Database and Recordset objects in VB applications. To represent a product tree, a relationship table is designed in MLCA database as shown in Table 4.4:

Table 4.4 Relationship Relation

Project_ID	ID	Root	Child

Project_ID: the foreign key to distinguish different projects.

ID: the primary key of the Relationship relation.

Root: the identification number of the subassembly with another subassembly or with a part as a child.

Child: the identification number of the subassembly or part with its subassembly parent.

The product tree can be shown automatically by joining above three relations together and retrieving related component names.

To execute an MLCA assessment over the entire lifecycle, we need to design other databases for each lifecycle stage.

4.2.2 Multi-lifecycle Stages

After users complete the product description stage, they then access the multi-lifecycle stages to input specific information to each life-cycle stage of a product. Related databases are linked to store and retrieve data in each stage of the product life cycle. Users begin with a new project, input the data required to each life-cycle stage screen as shown in Figure 4.3 to Figure 4.11. The stored data can be retrieved from MLCA databases when users open the project later. The detailed relation tables used in each life-cycle stage are:

• **Material Processing Database**

The information related to the composition of the material, such as the virgin, recycled and reengineered contents, and information on the percentage of industrial scrap and post consumer recycled content are required from users and stored in Material_Processing table in MLCA database.

Table 4.5 Material_Processing Relation

Project_ID	Material_ID	Virgin	ScrapRecycled	PostRecycled	Reengineered	YieldRate

Project_ID: the foreign key to distinguish different projects.

Material_ID: the foreign key to distinguish different materials made up of a product.

Virgin: virgin contents.

ScrapRecycled: the percentage of industrial scrap recycled content.

PostRecycled: the post consumer recycled content.

Reengineered: reengineered contents.

YieldRate: material yield rate.

- **Production Database**

The production process information of each part, process materials used in production processes, energy consumption, and environmental burdens of subassemblies are required at this stage. Objects of Production_Process and Process_Material relation tables are set to track production process information and process material information, respectively.

Table 4.6 Production_Process Relation

Project_ID	PFS_ID	ID	Process_Name

Project_ID: the foreign key to distinguish different projects.

PFS_ID: the foreign key to specify the relationship between a production process and a component

ID: the primary key to specify the production process of different materials.

Process_Name: the name of a production process.

- **Packaging and Transportation Databases**

Since package material burden is nowadays one of the important issue of the environmental burdens, we use independent Packaging and Transportation databases to keep information on packaging and packaging materials. The packaging database contains package weight of a product, product weight, and weight ratio packaging to a product, etc. Package material database is used for storing material name, weight of a certain material, and volume of the material, which are useful for the environmental affects analysis later. The product also has transportation consumption from its manufacturing stage to final shipment to the customers. Transportation database has standard data on different transportation tools. The database has the default values on

heavy duty truck, medium duty truck and light duty truck now, and the transportation like air shipment, rail, and ship will be included in the database as well, when the data is available.

Packaging, packaging materials information, and transportation information of a product can be accessed in this stage by creating three related relation tables named Packaging_Material, Packaging_Information, and transportation.

Table 4.7 Packaging_Material Relation

Project_ID	ID	Packaging_Material	Recycle_%	Weight	Volume

Project_ID: the foreign key to specify the relationship between a material and a
    component

ID: the primary key to a packaging material of different projects.

Packaging_Material: name of packaging material used in a product.

Recycle_%: the recycled percentage of a packaging material.

Weight: the weight of a packaging material used in a product.

Volume: the volume of a packaging material used in a product.

Table 4.8 Packaging_Information Relation

Project_ID	ID	Product_Volume	Packaging_Volume	Packaging_Weight	Product_Number

Project_ID: the foreign key to specify the relationship between packaging information
    and a project

ID: the primary key of the packaging information relation

Product_Volume: the volume of a product

Packaging_Volume: the packaging volume of a product

Packaging_Weight: packaging weight of a product

Product_Number: number of products packaged in a package

- **Use Stage Database**

Energy consumption of each mode in use stage of a product is stored in Use relation. The total energy consumptions in the use stage of a product can be summarized with the data in the use relation table.

Table 4.9 Use Relation

Project_ID	ID	Active	A_%	Idle	I_%	Power_Save	P_%	Off	O_%	Life_Span	Unit

Project_ID: the foreign key to specify the relationship between Use stage and a project

ID: the primary key of the use relation

Active: energy consumption in active mode of a product.

A_%: the utilization percentage of active mode in Use stage of a product

Idle: energy consumption in idle mode of a product

I_%: the utilization percentage of idle mode in Use stage of a product

Power_Save: energy consumption in power save mode of a product

P_%: the utilization percentage of power save mode in Use stage of a product

Off: energy consumption in off mode of a product

O_%: the utilization percentage of off mode in Use stage of a product

Life_Span: the life years a product is excepted

Unit: the unit of energy consumption. The default option is MJ.

4.2.3 Other Databases

Other databases such as energy source database, material database, and process databases are also designed for maintaining the information required in each multi-lifecycle stage.

- **Material Database**

Material database is a core part of the MLCA databases helping MLCA software carry out impact analysis of a product. The material database provides primary energy consumption data of a material, air borne emissions, solid wastes, and water based emissions of a material. The data was obtained through literature searches involving various technical reports, computer databases, and information from industry and governmental agencies.

- **Process Databases**

MLCA databases also stores process information in process database. If a process with one or more than one-process materials, they will be stored in the process material database.

4.3 User Interface Design

A friendly user-interface is preferred by all customers, which can bring them an easy understanding and application of a developed software. MLCA software supplies an easy windows-based interface by using the popular VB5.0 technology, including many advanced features used in Microsoft softwares. For instance, the ability of viewing the product by graphical tree structures and using OLE container to import flexible graphs

for the analysis reports. The MLCA software development is classified in three main stages: product description stage, life cycle stage, and analysis and reports stage. The detailed design description is explained in the following subchapters.

4.3.1 Product Description Interface Design

Following the MLCA methodology introduced in Chapter 3, to perform an LCA evaluation on a product, we have to address the most important issue, i.e., the data collection. Without real data of a product, we can do nothing on the assessment. The product description interface is designed for the product information gathering. Its structural design is shown in Figure 4.2.
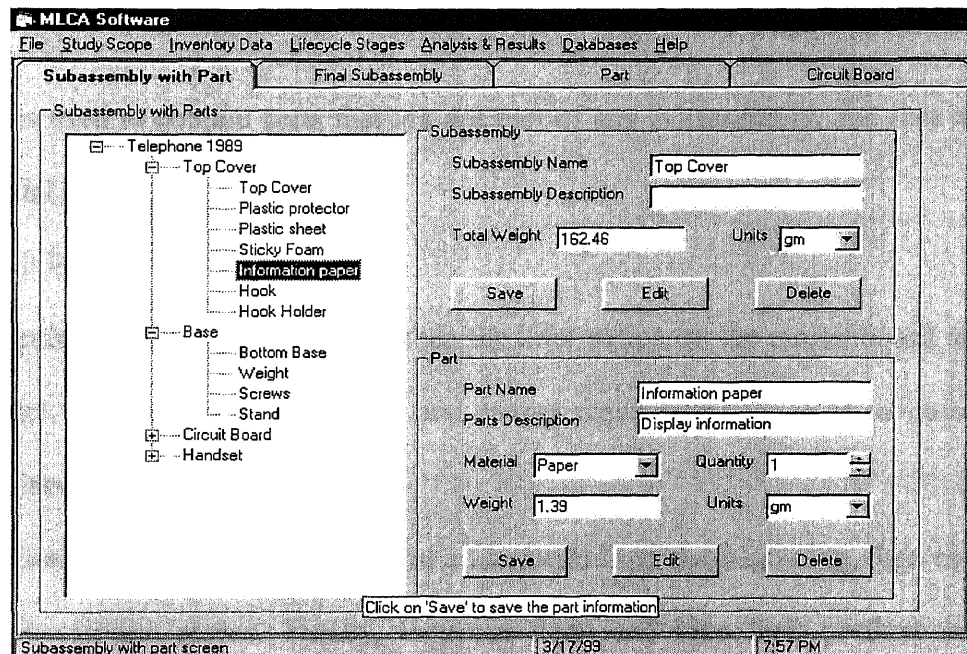
Figure 4.2 Product Description Screen of the MLCA Software

We use four tabs to deal with different situations in a product's assembly i.e., subassembly with part, final subassembly, part, and circuit board.

1) Subassembly with Part Tab:

This tab contains subassemblies assembled by parts or subassemblies assembled by other subassemblies in a product. Information such as material type, quantity and weight of the subassembly or part is required to input into the subassembly or part section.

2) Final Subassembly Tab:

It contains subassemblies that with no further parts or other subassemblies, but maybe the ones consist of more than one material. The information required in this tab relates to various materials and total weight of the subassembly.

3) Parts Tab:

This is used to contain parts that are not part of any subassembly, and just with one material making.

4) Circuit Boards Tab:

A circuit board tab is designed to keep the information on the circuit board used in a product. The area of circuit board and energy requirement for PCB manufacture is contained in this tab.

Users can create a new project in a file menu from the beginning, then come to a product description screen. Finally, they can input and save their product inventory information from the screen in different fields according to different situations, at the same time, a run-time product tree is activated on the most left side of the screen. During the data input processing, the software will give a guide in each step by automatically

pop-up messages. Users who are interested in the product later can access the product assembly information clearly and directly by keeping an eye on the product tree. If they want to know the detailed information about a particular component of a product, simply clicking on that part on the product tree. The corresponding material name, weight, quantity and unit it uses appear in the information boxes on the right side. Users can edit or delete some data in the information boxes if they would like to make some changes on the product.

4.3.2 Lifecycle Stage Interfaces Design

In order to get a complete analysis result on a product in the Analysis and Report stage, we design the lifecycle stage interfaces for each specific lifecycle stage, from which we try to collect enough information for later calculations and report. The information from here will also be very useful for the impact analysis and improvement analysis.

4.3.2.1 Material Processing Stage: This stage focuses on material information of a product. A material inventory tree can be displayed clearly on the material processing screen, which is another way to show the product inventory information. All the materials used in a product are shown by material names as the parents in the tree structure and all the parts using the same material are shown under a material name as children. By clicking on one of the child nodes in the material inventory tree, users can also get information about a particular part. The corresponding part name, weight and quantity of that part are shown on the right top boxes.

MLCA software can summarize more material information of a product with a pull down material information menu at the right bottom of the screen. At first, users are required to input the percentage of virgin contents and the percentage of recycled contents, including industrial scrap recycled content, post consumer recycled content and reengineering content. This information helps in allocation of energy and environmental burdens to the product, based on the MLCA methodology. Then, users can view the detail information about certain material by graphs and by display boxes, by selecting one of material nodes in the left material inventory tree first, choosing the information they are interested in, and clicking the Go button beside. The Material Processing Screen is shown in Figure 4.3.
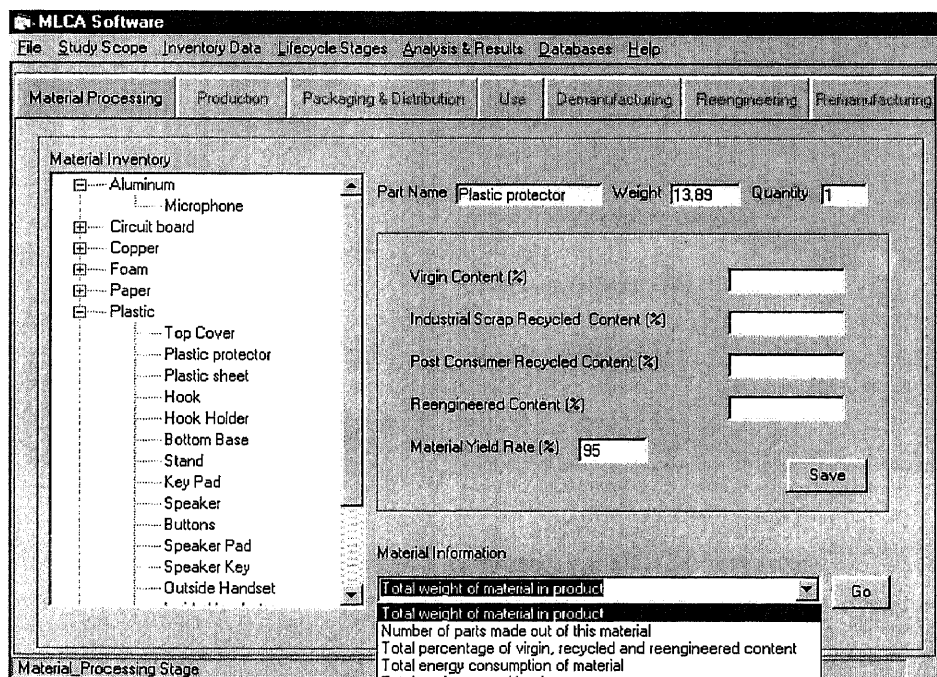
Figure 4.3 Material Processing Screen of MLCA Software

The material information includes: Total weight of material in product, Number of parts made out of this material, total percentage of virgin, recycled and reengineered contents, total energy consumption of material, total environmental burdens, material substitution options and value of material cost.

4.3.2.2 Production Stage: Production Screen shown in Figure 4.4 is designed for specifying the production processes that produce each part of a product.
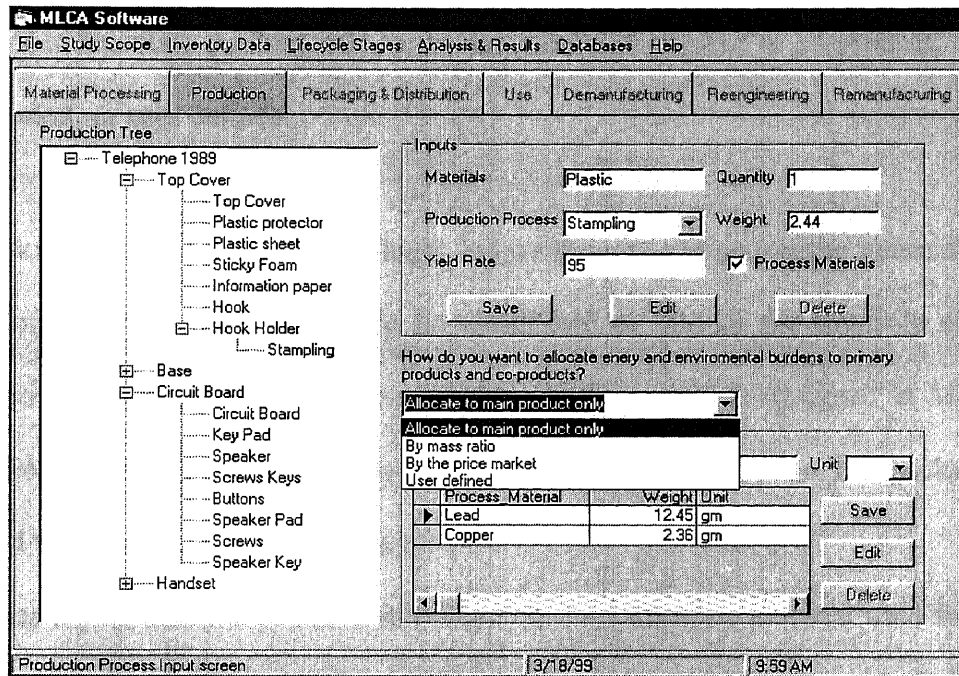
Figure 4.4 Production Screen of MLCA Software

By selecting the product parts or subassemblies of a product on the production tree first, users are required to decide the production process of that part or subassembly from a given production process list. We have a process database which contains information on eight production processes: Extrusion, Injection, Thermoforming,

Stamping, Milling, Turning, Semiconductor processing, and Glass forming. After users click on a part or subassembly in the production tree, the material, quantity and weight information of that part or subassembly are shown on the right top hand of the screen automatically. If a process is companied with new materials consuming, users need to mark the process material check box. With a pop up frame of process materials, they can input different materials used during that process, including the weight used of that material. The yield rate for that particular process needs to be specified as well. Finally, users should make a decision of the allocation of energy and environmental burdens. It can be either to the main product only, or by mass ratio of product to co-product, or by the price market, or user defined.

4.3.2.3 Packaging and Distribution Stage: Information on the packaging material and transportation of a product should also be considered as one of the lifecycle of the product. The packaging and distribution interface in Figure 4.5 is designed in MLCA software, from which the user can input the specific information on the packaging material and transportation of that product.

In packaging material frame, information on the packaging material used for the product, the percentage of recycled material, material weight, and volume of that material can be filled in. The specific information on each of the packaging material used is shown in the right hand material information table. Informations on the volume of the product, total packaging weight and other concerned information are specified in packaging frame. The user can also qualify the transportation information of a product in Product Transportation Screen as shown in Figure 4.6.

Figure 4.5 Packaging and Distribution Screen of MLCA Software

Figure 4.6 Product Transportation Screen

The transportation information includes: the mode of transportation, actual load, load ratio, and distance traveled. When users select a transportation mode, the corresponding default values of weight in pounds, Maximum payload in pounds, and the fuel efficiency in miles per gallon are displayed at the top right side of the screen automatically. Users can edit the default ones by inputting their values in the textbox beside. Users can also assume the distance traveled to be roundtrip or not. By clicking the Transportation Energy & Emission Report button at the bottom, we can get the final report on transportation energy consumption and environmental emissions. The detail report is shown in Figure 4.7.

Figure 4.7 Transportation Energy & Emissions Report of MLCA Software

4.3.2.4 Use Stage: This stage relates to the energy consumed by the product in different modes during its use stage. They are classified in four modes: active, idle, power save and off. In each mode a product consumes a certain amount of energy that must be entered into this screen. The amount of time a product used in each mode and the excepted life span of a product is required. The total energy consumption of a 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. Users can access the calculation result by clicking on the Calculate Use-Stage Energy Consumption button. Figure 4.8 displays the use stage screen, value 116 is the total energy consumption in MJ.

Figure 4.8 Use Stage Screen of MLCA Software

4.3.2.5 Demanufacturing Stage: We now focus on the other three stages, Demanufacturing, Reengineering and Remanufacturing, which are new in the concept of Multi-Lifecycle Engineering. Demanufacturing is an important stage of the product multi-lifecycle. The end fate of the various parts and subassemblies is determined here. The first step in analyzing the demanufacturing process is to quantify 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 a product. Then, users need to determine the end fate options for the product. MLCA software provides a list of end fate options as reuse product, remanufacture parts and subassemblies, recover basic material, or remaining carcass.

- Reuse Product

If the end fate chosen for a product is reuse, users are required to input its anticipated inspection pass rate, which means that this percentage of a generation of the product can be resell. The reselling price of a product is also required. Reuse of a product means taking the whole product back to its second life cycle without any additional costs and energy consumption. The benefit from reuse option can be obtained by multiplying the reselling price and the percentage of anticipated inspection pass rate, subtracting the cost from remanufacturing and reengineering stages.

As to the remaining percentage of products that can not be reused again, its end fate option needed to be determined.

- Remanufacture Parts and Subassemblies

This option is chosen when some subassemblies or parts of a product can be remanufactured with an optimum value. Users need to add those subassemblies and parts into the Remanufacture subassemblies and parts table provided in the screen. After 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.

- Recover Basic Material

Material can be recovered from parts and subassemblies of a product by disassembly or shredding recovery method. Users create a custom bin table from a recovered material type list. This list includes various recovered materials with both recovery methods mentioned above. For example, if commingled plastic is part of the material in a product, then the columns of the bin table include: commingled plastic–disassembly and commingled plastic–shredding. The same method applies to all other materials in a product to be recovered. Parts and subassemblies made out of that material is selected from the production tree and dropped to the various bin columns. Users then specify the four end fate options for each bin, which are: Reengineering, Waste to Energy, Smelting, and Landfill.

- Remaining carcass

The remaining parts and subassemblies of a product that do not apply to the above end fate options are entered in this stage. They can not be reused anymore, and are either to smelter, waste to recovery, or to landfill.
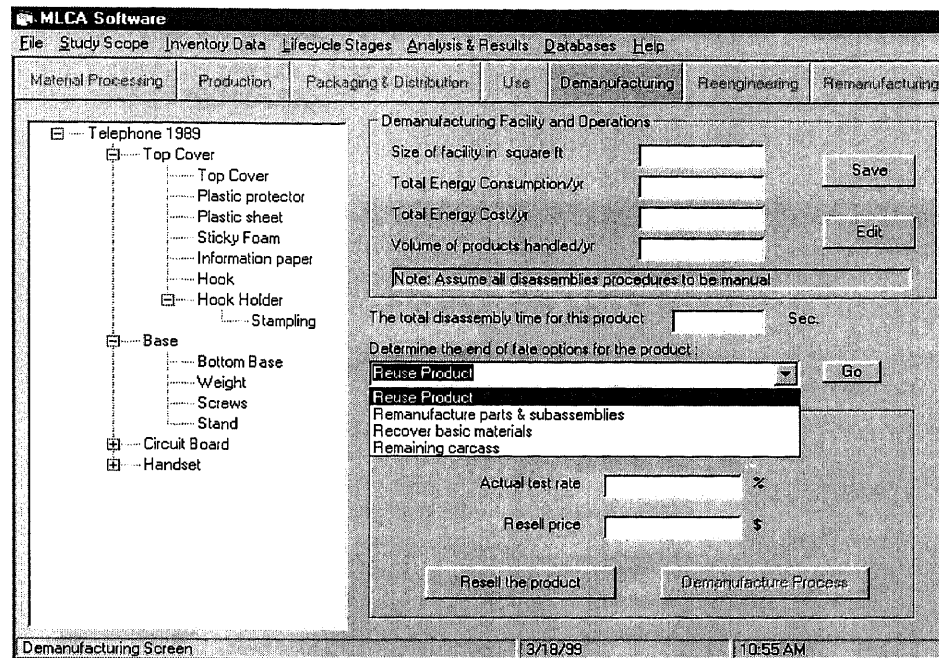
Figure 4.9 Demanufacturing Stage of MLCA Software

4.3.2.6 Reengineering Stage: This stage specifies the process required to recover basic

materials from selected materials in demanufacturing stage, and obtains the materials,

energy and environmental burden information in each step of the reengineering process.

Figure 4.10 displays the screen with a main cleaning process in the recovery of materials.

Users first select a material for reengineering, then specify the percentage of

hazardous material or contaminants in the material in pounds. After above two steps,

users need to select a reengineering process for the material from a given list. There are

six reengineering processes identified for material recovering: Reprocess, Compatibilize,

Pyrolysis to fuels, Pyrolysis/ Hydrolysis to monomers, Shredding for metals, and

Smelting. The step by step procedure for the selected process is appeared in an interactive

box when a reengineering process is chosen. For each step in a process, a window frame

pops up with main questions concerned for each of the reengineering processes. They are:

environmental burdens, energy requirements, material flows, additional process

materials, and cost of the process.

Figure 4.10 Reengineering Screen of MLCA Software

4.3.2.7 Remanufacturing Stage: The screen shown in Figure 4.11 aims to quantify such

data as material flow, energy consumption, environmental burdens and time requirement

for each step to remanufacture subassemblies and parts.

Users are required to specify the remanufacturing facility with descriptions as facility

size in square feet, volume of products handled per year, and total energy consumption

and environmental burdens per year. Users then a subassembly or part for

remanufacturing from a given list, which is taken from remanufacturing subassemblies

and parts selected earlier in demanufacturing stage. The step by step remanufacturing

process is shown in an interactive box. Finally, users select each remanufacturing step and input the required data in each popped up frame.

Figure 4.11 Remanufacturing Screen of MLCA Software

4.4 Algorithm Design

Combined with product information stored in MLCA databases, MLCA software supplies following algorithms to analyze the assessment result of a product or to compare different designs of the product or different products. To perform a MLCA assessment on a product, five-performance metrics and indices should be concentrated on for each life cycle: Environmental Burdens, Energy Consumption, Material Utilization, Composite Performance Measures, and Life-cycle Economics.

- **Environmental Burdens**

It is one of the most important points in environmental engineering, which includes subclasses as air emission, water effluents, and solid wastes.

Material Processing

The analysis of environmental burdens generated from production of feedstock materials and emissions generated from power sources during this stage is summation in material processing stage. The formula describing the environmental emissions of a product material generated from its material processing stage is:

$$\sum_{i=1}^{n} A_i * (B_i + C_i)$$

where Ai is total weight of material i used in the product, B_i is environmental burden generated from production of material i in unit gram, and C_i is environmental burden generated from power sources used during production of feedstock material i in unit gram. B_i and C_i values of several materials are listed in Appendices B.1, B.2, and B.3.

Production Stage

Environmental burdens in Production stage are generated from the use of electric power sources, and processing of materials. Users are required to input information about environmental emissions from production life-cycle screen. The total environmental burdens generated from this stage are the summarization of environmental burdens generated from each subassembly of a product.

Packaging and Distribution Stage

Environmental burdens in this stage are from transportation tools used to transport a product. Environmental burdens generated from production of packaging materials are not included in this study. Total emissions from product transportation can be calculated by:

$$\sum_{i=1}^{n}(M_i * N_i)$$

where M_i means environmental emission generated from transportation tool i per mile, and N_i is traveled distance using transportation tool i. Since environmental emission generated from transportation tool is different, MLCA software owns different calculation engines on M_i [Ketan 99]:

- *Light Duty Truck*:

  Solid Waste: 1.02 + (0.2 * Actual_Load / 1000)

  Air emissions:

Particulate:	3.57 + (0.7 * Actual_Load / 1000)
Hydro Carbons:	8.21 + (1.61 * Actual_Load / 1000)
CO:	34.94 + (6.85 * Actual_Load / 1000)
NO2:	8.26 + (1.62 * Actual_Load / 1000)
Lead:	0.045 + (0.009 * Actual_Load / 1000)
Others:	3.39 + (0.76 * Actual_Load / 1000)

  Waterborne Effluents:

Suspended Solids:	3.16 + (0.62 * Actual_Load / 1000)
Acid:	0.33 + (0.065 * Actual_Load / 1000)
Others:	0.01 + (0.0028 * Actual_Load / 1000)

63

- *Medium Duty Truck*

  Solid Waste: $1.9 + (0.2 * Actual\_Load / 1000)$

  Air emissions:

Particulate:	$6.65 + (0.7 * Actual\_Load / 1000)$
HydroCarbons:	$15.29 + (1.61 * Actual\_Load / 1000)$
CO:	$65.08 + (6.85 * Actual\_Load / 1000)$
NO2:	$15.39 + (1.62 * Actual\_Load / 1000)$
Lead:	$0.09 + (0.009 * Actual\_Load / 1000)$
Others:	$7.25 + (0.76 * Actual\_Load / 1000)$

Waterborne Effluents:

Suspended Solids:	$5.89 + (0.62 * Actual\_Load / 1000)$
Acid:	$0.33 + (0.61 * Actual\_Load / 1000)$
Others:	$0.01 + (0.02 * Actual\_Load / 1000)$

- *Heavy Duty Truck*

  Solid Waste: $3 + (0.2 * Actual\_Load / 1000)$

  Air emissions:

Particulate:	$10.5 + (0.7 * Actual\_Load / 1000)$
HydroCarbons:	$24.15 + (1.61 * Actual\_Load / 1000)$
CO:	$102.75 + (6.85 * Actual\_Load / 1000)$

  Air emissions:

NO2:	$24.3 + (1.62 * Actual\_Load / 1000)$
Lead:	$0.14 + (0.009 * Actual\_Load / 1000)$
Others:	$11.45 + (0.76 * Actual\_Load / 1000)$

Waterborne Effluents:

Suspended Solids:	$9.3 + (0.62 * Actual\_Load / 1000)$
Acid:	$0.98 + (0.61 * Actual\_Load / 1000)$
Others:	$0.04 + (0.02 * Actual\_Load / 1000)$

where Actual_Load is total weight loaded on a transportation tool.

Use Stage

Environmental emissions considered in Use stage are those generated from the use of electric power sources. The calculations are based on the MJ of energy consumed.

Demanufacturing Stage

Environmental emissions in this stage are those generated from electric power sources used. The calculations are based on the MJ of energy consumed from demanufacturing facility and operations.

Remanufacturing Stage

Environmental burdens from Remanufacturing stage are the summary of emissions generated from each remanufacturing process and remanufacturing facility power sources used. Users are required to input correct data in remanufacturing life cycle screen at first.

Reengineering Stage

Environmental burdens from Reengineering stage include emissions generated from processes on each recovered material of a product. Users are required to input correct data in reengineering life cycle screen at first.

- **Energy Consumption**

Material Processing

$$\sum (MaterialWeight * EnergyData)$$

ere *MaterialWeight* is total weight of a certain material and *EnergyData* is energy required

ducing each material in MJ.

iduction Stage

ergy consumption in production stage is generated from the use of electric power

rces, and process materials. Users are required to input information of energy

isumption from production life-cycle screen. The total energy consumption generated

n this stage is the summarization of energy consumption generated from each

assembly of the product.

ckaging and Distribution Stage

ergy consumption in this stage is from transportation tools used to transport a product.

ergy consumption generated from production of packaging materials is not included in

i study. Total energy consumption from product transportation can be calculated by:

$$\sum_{i=1}^{n} D_i * E_i$$

ere D_i means travelling distance by transportation tool i and E_i means total

isportation energy consumption by transportation tool i.

2 Stage

ere are four modes defined for energy consumption during Use stage: Active, Idle,

ver Save, and Off. Total energy consumption during this stage is based on the

mula:

$$\sum_{i=1}^{4}(M_i * N_i * 24 * E * 365)$$

where M_i means energy consumption in unit MJ in each mode, N_i means utilization factor

of each mode, the total percentage of all four modes $(\sum_{i=1}^{4})$ is 100%, and E is the excepted

life span of a product in unit year.

Demanufacturing Stage

Energy consumption in this stage comes from demanufacturing facility and operations.

Users are required to fill in the total energy consumption per year in demanufacturing

life-cycle screen.

Remanufacturing Stage

Energy consumption from Remanufacturing stage includes energy required for each

remanufacturing process and remanufacturing facility energy consumption per year.

Users are required to input the information from the remanufacturing life-cycle screen.

Reengineering Stage

Energy consumption from Reengineering stage includes energy required in each

reengineering process. Users are required to input the information from reengineering

life-cycle screen.

4.5 Analysis and Reports

With the data and algorithm required to evaluate a product, the analysis and report screen displayed in Figure 4.12 is designed to show product assessment results in different ways. Users can view their product analysis results by tables or graphics. They can focus on reports based on each life-cycle stage of a product or on all seven lifecycles. The evaluation results using different methodologies such as Eco-compass and Represent Product are also available. A cost model for multi-lifecycle engineering design is presented in [Zhou 96].
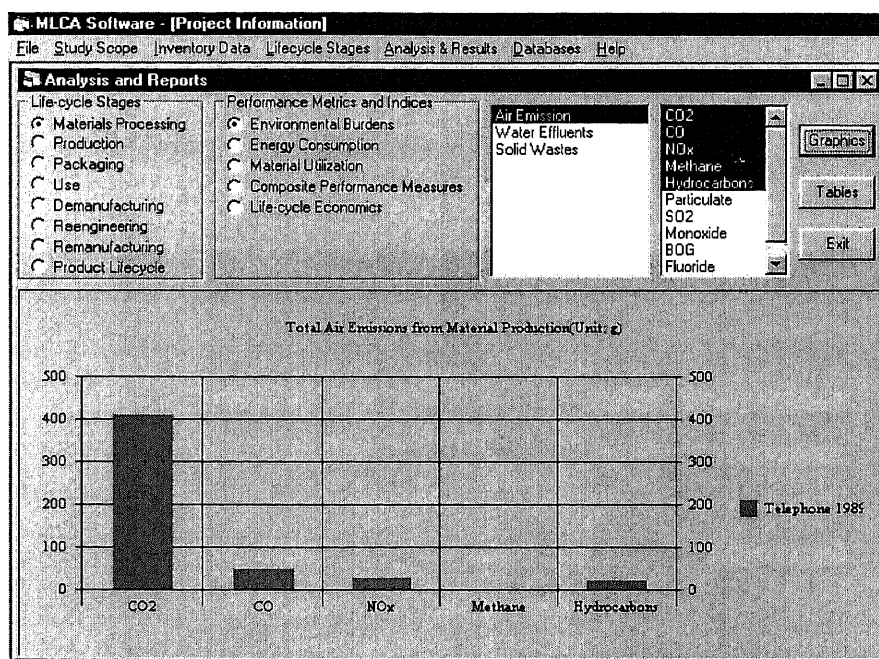
Figure 4.12 Analysis and Reports Screen of MLCA Software

4.6 Software Application

Steps to perform multi-lifecycle assessment (MLCA) on a product by MERC MLCA software are specified in this section.

Step 1: start MLCA software by double clicking the MLCA software icon.

Step 2: access the project information screen by selecting a new project or open a project from File Menu of MLCA software. The project name, project description, and user information are input by users from this screen, if it is a new project. As to a project already in MLCA database, users just need to select a project name from a pop up project selection list. The related project information is automatically shown in corresponding textboxes. Users can update the information if necessary. Figure 4.13 displays the project information screen.

Figure 4.13 Project Information Screen of MLCA Software

Step 3: specify study boundaries for multi-lifecycle analysis of the understudy product. Select study boundaries from Study Scope menu or from project information screen that shows the study boundaries for multi-lifecycle analysis. Users mark multi-lifecycle stages for which they are responsible or select complete lifecycle stages of that product. It can also be distinguished easily by color change in the multi-lifecycle analysis modeling. The color of a selected stage becomes blue, while unselected ones are kept in gray color. The study boundaries for multi-lifecycle analysis are shown in Figure 4.14.
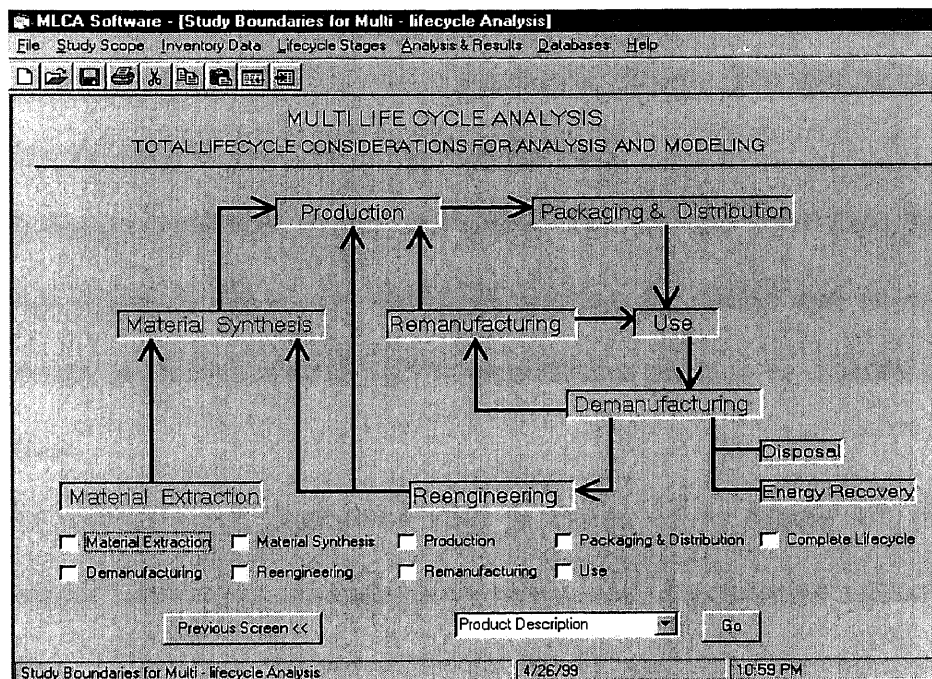
Figure 4.14 Study Boundary for Multi-lifecycle Analysis Screen

Step 4: Go to product description screen is the third step. The inventory table of a product

is entered from this screen. There are three cases during this input process, which

are distinguished by subassembly with part, final subassembly, parts, and circuit

board tabs in this screen. This screen is available in Figure 4.2.

From steps 2 to 4, the basic inventory information for a product is stored in databases of

MLCA software for later analysis. Further information on a product relates to multi-

lifecycle stages selected in step 2 is needed to input by users in the following steps:

Step 5: Percentage of certain contents is required to input in material processing stage

displayed in Figure 4.3: virgin content, industrial scrap recycled content, post

consumer recycled content, and reengineering content. The user is required to

input the material yield rate in this screen as well.

Step 6: Production processes of parts and process materials are input from Production

stage shown in Figure 4.4. Allocation schedule for energy and environmental

burdens to primary products and co-products also needs to be determined in this

screen.

Step 7: In packaging and distribution stage in Figure 4.5 to Figure 4.7, packaging

material information, packaging information, and transportation information are

input.

Step 8: Energy consumption and the percentage utilization factor per 24 hour in each use

mode, expected life span, and power sources used in the Use stage of a product

are required to input in the screen presented in Figure 4.8.

Step 9: End fate options for a product is required from users, and demanufacturing

facility information is supplied in the Demanufacturing stage in Figure 4.9.

Step 10: The energy consumption, environmental burdens, and cost of reengineering processes for recovering basic materials are considered in Reengineering stage displayed in Figure 4.10.

Step 11: Time required in each remanufacturing process is filled in the Remanufacturing stage shown in Figure 4.11, and facility information needed in this stage is required as well.

Step 12: click Analysis and Results Option in Analysis & Results Menu, double click the projects under study in the left hand side box, then, click OK button to access the analysis and results screen as shown in Figure 4.12, and select different options to review the results in graphics or tables.

CHAPTER 5

MLCA SOFTWARE DESIGN AND IMPLEMENTATION

5.1 Ideal Multi-Lifecycle Assessment Software

Life-cycle Assessment (LCA) is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases, to access the impact of those energy and material uses and releases on the environment, and to evaluate and implement opportunities to generate environmental improvements. Traditional LCA is a cradle-to-grave analysis whereas multi-lifecycle assessment emphasizes a cradle-to-cradle perspective. Consequently, a gap exists between the current status and future needs for modeling and assessing end-of-life demanufacturing, recovery and reengineering processes necessary for full multi-lifecycle consideration [Caudill 99]. An ideal MLCA software aims to [Caudill 99]:

- support the designers to implement the MLCA methodology ,

- develop generic screens that can be utilized by most consumer electronic producers, with particular focus on telephones, computers, monitors and televisions.

- have environmental information on products and processes readily accessible to designers, which simplifies the integration of DFE into a design process.

- help designer-makers to track the environmental performance of products by using performance metrics and other indices such as Eco-Compass.

5.2 Software Implementation

Multi-lifecycle assessment software is now under development to apply the MLCA methodology on electronic products and help designers obtain environmental performance of their products. The initial prototype version of a multi-lifecycle assessment software tool has been completed. It starts from product description screens, goes through seven multi-lifecycle stages, finally, ends with final analysis and reports. There are three key levels in the development of MLCA software:

The first one is the import of product information. The information of a product that consists of certain subassemblies and parts is needed to evaluate a product layout, in a general case, including:

- material type, weight, and quantity of each component in a product, and

- the tree structure of a product.

The second level is the multi-lifecycle screen development. Information specific to each multi-lifecycle stage of a product is input in these screens. There are seven screens related to each multi-lifecycle stage:

- Material Processing

- Production

- Packaging and distribution

- Use

- Demanufacturing

- Reengineering

- Remanufacturing

The third one is to use environmental impact evaluation algorithms to transfer the product information into assessment reports mainly on energy environmental burdens and energy consumption. This is also the goal of MLCA software, which aims to supply a MLCA methodology to a product, then generate analysis reports of a product to designers. With these reports, designers can get a clear view on environmental impacts of their products. The reports of the actual energy consumptions and environmental burdens consumed and generated during the lifecycles of their products may help designers make improvements to their product design. Thus the devised ones have less energy consumptions and environmental burdens, while keeping the same basic functions.

Other than screen implementations of MLCA software, data storage and retrieval to and from Microsoft Access 97 database is another key point to handle with much product information. SQL queries are the normal way to do it. To link SQL queries with Visual Basic, the process is usually done with statements that create Recordsets, which is an easy way to create an object that gives us access to all the data in our query. The codes in VB point to exactly schema objects, such as tables in Access 97, which we want to access. The MLCA software architecture is shown in Figure 5.1. The source code of MLCA software is represented at [MERC 99].
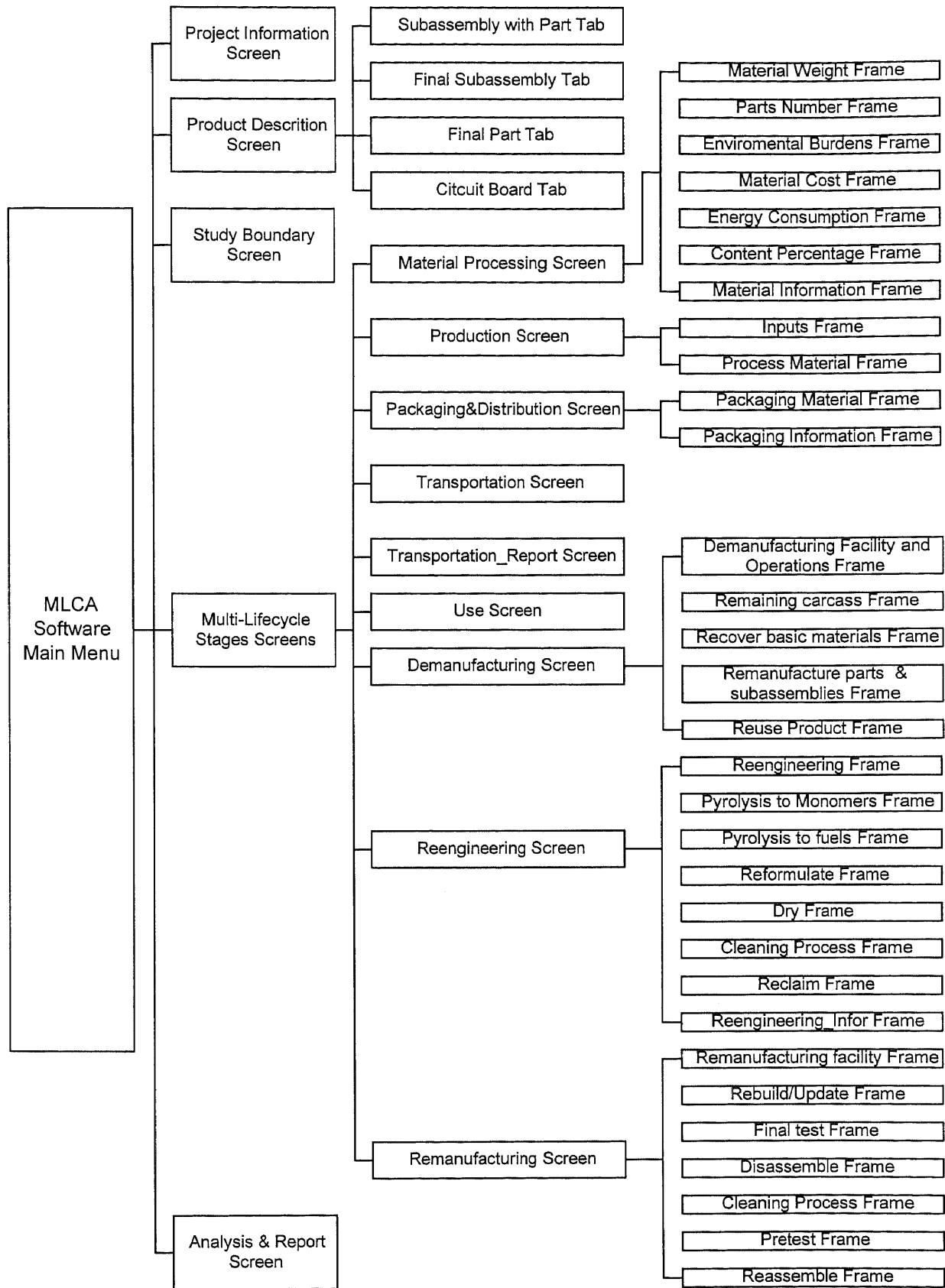
Figure 5.1 MLCA Software Architecture

5.2.1 MLCA Main Menu Screen

The main menu screen of MLCA software uses the following embedded VB objects and controls to supply the software with a multi-document interface(MDI), pull-down menu, toolbar, and coverage page:

- **MDIForm Object**

An MDI (multiple-document interface) form is a window that acts as the background of an application and is the container for forms that have their MDIChild property set to True. As the first step of MLCA software implementation, an MDIForm object named MLCA is created by choosing MDI Form from the Insert menu in Visual Basic. When any other form in the software is created, it acts as an MDIChild of the MLCA object.

- **Menu Control**

A Menu control displays a custom menu for the user application. A menu can include commands, submenus, and separator bars. Each menu the user creates can have up to four levels of submenus. To create a Menu control, select the Menu Editor option in Tool menu in Visual Basic and enter the name of the Menu control in the Caption box. To create a separator bar, enter a single hyphen (-) in the Caption box. Some of the custom pull-down menus are shown in Figure 5.2.

```
File Menu                    Lifecycle Stages                 Databases
     ├── New Project              ├──Material Processing           ├── Materials
     ├── Open Project             ├── Production                   │      ├── Standard
     ├── Edit Project             ├──Packaging & Distribution      │      └── User Defined
     ├── Delete Project           ├── Use                          │
     └── Exit                     ├── Demanufacturing              └── Processes
                                  ├── Reengineering                       ├── Standard
                                  └── Remanufacturing                     └── User Defined
```
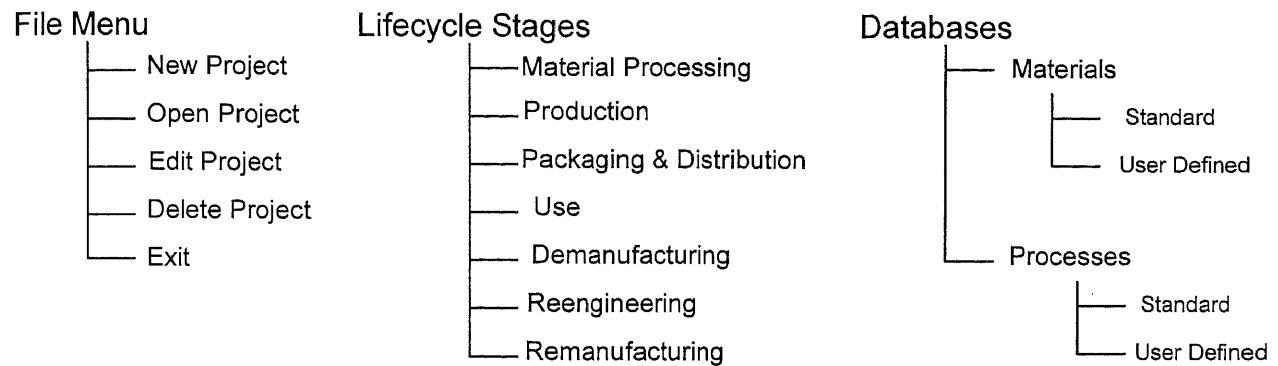
Figure 5.2 Part of Main Menu of MLCA Software

- **Toolbar Control**

A Toolbar control contains a collection of Button objects used to create a toolbar that is associated with an application. Typically, a toolbar contains buttons that correspond to items in an application's menu, providing a graphic interface for the user to access an application's most frequently used functions and commands. The Toolbar control allows creating toolbars by adding Button objects to a Buttons collection. Each Button object can have optional text or an image, or both, supplied by an associated ImageList control. An image can be displayed on a button with the Image property, or display text with the Caption property, or both, for each Button object.

To program the Toolbar, add code to the ButtonClick event to respond to the selected button. The Toolbar control is a part of a group of ActiveX controls that are found in the COMCTL32.OCX file [VB5.0]. To use the Toolbar control in an application, the COMCTL32.OCX file must be added to the project at first.

- **ImageList Control**

An ImageList control contains a collection of ListImage objects, each of which can be referred to by its index or key. The ImageList control supplies other controls such as Toolbar control with images to provide a graphic interface for the user.

Images of different sizes can be added to an ImageList control, but it constrains them all to be the same size. The size of the ListImage objects is determined by one of the following:

1. The setting of ImageWidth and ImageHeight properties before any images are added, and

2. The dimensions of the first image added.

- **Image Control**

Image control is used to display a graphic box. An Image control can display a graphic result from a bitmap, icon, or metafile, as well as enhanced metafile, JPEG, or GIF files.

5.2.2 Project Information Interface

Controls and objects used to create the project information interface are:

- **Label Control**

A Label control is a graphical control used to display text that a user can't change directly. To display text in a form, add a label control to the exact place, and fill in the text in Caption property in property window.

- **TextBox Control**

A TextBox control, sometimes called an edit field or edit control, displays information entered at design time, entered by the user, or assigned to the control in code at run time. The code example of assigning to a textbox control is:

```
Private Sub Form_Load()
        Me.Text1.Text = "Telephone 1989"
        Me.Text2.Text = "Black 89 Telephone"
End Sub
```

- **DBGrid Control**

DBGrid Control displays and enables data manipulation of a series of rows and columns representing records and fields from a Recordset object. Setting the DBGrid control's DataSource property to a Data control so that the control is automatically filled and its column headers are set automatically from a Data control's Recordset object.

- **Dynaset-Type Recordset Object**

A dynaset-type Recordset object is a dynamic set of records that can contain fields from one or more tables or queries in a database and may be updatable. A dynaset-type Recordset object is a type of Recordset object the user can use to manipulate data in an underlying database table or tables. The wonderful thing is that it stores only the primary key for each record, instead of actual data, which saves the workspace. As a result, a dynaset is updated with changes made to the source data. Like the table-type Recordset object, a dynaset retrieves the full record only when it's needed for editing or display purposes.

To create a dynaset-type Recordset object, use the OpenRecordset method on an open database. When the user requests a dynaset-type Recordset object, the Microsoft Jet database engine can gain read/write access to the records.

As users update data by using the AddNew and Update methods, the base tables reflect these changes. Therefore, current data is available to your application when you reposition the current record. In a multiuser database, more than one user can open a dynaset-type Recordset object referring to the same records. Because a dynaset-type Recordset object is dynamic, when one user changes a record, other users have immediate access to the changed data. However, if one user adds a record, other users won't see the new record until they use the Requery method on the Recordset object. If a user deletes a record, other users are notified when they try to access it. The user can use a WHERE clause to filter the records so that only certain records are added to the Recordset object.

- **Workspace Object**

A Workspace object defines a named session for a user. A Workspace is a non-persistent object that defines how an application interacts with data — either by using the Microsoft Jet database engine, or ODBCDirect. Use the Workspace object to manage the current session or to start an additional session. In a session, multiple databases or connections can be opened. Use the OpenDatabase method to open one or more existing databases on a Workspace.

- **Database Object**

A Database object represents an open database. The user uses the Database object and its methods and properties to manipulate an open database. In any type of database, The user can use the OpenRecordset method to execute a select query and create a Recordset object with a Microsoft Jet database (.mdb file).

- **Data Control**

Data control provides access to data stored in databases using any one of three types of Recordset objects. The Data control enables you to move from record to record and to display and manipulate data from the records in bound controls. Without a Data control or an equivalent data source control like the RemoteData control, data-aware (bound) controls on a form can not automatically access data.

- **CommandButton Control**

Use a CommandButton control to begin, interrupt, or end a process. When chosen, a CommandButton appears pushed in and so is sometimes called a push button. To display text on a CommandButton control, set its Caption property. A user can always choose a CommandButton by clicking it.

- **ComboBox Control**

A ComboBox is used to enter information in the text box portion or select an item from the list box portion of the control by dropping down a list. To add or delete items in a ComboBox control, use the AddItem or RemoveItem method.

The functions of project information screen are:

1. Save project information into Microsoft Access database table, and

2. Retrieve data from database, and display the result in table format.

Following is the code to implement the above two functions.

```
' variables declaration
Dim db As Database
Dim rs1 As Recordset
Dim rs2 As Recordset
Dim rs3 As Recordset
Public reco As Integer


' create a database object db and  RecordSet object rs1,rs2, rs3 to access database tables
' create a Data control Data1 to retrieve data in database
Private Sub Form_Load( )
        Set db = Workspaces(0).OpenDatabase(App.Path + "\lca.mdb")
        Set rs1 = db.OpenRecordset("select * from Project", dbOpenDynaset)
        Set rs2 = db.OpenRecordset("select Project_Name,Project_Description,User_name,Company,
        Address, City,State,Zip,Telephone,Fax,E_mail,Project_ID from Project order by Project_Name
        asc", dbOpenDynaset)

        Set Data1.Recordset = rs2
        If reco <> 0 Then
                Set rs3 = db.OpenRecordset("select * from Project where project_id = " & reco & "
                order by Project_Name asc", dbOpenDynaset)
                With rs3
                        Me.Text8.Text = .Fields(1).Value & ""
                        Me.Text9.Text = .Fields(2).Value & ""
                        Me.Text10.Text = .Fields(3).Value & ""
                End With
                rs3.Close

                Set rs2 = db.OpenRecordset("select   Project_Name, Project_Description, User_name,
                Company, Address, City, State, Zip, Telephone, Fax, E_mail, Date, Project_ID from
                Project order by Project_Name asc", dbOpenDynaset)
                Set Data1.Recordset = rs2
        End If
End Sub


' use AddNew method to save data into database table when click Add button in the screen
Private Sub Command1_Click( )
    If rs1.EOF = True Then
        GoTo finish1
    Else
        rs1.MoveFirst
        Do While Not rs1.EOF
                If Trim (Me.Text8.Text) = Trim (rs1.Fields (1).Value) Then
                        Dim msg As Integer
                        msg = MsgBox("The project name already existed, please use a new one as your
                        project name.", vbOKOnly + vbExclamation, "LCA Software")
                        GoTo finish
```

```
                End If
                    rs1.MoveNext
            Loop
        End If
finish1:
        With rs1
            .AddNew
            .Fields(1).Value = Me.Text8.Text & ""
            .Fields(2).Value = Me.Text9.Text & ""
            .Fields(3).Value = Me.Text10.Text & ""
            .Update
        End With
        Set rs2 = db.OpenRecordset("select Project_Name, Project_Description, User_name, Company,
                    Address, City, State, Zip, Telephone, Fax, E_mail, Date, ID from Project order by
                    Project_Name asc", dbOpenDynaset)
        Set Data1.Recordset = rs2
finish:
End Sub
```

5.2.3   Product Description Screen

This is a main screen in MLCA software. It is designed to input basic inventory

information of a product, and display the information by a product tree. Two advanced

controls and some methods are used here:

- **SSTab Control**

SSTab control provides a group of tabs, each of which acts as a container for other

controls. Only one tab is active at a time, displaying the controls it contains to the user

while hiding the controls in the other tabs. Using an SSTab control, the user can define

multiple pages for the same area of a window in an application. Using the TabCount,

TabPerRow, Tab Caption and Style properties of this control, the user can:

- Determine the number of tabs.

- Organize the tabs into more than one row.

- Set the text for each tab.

- Determine the style of tabs used.

At run time, users can navigate between tabs by either mouse clicking that Tab or by pressing CTRL+TAB. Four Tabs named *Subassembly with Part, Final Subassembly, Part,* and *Circuit Board* are used in the production description screen to define different components of a product.

- **TreeView Control**

A TreeView control displays a hierarchical list of Node objects, each of which acts as a parent or a child. After creating a TreeView control, the user can add and remove Node objects by setting properties and invoking methods. A Node object is an item in a TreeView control that can contain text, and Nodes collection contains one or more Node objects.

- **Right Function and Left Function**

Right function returns a Variant (String) containing a specified number of characters from the right side of a string. Left function returns a Variant (String) containing a specified number of characters from the left side of a string. An example is as following:

```
Dim AnyString, MyStr
AnyString = "Hello World"        ' Define string.
MyStr = Left (AnyString, 1)      ' Returns "H".
MyStr = Left (AnyString, 5)      ' Returns "Hello".
MyStr = Right (AnyString, 1)     ' Returns "d".
MyStr = Right (AnyString, 5)     ' Returns "World".
```

- **User-Defined Tree Function**

This function creates a dynamic product tree. It is designed to deal with the situation of updating three treeview controls in Subassembly with Part, Final Subassembly, or Part

tab at the same time. When the user input inventory information of a product component

in any tab, the treeview control in each tab is updated automatically. The function code

is:

```
Public Function Tree( ) As TreeView
        TreeView1.Nodes.Clear
        TreeView2.Nodes.Clear
        TreeView3.Nodes.Clear
        TreeView1.LineStyle = tvwRootLines
        TreeView2.LineStyle = tvwRootLines
        TreeView3.LineStyle = tvwRootLines

        Set rs31 = db.OpenRecordset("select * from Project where project_id = " & reco, dbOpenDynaset)
        Set tmp = TreeView1.Nodes.Add(, , "R0", rs31.Fields(1).Value)
        Set tmp1 = TreeView2.Nodes.Add(, , "R0", rs31.Fields(1).Value)
        Set tmp2 = TreeView3.Nodes.Add(, , "R0", rs31.Fields(1).Value)
          'rs11 for level1
          Set rs11 = db.OpenRecordset("select a.pfs_id, a.name, a.root_id, a.project_id from production a
          where a.project_id = " & reco, dbOpenDynaset) 'where a.root_id = 'R' and
          Do While Not rs11.EOF
                If Trim(rs11.Fields(2).Value) = Trim("R") Then
                        Set tmp = TreeView1.Nodes.Add("R0", tvwChild, "A" & rs11.Fields(0).Value,
                                rs11.Fields(1).Value)
                        Set tmp1 = TreeView2.Nodes.Add("R0", tvwChild, "A" & rs11.Fields(0).Value,
                                rs11.Fields(1).Value)
                        Set tmp2 = TreeView3.Nodes.Add("R0", tvwChild, "A" & rs11.Fields(0).Value,
                                rs11.Fields(1).Value)
                  'rs12 for finding level2 children
                  Set rs12 = db.OpenRecordset("select a.pfs_id, a.name from Production a, Relationship b
                        where b.child = a.pfs_id and b.root = " & rs11.Fields(0).Value, dbOpenDynaset)
                  Do While Not rs12.EOF
                        Set tmp  = TreeView1.Nodes.Add("A" & rs11.Fields(0).Value, tvwChild, "A" &
                                rs12.Fields(0).Value, rs12.Fields(1).Value & "")
                        Set tmp1 = TreeView2.Nodes.Add("A" & rs11.Fields(0).Value, tvwChild, "A" &
                                rs12.Fields(0).Value, rs12.Fields(1).Value & "")
                        Set tmp2 = TreeView3.Nodes.Add("A" & rs11.Fields(0).Value, tvwChild, "A" &
                                rs12.Fields(0).Value, rs12.Fields(1).Value & "")
                      'rs13 for finding level3 children
                      Set rs13 =  db.OpenRecordset("select a.pfs_id, a.name from production a,
                                Relationship b where b.child = a.pfs_id and b.root = " &
                                rs12.Fields(0).Value, dbOpenDynaset)
                      Do While Not rs13.EOF
                            Set tmp = TreeView1.Nodes.Add("A" & rs12.Fields(0).Value, tvwChild, "A"
                                    & rs13.Fields(0).Value, rs13.Fields(1).Value)
                            Set tmp1 = TreeView2.Nodes.Add("A" & rs12.Fields(0).Value, tvwChild, "A"
                                    & rs13.Fields(0).Value, rs13.Fields(1).Value)
                            Set tmp2 = TreeView3.Nodes.Add("A" & rs12.Fields(0).Value, tvwChild, "A"
                                    & rs13.Fields(0).Value, rs13.Fields(1).Value)
                          'rs14 for finding level4 children
                          Set rs14 = db.OpenRecordset("select a.id, a.name from production a,
                                    Relationship b where b.child = a.id and b.root = " &
```

```
                    rs13.Fields(0).Value, dbOpenDynaset)
            Do While Not rs14.EOF
                    Set tmp = TreeView1.Nodes.Add("A" & rs13.Fields(0).Value, tvwChild,
                        "A" & rs14.Fields(0).Value, rs14.Fields(1).Value)
                    Set tmp1 = TreeView2.Nodes.Add("A" & rs13.Fields(0).Value, tvwChild,
                        "A" & rs14.Fields(0).Value, rs14.Fields(1).Value)
                    Set tmp2 = TreeView3.Nodes.Add("A" & rs13.Fields(0).Value, tvwChild,
                        "A" & rs14.Fields(0).Value, rs14.Fields(1).Value)
                    rs14.MoveNext
        Loop
            rs14.Close
            rs13.MoveNext
    Loop
        rs13.Close
        rs12.MoveNext
    Loop
        rs12.Close
    End If
        rs11.MoveNext
    Loop
        rs11.Close
End Function
```

The flow chart of creating a product tree is shown in Figure 5.3, where rs31, rs11, rs12,

rs13, rs14 are the objects of recordsets which join project, production, and relationship

tables.
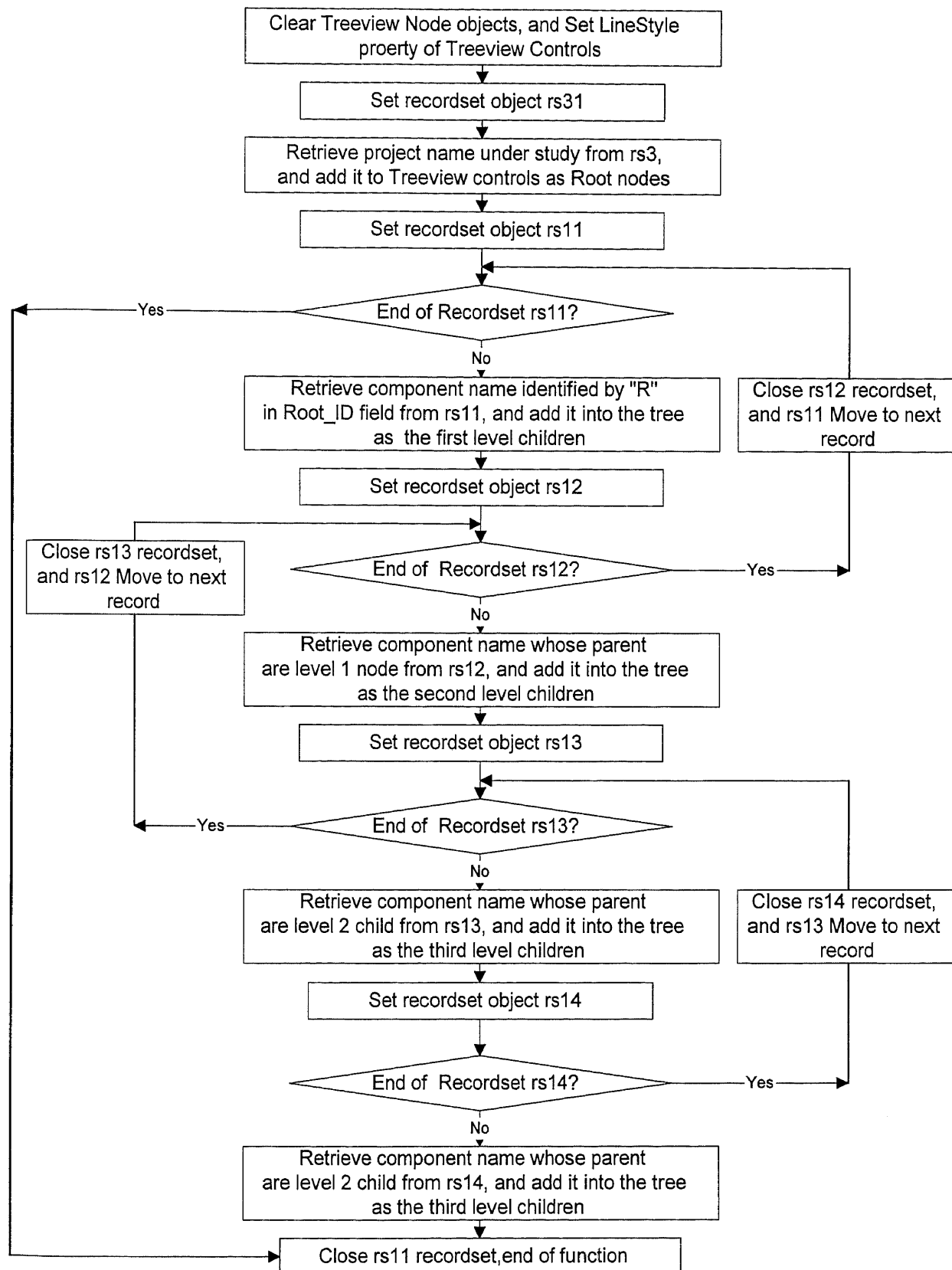
Figure 5.3 The Flow Chart to Create a Product Tree Structure

.4 Study Boundary Screen

ɘ controls used in this screen are Label, CommandButton, ComboBox, Line and

eckBox control.

CheckBox Control

CheckBox control displays an X when selected; the X disappears when the CheckBox

:leared. It can be used to display multiple choices from which the user can select one

more CheckBox at a time. The Value property of the control determines the state of

control: unselected, selected, or unavailable to be 0,1, 2.

Line Control

Line control is a graphical control displayed as a horizontal, vertical, or diagonal line.

.5 Multi-lifecycle Stages Screens

.5.1 Material Processing: Material information of a product is listed in this screen. A

ɘview control is placed to display a material inventory tree based on the inventory

ɔrmation input in previous product description screen. Whenever the inventory_tree

ɪction is called, the material inventory tree shown in Figure 4.3 pops up. All materials

ɪd in the product are added to the tree as parent nodes, and parts made out of that

terial are added into the tree as children nodes of each parent. The code for this

ɪction is:

```
vate Function inventory_tree() As TreeView
Create material inventory tree
)im nodX1 As Node
.ey = 0
'reeView1.LineStyle = tvwRootLines

If rs3.EOF = False Then
     Set  rs17  =  db.OpenRecordset("select  distinct  Material_Name  from  PFS_Material  where
ject_id="
```

```
                          & reco, dbOpenDynaset)
        rs17.MoveFirst
        Do While Not rs17.EOF
           key = key + 1
           Set nodX1 = TreeView1.Nodes.Add(, , "A" & key, Trim(rs17.Fields(0).Value))
           Set rs18 = db.OpenRecordset("select a.pfs_id, a.material_name,a.id,project_id from pfs_material
                      a where project_id = " & reco, dbOpenDynaset)
           rs18.MoveFirst
           Do While Not rs18.EOF
                If Trim(rs18.Fields(1).Value) = Trim(rs17.Fields(0).Value) Then
                    Set rs19 = db.OpenRecordset("select pfs_id,name from production where pfs_id= " &
                               rs18.Fields(0).Value, dbOpenDynaset)
                    Set nodX1 = TreeView1.Nodes.Add("A" & key, tvwChild, "B" & rs18.Fields(2).Value,
                               Trim(rs19.Fields(1).Value))
                End If
                rs18.MoveNext
           Loop
           rs18.Close
           rs17.MoveNext
        Loop
    End If
End Function
```

Several other functions are designed to get more detailed material information such as

total weight of a material in the product, total energy consumption of a material, and etc.

These functions complement different user-defined MSChart control. The embedded

MSChart control in VB and one example of the user-defined MSChart control are

introduced as follows:

- **MSChart Control**

A MSChart is a chart that graphically displays data. The MSChart control supports the

following features:

- True three-dimensional representation.

- Support for all major chart types.

- Data grid population via random data and data arrays.

- **User-Defined Material_weight Function**

This function is designed to calculate total weight of a material in a product, total weight

of a product, and the percentage of the material weight over the product weight.

```
Private Function material_weight() As MSChart
If sign_m = "A" Then
    rs3.MoveFirst
    Do While Not rs3.EOF
        If Trim(rs3.Fields(2).Value) = Trim(s) Then
            sum = sum + rs3.Fields(3).Value * rs3.Fields(4).Value
            num = num + 1
        End If
        rs3.MoveNext
    Loop

    MSChart1.row = 1
    rs3.MoveFirst
    MSChart1.Data = sum
    Me.Label59.Caption = Str(sum)

    Set rs7 = db.OpenRecordset("select sum(weight*quantity)from PFS_Material where
            project_id=" & reco, dbOpenDynaset)
    MSChart1.row = 2
    rs3.MoveFirst
    MSChart1.Data = rs7.Fields(0).Value
    Me.Label60.Caption = Format(rs7.Fields(0).Value, "fixed")
    Me.Label58.Caption = Format(sum / rs7.Fields(0).Value * 100, "fixed")
Else
    Frame12.Visible = False
    Dim msg1 As Integer
    msg1 = MsgBox ("Please select a material.", vbOKOnly + vbExclamation, "LCA
            Software")
End If
End Function
```

5.2.5.2 Production: Controls used in this stage are treeview, frame, DBGrid, ComboBox,

CommandButton, Check, and TextBox. The production tree is the same as that in the

product description screen. The input frame contains such production process

information as material name, quantity, weight, and production process of that material,

and other materials used in the production process. The process material list is shown in

Process materials frame in this screen.

.2.5.3 **Other Life-cycle Stages Screens:** The implementation of packaging & istribution, use, demanufacturing, reengineering, and remanufacturing life-cycle screens an be available by using the controls and functions introduced in the previous section in nis chapter.

.2.6 Analysis and Reports Screen

Analysis reports on a product are one of the key parts of MLCA software. The Mschart ontrol is used to graphical display results, and MsFlexGrid control is applied to show the able result of the analysis. The product information needed in analysis is obtained and stored in previous screens. The fomulations needed for the calculation are presented in Algorithm design section in Chapter 4.

▸ MsFlexGrid Control

MSFlexGrid control displays and operates on tabular data. It allows complete flexibility :o sort, merge, and format tables. The text is input in any cell of a MSFlexGrid. The Row and Col properties specify the current cell in a MSFlexGrid. The current cell can be specified in code, or the user can change it at run time using the mouse or the arrow keys. The Text property references the contents of the current cell.

If a cell's text is too long to be displayed in the cell, and the WordWrap property is set to True, the text wraps to the next line within the same cell. To display the wrapped text, you may need to increase the cell's column width (ColWidth property) or row height (RowHeight property). Use the Cols and Rows properties to determine the number of columns and rows in a MSFlexGrid control.

- **OptionButton Control**

An OptionButton control displays an option that can be turned on or off. Usually, OptionButton controls are used in an option group to display options from which the user selects only one. OptionButton controls can be grouped in a Frame by drawing the Frame first, and then draw the OptionButton controls inside. All OptionButton controls within the same container act as a single group.

- **User-Defined Analysis Report Functions**

The analysis report can be a report on energy consumption, air emission, or environmental burdens in one of the life-cyle stage. The functions are designed to deal with different life-cycle stage selection and different analysis point. Since they are almost in the same feature, one of the function code examples is shown as follows:

```
Private Function material_enviro_burden()
    Set rs3 = db.OpenRecordset("select * from Total_Air_Emission", dbOpenDynaset)
    With MSChart1
        .chartType = VtChChartType2dBar
        .TitleText = "Total Air Emissions from Material Production(Unit: g)"
        .ColumnCount = Compare_List.List2.ListCount
        .RowCount = List2.SelCount
            For row = 1 To List2.SelCount
                List2.ListIndex = row - 1
                If List2.Selected(row - 1) Then      'item is selected
                    .row = row
                    .RowLabel = List2.List(row - 1) 'add this item to column

                    Select Case row - 1
                    Case 0
                        For Column = 1 To Compare_List.List2.ListCount
                            .Column = Column
                            rs3.MoveFirst
                            Do While Not rs3.EOF
                                If Compare_List.List2.ItemData(Column - 1) = rs3.Fields(0).Value Then
                                    .ColumnLabel = Trim(rs3.Fields(1).Value)
                                    .Data = Format(rs3.Fields(2).Value, "fixed")
                                End If
                                rs3.MoveNext
                            Loop
                        Next Column
                    End Select
```

```
            End If
         Next row
         .ShowLegend = True
      End With
End Function
```

CHAPTER 6
CASE STUDIES ON TELEPHONE

6.1 Introduction

In this chapter, we select four generations of low-end business telephones used in Hussam's thesis [Hussam99] as MLCA software application examples. Phones designed and manufactured in 1965, 1978, 1989 and 1997 are available for study [Caudill & Hussam 99]. Based on the MLCA software, a MLCA inventory database can be generated by keeping the track of Steps 1 to 3 specified in Chapter 4.5. Initially, a new project is created with project information screen. Second, system boundary needs to be defined. Then, product information required in product description level of the MLCA software is entered. Finally, MLCA methodology is performed on four generation telephones by applying the analysis and report algorithms described in Chapter 4. As a result, evaluation on each generation telephone represents environmental performance of the business telephones. The prime objectives of carrying out the MLCA methodology are to provide decision-makers the actual data on environmental effects of a product and identify opportunities for environmental improvements of that product. 1989 telephone is used here as a specific example to show how to execute Multi-lifecycle assessment with MLCA software on a product in the following sections.

The inventory analysis generally includes energy consumption, waste emissions and process material requirements at each stage in the production of any raw material. In our 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, and use of the telephones will also be quantified. The energy

consumption during the demanufacturing, reengineering, and remanufacturing will not be quantified due to the unavailable resource data. The environmental burdens associated with the production, use, demanufacturing, reengineering, and remanufacturing 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.

6.2 Software Application

6.2.1 Start of a New Project

To perform a Multi-lifecycle assessment on 1989 telephone, we need information on the product stored in MLCA database at first. It can be obtained from users by the product description stage in the software. We start MLCA software by double clicking the MLCA icon in the Windows program manager. The program will start up and display a toolbar with all functions it has.

All work carried out in MLCA is stored as a *project* in the full software. Users can enter new projects of their own by selecting the *New Project* option in the **File** menu

at the top of the MLCA screen. The project information screen then appears. The project information already stored in the MLCA database is retrieved from the database automatically and showed in project information table in the screen. Users can input the information about 1989 telephone project in exact boxes such as "Telephone 1989" in Project Name box as shown in Figure 6.1. Users are not allowed to enter the same project name if it is already stored in MLCA database. To review other project information already in the database, move the mouse to that project and click once to pop up the information in the corresponding boxes automatically by the software. After users enter the available data, they should click "Add" button to save the new project information in the database. The new project added right now into the database appears in the project information table automatically. Figure 6.1 displays the detailed information.

Figure 6.1 Project Information Screen of Telephone 1989

6.2.2 Specifying Study Boundary

At the start of an MLCA, it is important to define the study boundary of the under study product. It brings a clear purpose and process to carry out the MLCA. Users can access the study boundary stage by selecting study boundary option in the bottom box of project information screen in Figure 6.1, then, click "Go" button besides the option box. According to the purpose of the study, users select different life-cycle stages by marking the exact checkbox or the complete lifecycle box to study all the life-cycle stages. The selected stage is highlighted into blue color. The complete lifecycle box is checked in the study of telephone 1989. Figure 6.2 shows the study boundaries for multi-lifecycle analysis of Telephone 1989.
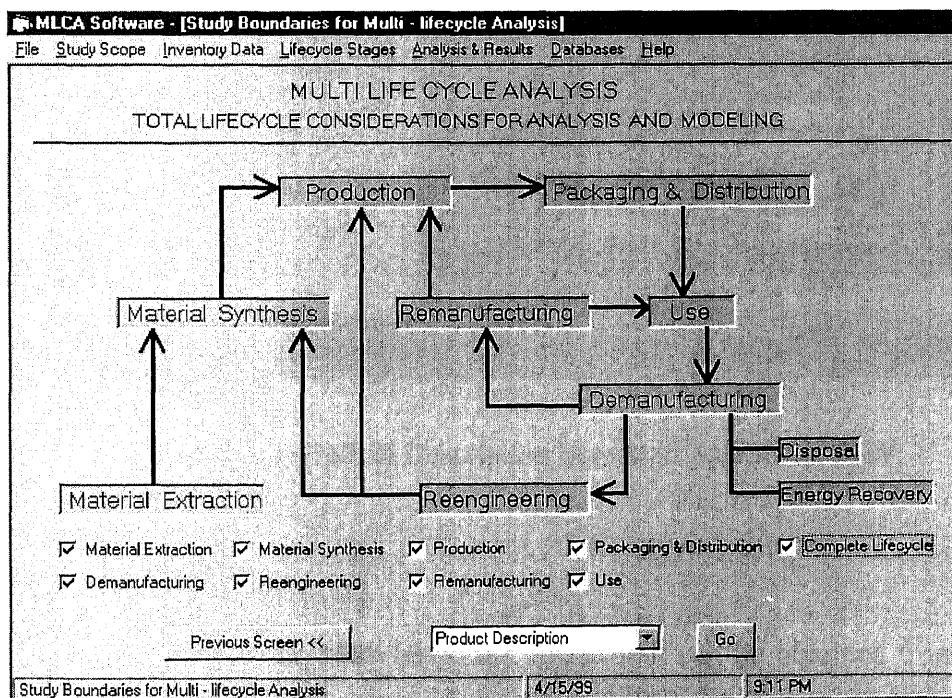
Figure 6.2 The Study Boundaries for Multi-Lifecycle Analysis Screen
of Telephone 1989

6.2.3 Product Description Stage

A detailed inventory table shown in Appendix A on page 109 provides a detailed list of all the parts in 1989 telephone product, quantifying for each part the quantity, function, weight, material type, and market value. Users can input all the information from the product description screen. After it has been done, the inventory table can be displayed directly with a tree structure as shown in Figure 6.3.

Figure 6.3 The Product Description Screen of Telephone 1989

6.2.4 Multi-Lifecycle Stages

Other information needed for 1989 telephone assessment can be obtained from each of seven multi-lifecycle stages screens.

6.2.4.1 Material Processing Stage: All the materials used in 1989 telephone are shown in material inventory tree in Figure 6.4. From that we know the material information of the telephone 1989 clearly. From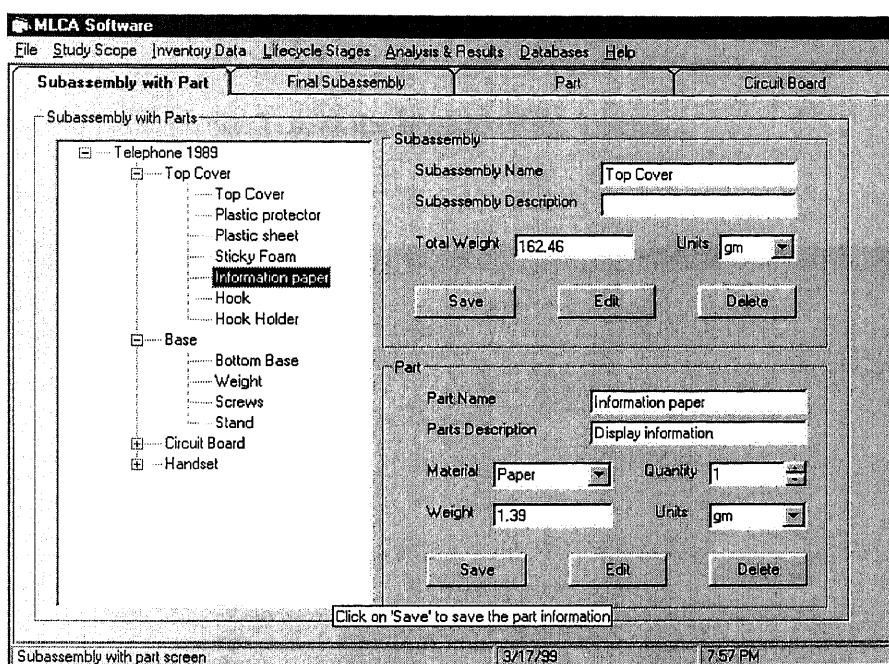 the material inventory tree on the left side of the screen, we see that there are totally five materials used in 1989 telephone: Aluminum, Circuit Board, Copper, paper, and plastics. Clicking on each material node, the tree is expanded to show all the parts using the same material. Detailed information such as total weight of selected material, number of parts made out of this material, total energy consumption and environmental burdens of the material can also be accessed by selecting related topics in material information box at the bottom of the screen.
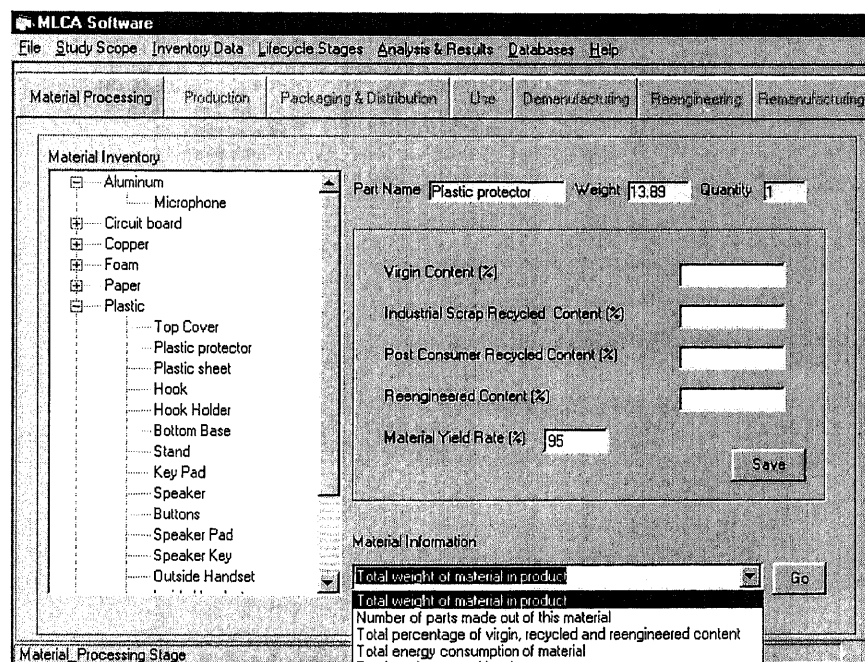
Figure 6.4 Material Processing Screen of Telephone 1989

6.2.4.2 Production Stage: Production process of each part is specified in this stage. The database quantifies mainly materials, energy and environmental burdens associated with those processes. Considering factors as yield rate, the way users allocate energy and environmental burdens to primary products and co-products, we are able to get the energy consumption and environmental emissions of 1989 telephone in production stage. This information is used to help evaluate the total lifecycle energy, materials and environmental burdens of the product. Production stage screen of 1989 telephone is shown in Figure 6.5.
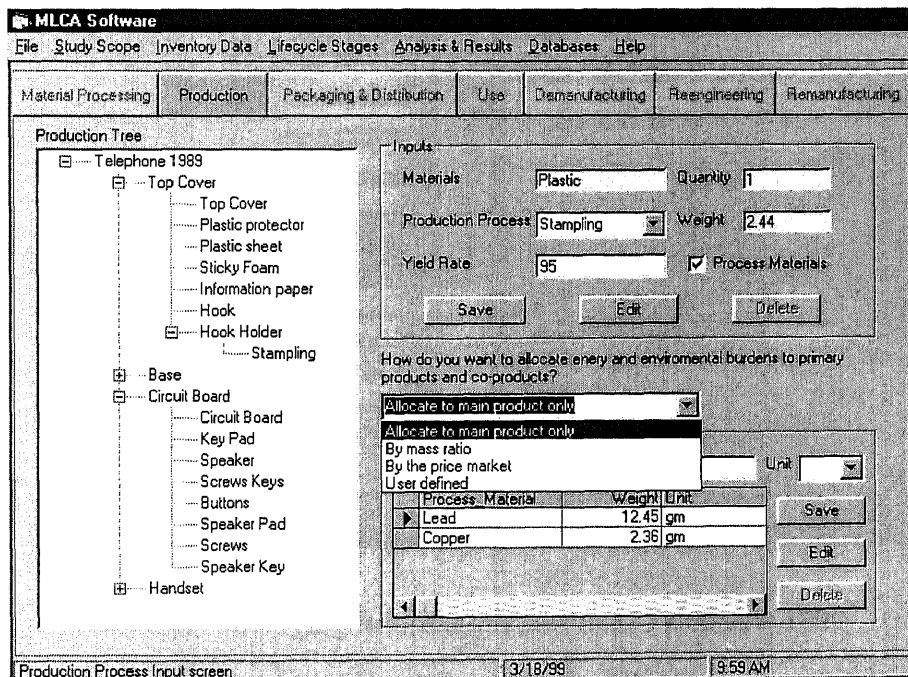
Figure 6.5 Production Stage Screen of Telephone 1989

6.2.4.3 Packaging and Distribution Stage

Energy consumption and environmental burdens in this stage come from packaging materials and transportation tools used for transporting the telephone 1989. For telephone packaging, usually, papers and plastics are used, meanwhile, we assume that the transportation tool is light duty truck. With assumed data filled in Figure 6.6 and Figure 6.7, we can get total energy consumption and environmental emissions shown in Figure 6.8.

Figure 6.6 Packaging Information Screen of Telephone 1989

Figure 6.7 Transportation Screen of Telephone 1989

Figure 6.8 Transportation Reports of Telephone 1989

6.2.4.4 Use Stage: According to the data entered in Use stage and the formula developed in Section 4.4, we can obtain lifetime energy consumption in this stage shown in Figure 6.9. For Telephone1989, it works in Active mode and Idle mode. The total energy consumption during the use stage can be achieved by the following assumption:

In active mode:

Energy Consumption = 0.059MJ

Utilization Factor = 3% per 24 hours (0.72 hours per day)

In idle mode:

Energy Consumption = 0.02376MJ

Utilization Factor = 97% per 24 hours (23.28 hours per day)

Excepted Life Span = 7.5 years

Total Energy Consumption during the use stage is:

0.059 * 0.03 * 24 *7.5 *365 + 0.02376 *0.97 *24 * 7.5 *365

=116.289 + 1514.20 = 1630.49 MJ

MLCA Software - [Project Information]

File Study Scope Inventory Data Lifecycle Stages Analysis & Results Databases Help

Material Processing | Production | Packaging & Distribution | Use | Demanufacturing | Reengineering | Remanufacturing

	Amount	Units		% Utilization Factor/24HR.
Active Mode	0.059	MJ		3
Idle Mode	0.02376	MJ		97
Power Save Mode	0	MJ		0
Off Mode	0	MJ		0

Expected Life Span (Years) 7.5   Power Source Electric

Calculate Use-Stage Energy Consumption

Lifetime Energy Consumption (MJ): 1630.49004

Next >>

Back<<

Use Stage Screen --- Power Consumption   4/20/99   12:45 PM

Figure 6.9 Energy Consumption generated from Use stage of Telephone 1989

6.2.4.5 Demanufacturing Stage: The main task in demanufacturing stage is to distribute four end fate options for telephone1989. Energy consumption and environmental burdens are from demanufacturing facility and operations to execute demanufacturing processes on telephone. The data of Telephone 1989 in this stage is not available yet.

6.2.4.6 Reengineering Stage: To reuse materials listed in recovered basic materials table from a demanufacturing process, Reengineering stage provides the complete process to recover basic materials. For instance, to recover aluminum of 1989 telephone, we need go through the reengineering screen to fill the data into each box, from which we can get the energy consumption and environmental burden information of Telephone 1989 by combining all the recoverable material information together. The data of Telephone 1989 in this stage is not available yet.

6.2.4.7 Remanufacturing Stage: Subassemblies and parts of a product that can be reused from Demanufacturing stage need to go through each remanufacturing process in this stage. Energy consumption and environmental burdens for each remanufacturing subassembly and part are required to obtain total environmental emission and energy consumption generated during this stage. The data of Telephone 1989 in this stage is not available yet.

6.2.5 Analysis and Report

The analysis reports are obtained by summarizing information in each life-cycle stage. One of the summarization reports on air emissions from material production of 1989 telephone is shown in Figure 6.10. We can follow the same way to get the assessment on other three generations of telephones. Then, we can compare the four generations of telephones and show the result in graphic forms that make the conclusions clear.
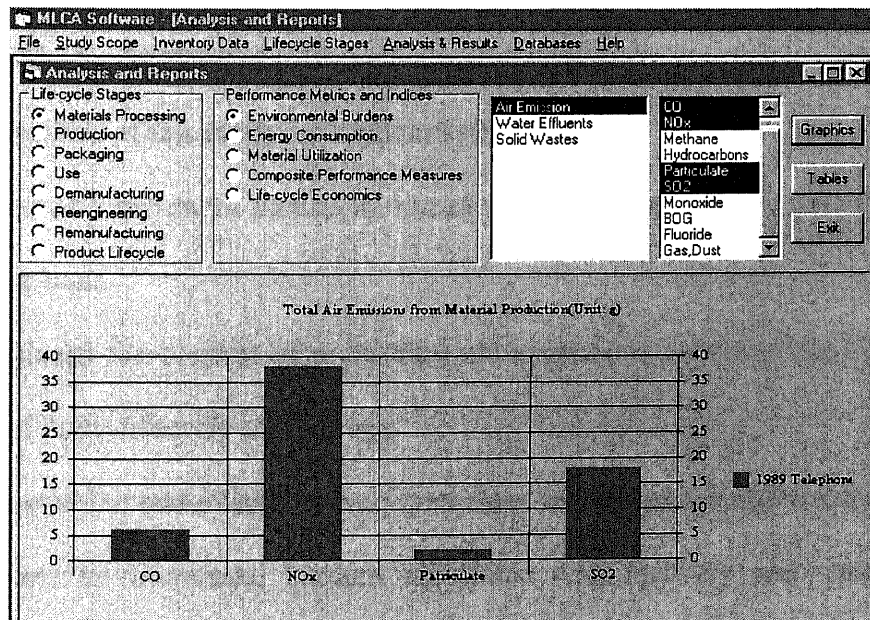
Figure 6.10 Total Air Emission from Material Production of Telephone 1989

CHAPTER 7

CONCLUSION

7.1 Contributions of this Thesis

Multi-lifecycle assessment (MLCA) is a new methodology that extends the traditional lifecycle stage assessment to multi-lifecycle stage assessment. It is an objective process to evaluate environmental burdens associated with a product. MLCA emphasizes 1) quantifying materials, energy and environmental burdens associated with end-of-life options and 2) obtaining value of return 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. This thesis discusses the concept of Multi-lifecycles and the methodology for evaluating the energy consumption and environmental emissions of a product. The idea and results of this thesis supply product designers an MLCA-based computer tool to improve their product design, reduce the energy and material uses and environmental releases of their products. Also, they are useful for further multi-lifecycle research work.

The contributions of this thesis are summarized as follows:

1. It presented a review of traditional life-cycle assessment concept, methodology, and software tools.

2. It introduced the concept of multi-lifecycle assessment by extending LCA's to the realm of multi-lifecycle engineering.

3. It discussed the end-of-life recovery processes to account for material flows, energy usage and environmental burdens associated with recovery and reprocessing of components and basic materials.

4. It formulated and integrated the environmental emissions and energy consumption for each life cycle of a product.

5. It specified the detailed designs on MLCA software including the database, user interface, and algorithm designs.

6. It completed the initial prototype version of the multi-lifecycle assessment software tools with three main levels: Product Description, Lifecycle stages, and Analysis and Results.

7. It applied the MLCA software tool to MLCA of Telephones.

7.2 Limitations and Future Research

Multi-lifecycle assessment is more than a systematic approach in analyzing a product which focuses on the multiple lifecycles those 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 a product is one of the prime goals of multi-lifecycle engineering. Prototype of each life-cycle stages is completed, but the MLCA software needs further developments.

Data collection is a main issue for the software. To perform the multi-lifecycle methodology on a product and get an accurate result through the analysis, we require data and information on energy consumption, materials usage, and environmental emissions of each process in the entire product life cycle. We have had some raw material data and process information:

- The inventory tables of CRT, TV, PC computer, and four generation telephones.

- The energy consumption and environmental burdens generated from the production of such feedstock materials as plastics, metals, glass, and lead,

- Disassembly data on shredding operation, and

- Remanufacturing polymers.

The resources of the information are from different sites, including the public free data on the web, the technical books and publications. The help from companies is another main path. The problems of data item uncertainty and data distribution should be considered. One solution is to associate a data item with such values as its mean, deviation, and certainty. The data still under search includes:

- Process data such as clean process in reengineering and remanufacturing stages,

- Energy requirement in processes, and

- Demanufacturing data.

The software now is a stand-alone PC Window 95 based on Microsoft Access 97 database. Further work is needed to convert the software into a multi-user version with Oracle 8.0 database. Efforts should be concentrated on connecting the product description stage to a Computer Aided Design (CAD) tool, so that the product description can be retrieved from a CAD file, instead of from users' manual inputs. More work is also required to enable the software to perform sensitivity analysis over a range of varying parameters.

APPENDIX A

INVENTORY TABLE FOR THE TELEPHONE 1989

Subassembly	Part	Quantity	Function	Weight (g)	Material
Handset					
	cord	1	transmit signal	40.28	plastic / copper
	speaker gasket	1	block debris	5.07	rubber
	outside handle	1	house spkr/Mic..	53.54	ABS
	inside handle	1	house spkr/Mic..	56.64	ABS
	wiring	1	transmit signal	2.86	plastic/ copper
	foam	1	sound enhancer	0.12	foam
	speaker	1	transmit voice	35.31	steel/plastic
	Mic Cover	1	Protects Mic	0.71	rubber
	microphone	1	transmit voice	0.85	aluminum
Top Cover					
	cover	1	house internal parts	187.96	ABS
	number keys	1	function buttons	17.22	plastic
	function keys	1	function buttons	10.12	plastic
	3 buttons	1	function buttons	2.95	plastic
	hook	1	turn phone "on"	4.85	plastic
	hook spring	1	tension for hook	0.41	steel
	plastic cover	1	cover information	9.7	plastic
	paper	1	display information	0.6	paper
	clear indicators	4	indicate extensions	1	plastic
Base					
	stand	1	support phone/ upright display	145.61	ABS
	rubber legs	4	support phone	1.12	rubber
	bottom base	1	house internal parts	263.65	ABS
Circuit Board					
	circuit board	1	electronic functions	110.83	circuit board
	speaker	1	transmits voice	110.79	steel/plastic
	speaker gasket	1	block debris	2.05	rubber
	speaker foam	1	cushion speaker	1.29	plastic (foam)
	keypad	1	makes contact with circuit board	19.55	rubber

APPENDIX B

ENVIRONMENTAL BURDENS GENERATED FROM FEEDBACK MATERIALS

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.

Table B.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	0.0490258	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	0.0025307	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	0.0025036	0.0037567
	COD	0.0133064	0.0077513	0.0099549
	Suspended Solids	0.0051366	0.003381	0.0043361
	Oil	0.00163613	0.001012	0.0010891
	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 B.2 Environmental Burdens Generated from Production of Metals
[Badwe 97]

Air Emissions		Steel	Aluminum	Copper
		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 B.3 Environmental Burdens Generated from Power Sources Used
during Production of Feedstock Material

	ABS	Steel	Aluminum	Copper
Air Emissions	(Lb/ 1000 Lb)	g/1 Kg	g/1 Kg	g/1 Kg
CO2	18004.92	782.32078	91276.719	16819.582
CO	6.26	0.2719595	31.730684	5.8470205
NOx	53.11	2.4270204	263.5998	49.800011
Methane	48.32	2.099542	244.96257	45.139308
Hydrocarbons	4.592108268	0.4741105	10.25751	4.7137627
Particulate	0.030923288	0.0031927	0.0690741	0.0317425
SO2	0.069577398	0.0071835	0.1554168	0.0714206
Monoxide	0.726697268	0.0750276	1.6232423	0.745949
Solid Wastes	2908.67	126.38294	14745.639	2717.1823
Waterborne Effluents				
Dissolved Solids	1.70078084	0.1755965	3.7990777	1.7458381
Acids	0.286040414	0.0295321	0.6389358	0.2936182
Metal Ion	0.085039042	0.0087798	0.1899539	0.0872919

REFERENCES

[Thomas 95] T. S. Thomas, *Industrial Pollution Prevention* by Springer, New York, 1995.

[Nissen 97] N.F.Nissen, et al. "*Environmental Assessments of Electronics: A New Model to Bridge the Gap Between Full Life Cycle Evaluations and Product Design*", Proceedings of the 1997 IEEE International symposium on Electronics and the Environment, May 1997, p182.

[Allred 97] R.E.Allred, L.D.Busselle "*Economical Tertiary Recycling Process for Mixtures of Electronic Scrap*", Proceedings of the 1997 IEEE International symposium on Electronics and the Environment, May 1997, p115.

[Marion 98] M.A. Hersh "*A survey of Systems Approaches to Green Design with Illustrations from the Computer Industry*", IEEE Transactions on systems, Man, and Cybernetics, Vol. 28, No.4, November 1998.

[Caudill 97] R.Caudill, et al. "*A Final Proposal to the National Science Foundation Engineering Research Centers Program*", Multi-Lifecycle Engineering Research Center, New Jersey Institute of Technology, Newark, NJ, September 1997.

[Brinkley 97] A. Brinkley, T. Mann, "*Documenting Product Environmental Attributes*", Proceedings of the 1997 IEEE International symposium on Electronics and the Environment, May 1997, p52.

[Mary 96] M. A. Curran, "*Environmental Lifecycle Assessment*" McGraw-Hill, New York, 1996.

[SETAC 91] *A Technical Framework for Life-cycle Assessments*, by SETAC Foundation, Pensacola, January 1991.

[Graedel 95] T.E. Graedal, B.R. Allenby "*Industrial Ecology*" by AT&T, 1995.

[Guinee 93] J. Guinee and R. Heijungs "*Software as a Bridge between Theory and Practice in Lifecycle Assessments*", Journal of Cleaner Production, 1(3-4): 185 (1993).

[ECO-it] "*ECO-it :Eco-Indicator Tool for environmentally friendly design* " by PRé Consultants BV, April 1999, http://www.pre.nl/eco-it.html

[GaBi] "*GaBi - the Software System for Life Cycle Engineering*" by IKP University of Stuttgart in cooperation with PE Product Engineering, October 1997, http://www.pe-product.de/

[TEAM] "*Ecobilan Group's Life-Cycle Assessment: TEAM*™" by Ecobalance, Inc., July 1998, http://www.ecobilan.com/

[SimaPro] "*SimaPro 4.0 - the Life Cycle Assessment Tool*" January 1999, http://www.pre.nl/simapro.html

[EPA 93] B.W.Vigon, et al., *"Life-Cycle Assessment: Inventory Guidelines and Principles"*, by Risk Reduction Engineering Laboratory Office of Research and Development U.S. Environmental Protection Agency, February 1993.

[Caudill 99] "*A Annual Report: Year Two on Multi-Lifecycle Engineering and Manufacturing Program*", by R. Caudill, et al. Multi-Lifecycle Engineering Research Center, New Jersey Institute of Technology, Newark, NJ, February 1999.

[Hussam 99] H.F. Al-Okush, *"Assessment the Impact of Design for Environment Guidelines: A Case Study of Office Telephones"*, Masters Thesis for Multi-Lifecycle Engineering Research Center, Mechanical Eng. Dept, New Jersey Institute of Technology, Newark, NJ, May 1999.

[Ketan 99] Limaye, K., "*System Simulation and Modeling of Electronics Demanufacturing Facilities*" Masters Thesis for Multi-Lifecycle Engineering Research Center, Mechanical Eng. Dept, New Jersey Institute of Technology, Newark, NJ, December 1998.

[VB5.0] "*Visual Basic 5.0 Enterprise Edition Disk*" by Microsoft.

[Caudill & Hussam 99] R.J. Caudill, H.F. Al-Okush, and V. Thomas, " *Understanding the Real Impact of DFE Guidelines: A Case Study of Four Generations of Telephones*", Proceedings of the 1999 IEEE International symposium on Electronics and the Environment, May 1999.

[Badwe 97] Badwe, D., "*Multi-Lifecycle Assessment of Cathode Ray Tubes*" Masters Thesis for Multi-Lifecycle Engineering Research Center, Industrial & Manufacturing Eng. Dept, New Jersey Institute of Technology, Newark, NJ, 1997.

[Zhou 96] Zhou, M.C., B. Zhang, R.J.Caudill, and D.Sebastian, "*A cost model for multi-lifecycle engineering design*," Proceedings of the 1996 IEEE International symposium on Emerging Technologies and Factory Automation, Hawaii, November 1996, p385-391.

[MERC 99] "Multi-*Lifecycle Assessment Software*", Multi-Lifecycle Research Center of New Jersey Institute of Technology, Newark, NJ, May 1999, http://www.njit.edu/merc/