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## Integration of e-business strategy for multi-lifecycle production systems

Yanchun Luo  
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## **ABSTRACT**

### **INTEGRATION OF E-BUSINESS STRATEGY FOR MULTI-LIFECYCLE PRODUCTION SYSTEMS**

**by  
Yanchun Luo**

Internet use has grown exponentially on the last few years becoming a global communication and business resource. Internet-based business, or e-Business will truly affect every sector of the economy in ways that today we can only imagine. The manufacturing sector will be at the forefront of this change. This doctoral dissertation provides a scientific framework and a set of novel decision support tools for evaluating, modeling, and optimizing the overall performance of e-Business integrated multi-lifecycle production systems. The characteristics of this framework include environmental lifecycle study, environmental performance metrics, hyper-network model of integrated e-supply chain networks, fuzzy multi-objective optimization method, discrete-event simulation approach, and scalable enterprise environmental management system design. The dissertation research reveals that integration of e-Business strategy into production systems can alter current industry practices along a pathway towards sustainability, enhancing resource productivity, improving cost efficiencies and reducing lifecycle environmental impacts.

The following research challenges and scholarly accomplishments have been addressed in this dissertation:

- *Identification and analysis of environmental impacts of e-Business.* A pioneering environmental lifecycle study on the impact of e-Business is conducted, and fuzzy



decision theory is further applied to evaluate e-Business scenarios in order to overcome data uncertainty and information gaps;

- *Understanding, evaluation, and development of environmental performance metrics.* Major environmental performance metrics are compared and evaluated. A universal target-based performance metric, developed jointly with a team of industry and university researchers, is evaluated, implemented, and utilized in the methodology framework;
- *Generic framework of integrated e-supply chain network.* The framework is based on the most recent research on large complex supply chain network model, but extended to integrate demanufacturers, recyclers, and resellers as supply chain partners. Moreover, The e-Business information network is modeled as a overlaid hyper-network layer for the supply chain;
- *Fuzzy multi-objective optimization theory and discrete-event simulation methods.* The solution methods deal with overall system parameter trade-offs, partner selections, and sustainable decision-making;
- *Architecture design for scalable enterprise environmental management system.* This novel system is designed and deployed using knowledge-based ontology theory, and XML techniques within an agent-based structure. The implementation model and system prototype are also provided.

The new methodology and framework have the potential of being widely used in system analysis, design and implementation of e-Business-enabled engineering systems.

**INTEGRATION OF E-BUSINESS STRATEGY  
FOR MULTI-LIFECYCLE PRODUCTION SYSTEMS**

**by  
Yanchun Luo**

**A Dissertation  
Submitted to the Faculty of  
New Jersey Institute of Technology  
in Partial Fulfillment of the Requirements for the Degree of  
Doctor of Philosophy in Mechanical Engineering**

**Department of Mechanical Engineering**

**August 2001**

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**This doctoral dissertation is dedicated  
to my beloved family**

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## TABLE OF CONTENTS

Chapter	Page
1 INTRODUCTION.....	1
1.1 Background.....	1
1.2 Objective and Significance .....	3
1.3 Dissertation Organization .....	6
2 LITERATURE REVIEW.....	9
2.1 Environment Impact of E-Business .....	10
2.2 Supply Chain Management and Engineering .....	14
2.2.1 Research Overview .....	14
2.2.2 Quantitative Models.....	16
2.2.3 Internet and E-Business in Supply Chain .....	21
2.3 Sustainable Development Methodology.....	23
2.4 Information Science and Technology in Mechanical and System Engineering	28
2.4.1 Engineering Information Management and Integration.....	29
2.4.2 Collaborative Product Commerce.....	33
2.5 System Analysis and Decision-making .....	38
3 RESEARCH ISSUES AND APPROACHES .....	43
3.1 Initial Lifecycle Environmental Study of the Impact of E-Business.....	43
3.2 Research Issues and Approaches .....	52
3.3 Research and Development Tasks .....	55
4 ENVIRONMENTAL PERFORMANCE METRICS .....	57

## TABLE OF CONTENTS (Continued)

Chapter	Page
4.1 Application of Eco-indicator Method in Evaluating Environmental Performance of Manufacturing Processes.....	58
4.1.1 Eco-indicator Lifecycle Model for Solid Freeform Manufacturing .....	58
4.1.2 Eco-indicator 95 Assessment of SLA Process and Tooling Process .....	62
4.2 A Universal Environmental Metric Using Target-based Methodology.....	69
4.2.1 Lucent Sustainability Target Metric Methodology.....	70
4.2.3 Carrying Capacity Estimates for Electrical Energy Consumption .....	75
4.3 Comparison and Discussion of Major Environmental Performance Metrics ....	79
4.3.1 Comparison of Four Major Environmental Performance Metrics.....	80
4.3.2 Case Studies.....	87
4.4 Summary.....	92
5 SUSTAINABLE E-SUPPLY CHAIN MODEL .....	94
5.1 Fuzzy Logic-based Approach on Exploring Environmental Impacts of E-Business.....	94
5.2 Hyper-network Modeling of Integrated E-Supply Chain System.....	101
5.2.1 Generic Framework of IESC .....	101
5.2.2 Basic Concept of IESC .....	104
5.2.3 Application Procedure of IESC Methodology.....	106
5.3 Fuzzy Multi-objective Optimization of IESC Model .....	107
5.3.1 Fuzzy Multi-Objective Optimization.....	107
5.3.2 Example .....	110

## TABLE OF CONTENTS (Continued)

Chapter	Page
5.4 Discrete-event Simulation of IESC Model .....	114
5.4.1 Discrete-event Simulation.....	114
5.4.2 IESC Simulation Model.....	117
5.5 Case Study and Discussion .....	120
5.5.1 Supply Chain Network Optimization.....	122
5.5.2 System Simulation .....	125
5.5.3 Discussion.....	128
5.6 Summary .....	129
6 SCALABLE ENTERPRISE ENVIRONMENTAL MANAGEMENT SYSTEM ...	131
6.1 Rationale and Motivation.....	132
6.2 Research Challenges .....	137
6.2.1 Enterprise Application Integration Model .....	138
6.2.2 Agent-based Design.....	142
6.2.3 Ontology-based XML Method for Knowledge Representation and Integration.....	144
6.3 Knowledge Management in SEEMS .....	147
6.3.1 Knowledge Modeling of the Lucent Sustainability Target Metric .....	147
6.3.2 Knowledge Extraction from Enterprise Business Applications.....	154
6.4 SEEMS Design and Implementation .....	156
6.4.1 SEEMS Architecture.....	156
6.4.2 Integration of IESC Model.....	158

## TABLE OF CONTENTS (Continued)

Chapter	Page
6.4.3 Implementation Model of SEEMS.....	160
6.5 Summary.....	162
7 CONCLUSIONS AND FUTURE WORK.....	164
7.1 Major Contributions.....	164
7.2 Future Direction.....	165
APPENDIX A DATA SHEET FOR NETWORK LINKS IN 5.3.2 .....	166
APPENDIX B MATERIAL AND ENERGY INVENTORY DATA FOR CASE STUDY .....	167
REFERENCES .....	168

## LIST OF TABLES

Table	Page
2.1 E-Business Application in Supply Chain Management.....	22
3.1 Material/Energy Inventory of Desktop Computer, Monitor, Keyboard & Mouse	50
3.2 Energy Saving due to E-Business over Product Lifecycle .....	51
4.1 Environmental Impact Due to Energy Use of SLA Process .....	64
4.2 Environmental Impact of SLA Process.....	65
4.3 Environmental Performance of RT Process.....	68
4.4 Lucent Sustainability Target Metric – Aspects and Impacts .....	76
4.5 Lucent Metric Assessment for Two laptop Computers .....	89
5.1 Lifecycle Cost Analysis .....	97
5.2 Lucent Sustainability Metric EI for Lifecycle Energy.....	98
5.3 Lucent Sustainability Metric EI for CO <sub>2</sub> Emission.....	98
5.4 Lucent Sustainability Metric EI Value for Energy Use and CO <sub>2</sub> Emission with Costs.....	99
5.5 Relationships Between Fuzzy Assessment Criteria and Grades.....	100
5.6 Fuzzy Decision-making Results .....	100
5.7 The Payoff Table.....	109
5.8 Optimization Result for the Simple Example .....	112
5.9 Optimization Result .....	123
5.10 Time for Components and Processes .....	125
6.1 Typical Lifecycle Inventory Data .....	155

## LIST OF FIGURES

Figure	Page
2.1 Projection of Future Growth of Business-to-business and Business-to-consumer Commerce in the US .....	10
2.2 Integrated Supply Chain Model .....	15
2.3 Supply Network Topology .....	17
2.4 A Common Ontology Reduces the Number of Translators .....	33
2.5 PTC Windchill Arcitecture .....	35
2.6 The Windchill Collaborative Design Environment .....	37
2.7 Membership Function and Possibility Function .....	39
2.8 MODM Solutions in the Objective Function Space .....	40
2.9 An Optimal Solution of a Maximum Problem .....	41
3.1 Illustration of Impacts of E-Business on Product Lifecycle Stages .....	46
3.2 Energy Savings over Lifecycle .....	52
3.3 CO2 Equivalent Emission Savings .....	52
4.1 Lifecycle Model of SFM Process .....	60
4.2 Lifecycle Environmental Performance Model of Indirect RT Process .....	61
4.3 Indirect Tooling Process .....	66
4.4 Linking Value Generation and Environmental Impact As a Target For Sustainability .....	74
4.5 Eco-indicator 95 Methodology .....	80
4.6 Eco-indicator 99 Methodology .....	81
4.7 Ecological Footprint Methodology .....	83
4.8 Results from Metrics Application Comparison .....	92

## LIST OF FIGURES (Continued)

Figure	Page
5.1 Membership Functions of Fuzzy Variables .....	95
5.2 A Product's Generic Supply Chain System .....	102
5.3 Stage Partner, Bill of Material (BOM) and Stock Keeping Unit (SKU) of a Supply Chain Stage .....	102
5.4 Integrated E-Supply Chain Network.....	104
5.5 A Product's Supply Chain Network .....	105
5.6 A Simple Example of IESC Model.....	111
5.7 Optimization Result for the Simple Example .....	113
5.8 Simulation Module for Manufacturer .....	119
5.9 A Picture of Simulation Model.....	119
5.10 Integrated Supply Chain Model for Desktop Computer .....	120
5.11 Case Study – A Desktop Computer IESC Network.....	121
5.12 Base case and Optimized E-Business Network .....	122
5.13 Network Optimization Result .....	124
5.14 Supply Chain Inventory Level .....	126
5.15 Suppliers Inventory Level.....	127
5.16 Energy Saving of Optimal Cases .....	127
5.17 Sensitivity of Batch Size to Inventory Level .....	128
6.1 Virtual Enterprise Integration Model.....	139
6.2 Agent-based Design of SEEMS.....	143
6.3 Target Metric Evaluation Ontology .....	149

**LIST OF FIGURES**  
**(Continued)**

<b>Figure</b>	<b>Page</b>
6.4 Target Metric Carrying Capacity Ontology .....	150
6.5 XML Schema for the Target Metric .....	152
6.6 An XML File for a Product Assessment.....	153
6.7 ERP Environmental Management Ontology .....	155
6.8 SEEMS Architecture Design .....	157
6.9 A Supply Chain Decision-Making Module in SEEMS System.....	159
6.10 SEEMS Implementation Model.....	160
6.11 SEEMS Web Portal (1).....	161
6.12 SEEMS Web Portal (2).....	161



# CHAPTER 1

## INTRODUCTION

### 1.1 Background

Internet use and e-Business have grown exponentially becoming a global communication and business resource. Society has broadly embraced the Internet technology and yet there is a failure to recognize that they may have unanticipated and unintended consequences for the environment, both positive and negative.

E-Business is business activities occurring over the Internet that uses non-proprietary protocols connecting a mixture of information and communication technologies [Wyckoff and Colecchia, 1999]. E-Business includes *business-to-business* (B2B) and *business-to-consumer* (B2C) practices. B2B practice uses the Internet to integrate and manage the supply chain, extending from the supplier of raw materials and components to the final consumer. Whereas, B2C commerce focuses on individual household purchases of products via Internet-based electronic storefronts or web sites. E-Business is truly affecting every sector of the economy. Certainly, the production sector—its products, business strategies and technologies — will be at the forefront of this change.

The Internet and e-Business extend the benefits of conventional proprietary electronic data interchange (EDI) systems to all levels of the value-added supply chain leading to potential reduction in procurement cycles and cost, mistaken orders and paper-based transactions, as well as shortened product development times and reduced inventories. E-Business also provides a direct link between the final consumer and the

product manufacturer or distributor. Consequently, built-to-order and mass customization for individual consumers via the Internet have been the cornerstone of the new business strategy exploited by Dell and Cisco [Cohen, 1999, Margherio et al, 1998]. With electronic linkage in the supply chains, it is possible to pass the information of buyer preferences and demands on to corporate partners and coordinate material and component procurement, a practice commonly referred to as collaborative planning forecasting and replenishment. According to studies by Ernst & Young [Romm, 1999] and the US automobile industry [Wyckoff A. and Colecchia, 1999], the potential exists for reducing overall inventories by 20 to 25 percent, with concomitant reduction in energy usage, through B2B commerce. E-Business is changing the means and rates of transportation and customer behaviors, thus, sophisticated structures and methodologies evaluating the environmental implications of these changes are needed and have to be recognized in the environmental community [Allenby, 1999]. In addition, with closer supply chain integration, the opportunity exists to exchange environmental information between businesses in response to increasing customer requests for product environmental data [Rejeski, 1999].

E-Business is still in its infancy and its impact on the environment is uncertain and difficult to quantify with any degree of rigor or level of confidence — the data is incomplete and the vision is still evolving. Little reliable data exists, sophisticated language and tools are hard to find to articulate the environmental implication of e-Business from any perspective. Currently, any attempt to describe the implications of these new business dealings may prove controversial, and the undertaking itself is a case

of evolving research. Nevertheless, research at this time is not premature, since we can only fall further behind if analysis is not attempted.

## 1.2 Objective and Significance

The Internet gives the foundation for electronic communication, interaction and transaction. It revolutionized traditional business processes and practices by increasing and accelerating the flow of information between partners, suppliers, customers and the marketplace as a whole. At the beginning, Internet-based commerce, or e-Commerce is just a new type of sales and marketing tool. Then, B2B e-Commerce began to substitute traditional EDI system as a new business-to-business communication and transaction tool. Today, Organizations are searching for ways to turn Web communication into a significant competitive advantage, where online integration and collaboration are rapidly gaining acceptance as the keys to achieve this goal.

At the same time, Information science and technology in mechanical and system engineering have emerged as a new research area utilizing and developing information models, technologies, and tools to aid design, manufacturing and analysis of products and systems. A new international journal, *ASME Journal of Computing and Information Science in Engineering*, sponsored by the American Society of Mechanical Engineering, was published in March 2001, indicating that this new research area has been attached sufficient importance in the research community of mechanical engineering. The issues involved in this area include advanced information models for representing, exchanging, managing and integrating the entire engineering product and process lifecycle; Internet-aided design, manufacturing and commerce; virtual environments and systems;

knowledge models and ontologies for engineering applications, etc. In the first decade of this century, e-Business integrated engineering system will open up vast vista for research and development work in this area.

The concept of sustainable development is widely accepted and promoted nowadays, where environmental and social responsibility is proactively embedded into core business activities such as product design, manufacturing and logistics. Multi-lifecycle Production Systems is one of the sustainable development methodology that fully integrates end-of-life stages such as demanufacturing, recycling, reengineering into product development lifecycle stages. The integration of e-Business strategy into Multi-lifecycle Production Systems can broaden the research boundaries and open up a unique window of research opportunity to develop new technologies and decision support tools that can alter current industry practices along a pathway towards sustainability, enhancing resource productivity, improving cost efficiencies and reducing lifecycle environmental impacts.

The **objective of this dissertation** is aimed to understand, design, develop, deploy and evaluate the framework of e-Business integrated Multi-lifecycle Production Systems for the purpose of increasing productivity, reducing cost, and improving environmental performance of production systems. The new methodology and framework have the potential of being widely used in analysis, design and implementation of e-Business-enabled sustainable engineering systems.

This dissertation works on a very broad and interdisciplinary area covering mechanical and production engineering, information technology, supply chain and operations research, system analysis and decision-making theory, and sustainable

development methodology. Each of these areas has been developed with profound scientific foundations. Building upon all these theoretical bases, this research work has developed novel methodologies, frameworks, and application approaches, and pushed forward to implementation models and methods in order to apply the outcome of the research into real world applications. The intellectual significance of this research work include:

1. An environmental lifecycle study on the impact of e-Business is conducted and fuzzy decision theory is applied to evaluate the e-Business scenarios. This is one of the first work that performed comprehensive and quantitative evaluation on this topic;
2. A Universal Target-based environmental performance metric, Lucent Sustainability Target Metric, is evaluated and implemented, and further utilized in the methodology framework;
3. An integrated e-supply chain framework is presented, in which a generic hyper-network supply chain model is defined. The model is based on most recent research on large supply chain network model, and extended to integrate demanufacturers, recyclers, and resellers as supply chain partners. Moreover, The e-Business information network is modeled, and environmental performance is evaluated for the supply chain, both of which have never been considered in the traditional supply chain engineering research.
4. A solution method to the integrated e-supply chain model is provided, which include fuzzy optimization algorithm and discrete simulation approach. Traditional supply chain research is more focused on inventory planning and service level control using

analytical models, while the solution method provided here deals with overall system parameter trade-offs and partner selections.

5. A Scalable Enterprise Environmental Management System (SEEMS) is designed and deployed, in which knowledge-based methodologies, agent-based design diagram, and implementation model are presented to push the research boundary to deployment and realization of e-Business integrated sustainable engineering systems.

This dissertation is a dedicated research work on the new and important area of mechanical engineering. The model and algorithm developed in the dissertation can help production system engineers to analyze complex system structures affected and coupled with information flows. The knowledge-based methodology utilized in SEEMS presents a novel and effective way to model and interoperate the product and enterprise information across different software applications. The SEEMS tools can provide product designers a powerful and useful platform to extract, access, and evaluate the environmental performance of products and enterprises.

### **1.3 Dissertation Organization**

This doctoral dissertation has seven chapters. Chapter 2 gives a comprehensive literature review on related topics. The research on the environmental impact of e-Business is first reviewed. The most recent research work on the Supply Chain Management and Engineering are surveyed, including methodologies, models, and approaches. The current research on the information technology in mechanical engineering is also reviewed. After that, sustainable development methodologies and system decision-making approaches are discussed and reviewed.

Chapter 3 first introduces the initial environmental lifecycle study of the environmental impacts of e-Business. The result reveals that e-Business does have environmental impact in terms of material, energy and air emissions throughout the product lifecycle. The initial study indicates further research work direction, and raises several research issues. The research approaches and tasks are also discussed in this chapter.

Chapter 4 is focused on environmental performance metrics. A suitable environmental performance metric is critical in analyzing and designing an e-Business enabled sustainable production system. A widely used methodology, Eco-indicator 95 is used in evaluating manufacturing processes. Some other performance metrics such as Ecological Footprint and Lucent Sustainability Target Metric are also described. A comprehensive comparison is conducted in terms of the background, applications, advantages and limitations of these three major metrics. Finally, the Lucent Sustainability Target Metric is selected to be used in this research work.

Chapter 5 presents a novel methodology for integration of e-Business into the multi-lifecycle production system. The e-Business enabled multi-lifecycle production system is viewed as an integrated e-supply chain network from raw material suppliers to manufacturers, distributors, retailers, consumers and finally to collectors and demanufactures. The methodology includes a modeling framework of integrated e-supply chain (IESC) network, a fuzzy multi-objective optimization approach for this IESC model, and a simulation model. Compared with traditional supply chain management methods, this new method extends the sequential supply chain structure to an integrated, more sustainable supply chain network structure, and combines two overlaid and

interconnected networks, material flow network and e-Business information network, to model the integrated strategy of e-Business. Moreover, fuzzy logic theory is applied and extended to deal with the data uncertainty and information gaps, and to optimize the network structure under multiple objectives. A comprehensive case study is provided with optimization and simulation results.

Chapter 6 extends the research further to an e-Business integrated application, Scalable Enterprise Environmental Management System (SEEMS). Advanced technologies are leveraged to address the issues in the area. Ontology-based knowledge representation and agent-based design model are introduced and applied in this chapter. XML structure is used to provide a unified and web inherent format for the environmental information residing in dispersed data repositories. The SEEMS architecture design and implementation are also presented. Chapter 7 concludes the dissertation and highlights future directions for this research works.



## **CHAPTER 2**

### **LITERATURE REVIEW**

The Multi-lifecycle Production Systems engineering deals with production system design, analysis, planning, and deployment using the Multi-lifecycle Engineering Methodology [Caudill, 1997] in order to achieve sustainable development and prosperity. The problems and issues involved in the Multi-lifecycle Production Systems have been investigated using new sustainable design guidelines and methodology, disassembly and demanufacturing system design and deployment methodology, material reengineering technology, etc. [Caudill, et al, 2001; Zhou, 1999; Sodhi, et al, 1999].

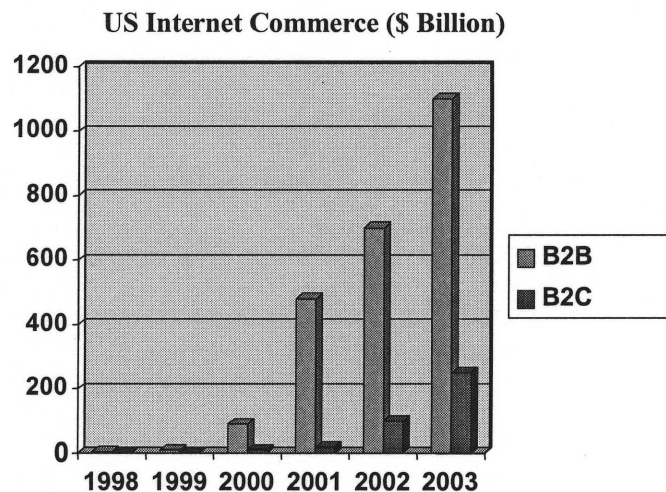
With the involvement and integration of e-Business strategy, the research field of e-Business integrated Multi-lifecycle Production Systems has become a broader interdisciplinary area. It extends the research boundary to cover the following theoretical areas:

- 1) Systems analysis – dealing with the analysis and decision-making theories of complex systems.
- 2) Sustainable development methodologies – dealing with theories, methodologies and tool of lifecycle assessment, design for environment, and environmental performance metrics.
- 3) Information science in engineering – dealing with e-Engineering system architecture and knowledge-based methodologies,
- 4) Operation research – dealing with supply chain engineering, routing, optimization, and simulation technologies.

This chapter first reviews recent research works on the environmental impact of e-Business. Then the scientific base and recent progress in the above research areas are reviewed. The currently available theories and approaches are briefly discussed in terms of their forms, applications, advantages and limitations. The purpose of this chapter is to provide scientific background information for this dissertation.

## 2.1 Environment Impact of E-Business

Internet use has grown exponentially becoming a global communication and business resource. In the US alone, over 30 million households are currently on-line, and, by 2003 nearly 75% of all American families will be surfing the net and buying products and services directly from the manufacturer or distributor [McQuivey, 1998 & Rasmusson, 1999]. Electronic Business (e-Business) will truly affect every sector of the economy.



**Figure 2.1** Projection of Future Growth of Business-to-business and Business-to-consumer Commerce in the US (Source: Forrester Research, 1998)

However, what will be the impact of e-Commerce on manufacturing sector and the environment? From 1999, researchers have begun to explore this question from many

perspectives examining the environmental impacts of the e-Business growth and the future trends in environmental strategy.

Since the end of the 20th century, researchers have pointed out that the Internet and e-Commerce will have significant social and environmental consequences in many aspects [Cohen, 1999; Rejeski, 1999; Romm, et al, 1999; Andrew Wyckoff and Alessandra Colecchia, 1998]. The e-Commerce will reshape manufacturing, distribution system, product design and the fundamental relationship of producer to customer, and thus will alter human life and even physical landscape dramatically [Cohen, 1999]; The Internet and e-Business have the potential to vastly improve the efficiency of business activities thus improve the resource productivity; Mass customization and dematerialization could reduce or eliminate the needs for the materials, energy, transportation and space consumed by products. With the advent of e-Commerce, third-party shippers can have incentive to devise cost-effective take-back systems for packaging materials and products in a closed loop; E-Commerce also has potential to create marketplace for secondary goods that might otherwise not have a chance at a second life, some Internet companies like e-Bay have already started this kind of business. On the other hand, the growth of e-Commerce could have negative impacts on environment when inefficient shipping logistics and packaging are used.

E-Business is not a stand-alone technology, but a complex and tightly-coupled system. The environmental effects of this system could be much larger than anticipated. Besides, some direct impacts due to changes of rates and means of transportation, and changes of consumer behaviors, the information flow in e-Business connecting the value chain from suppliers through manufacturers to customers is not limited to conventional

pricing, ordering, and inventory messages, but could include a variety of environmentally related data [Rejeski, 1999]. The expansion of inter-business network provides the necessary infrastructure to support the flow of environmental information across organizational boundaries, creating a potential fulcrum for leveraging and improving the environmental performance of the entire production network system.

The specific and quantitative examples of how the Internet is affecting energy use and the environment was given in a report from the Center for Energy and Climate Solutions of the Global Environment and Technology Foundation [Romm et al, 1999]. It is observed that from 1997 to 1999, there are two very remarkable, though seemingly unrelated changes having taken place in the U.S. economy. The first is the remarkable growth of the Internet and E-Commerce; the second is that in 1997 and 1998, while the U.S. economy grew by about 8%, U.S. energy consumption hardly grew at all, about 1%. Had the historical relationship between U.S. economic growth and energy consumption been the same in those two years as it had in the previous 10 years, it might be expected 6% growth in energy consumption. This is potentially very important because the vast majority of air pollution in this country come from the production and use of energy. In particular, virtually all of the emissions of CO<sub>2</sub>, the principal greenhouse gas emitted by human activity, come from fossil fuel combustion. Indeed, U.S. emissions of greenhouse gases rose only 0.2% in 1998, the smallest rise since 1991 [EPA, 1998]. If the relationship between energy use and economic growth is changing, that would have profound implications for long-term economic and energy forecasting in this country.

Internet energy efficiency gains cover a broad spectrum of activities from buildings sector, manufacturing sector to transportation sector. In B2C e-Commerce, for

instance, a warehouse can contain far more products per square foot than a retail store. Warehouses themselves also typically use far less energy per square foot than a retail store. More importantly, in the manufacturing sector, as traditional manufacturing and commercial companies put their supply chain on the Internet, reduce inventories, overproduction, unnecessary capital purchases, paper transactions, mistaken orders, they achieve greater output with less energy consumption. According to the report of Organization for Economic Co-Operation and Development, e-Commerce has led to a reduction in overall inventories of \$250-\$350 billion, or about a 20% to 25% reduction in current U.S. inventory levels [Andrew Wyckoff and Alessandra Colecchia, 1998]. In the energy-intensive sectors, not building plants that are not needed and not making products that would not have been sold can reduce significant negative environmental impacts.

The Internet and information technology itself does not consume a lot of electric energy. A most recent study shows that actual total electricity use for all computers, office equipments, network equipments, and telecommunications is 3% of all electricity use in this country, and Internet electricity use is only 1% [Kooimey, 2001].

The issues raised as above deserve far more rigorous analysis than it has been performed. The understanding of the systemic effects of e-Business is critically important in quantitatively evaluating the environmental performance. A study for economic and environmental impact of e-Commerce for book retailing has been conducted in Carnegie Mellon University [Mathews, et al, 2001]. In this study, two logistic models were built. One is the traditional retailing logistic in which books are shipped from the publishers through various distributors and warehouses and finally to the retail outlet, and the customer buy the book and bring it to home. The second is the e-Commerce model that

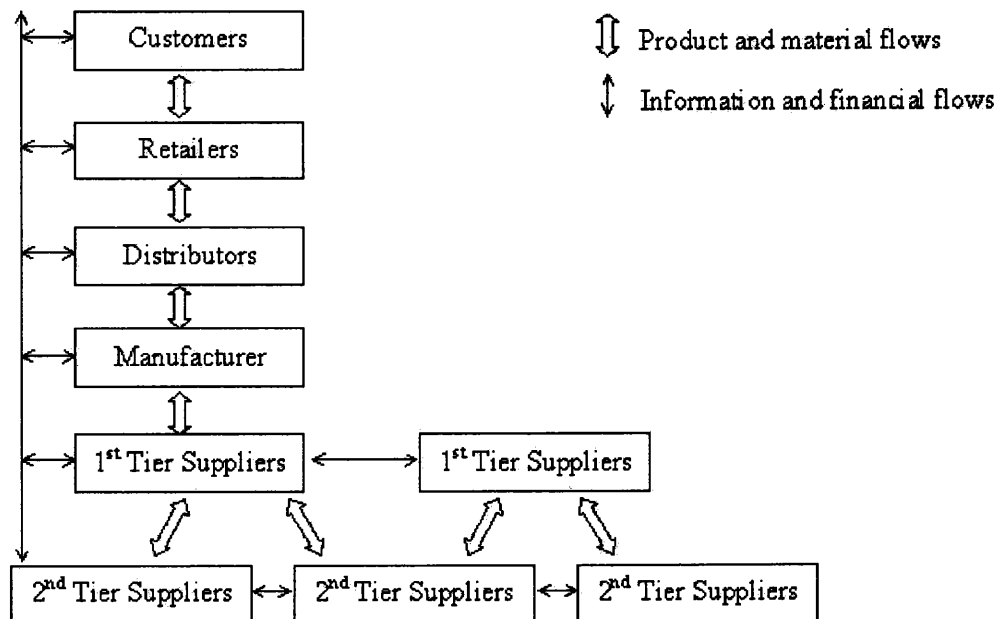
the book is shipped from the publisher to a single warehouse, forwarded by truck to a logistic network, and then air-freighting to a regional airport/hub from which the book is shipped by truck to the customer's home. In the study, a return rate of 35% is assumed for the traditional model due to the unsold book return from retail to the publisher. Average distances are also assumed in both models. The environmental impacts of the two models are evaluated by accounting and aggregating all the energy consumption and emissions across the supply chain. The result shows that, for the book retailing, e-Commerce has environmental benefits. However, the result is fairly sensitive to the input data of air and truck transportation distances, and other assumptions. If the air-freight distance is increased, the overall air emission of e-Commerce model may higher than the traditional model. The book retailing e-Commerce model is focused on the business-to-customer side. The logistic models are simple and predetermined. If the business-to-business side is involved, more complex supply chain model are needed, and sophisticated methods are required to evaluate the system effect of the e-Commerce.

## **2.2 Supply Chain Management and Engineering**

### **2.2.1 Research Overview**

The Supply Chain Management and Engineering (SCME) is defined as the integration of business processes from end user through original suppliers that provides products, services, and information that add value for customers [Lambert, et al, 1998]. It involves the flows of material, information, and finance in a network consisting of suppliers, manufacturers, distributors, logistics service providers, wholesalers, retailers, and customers. Material flows include both physical product flows from suppliers to

customers through the chain and reverse flows via product returns, servicing, recycling, and disposal. Information flows involve order transmission and delivery status. Financial flows include credit term, payment schedule, and consignment and title ownership arrangements. Coordination and integration of these flows are critical to effective supply chain management. Figure 2.2 illustrates the nature of supply chain management and engineering [Handfield and Nichols, 1999].



**Figure 2.2** Integrated Supply Chain Model

The goals of supply chain management and engineering include multiple dimensions from cost minimization, increasing level of service to improving communication among supply chain partners, etc. The research of SCME followed through original functional logistics dealing with routing modeling and control to integrated logistic that manages for all functions such as cost control, inventory planning, routing scheduling, etc., and covers such many different disciplines as marketing,

economics, system dynamics, operations research, management science. A broad taxonomy for understanding SCME research is present in [Geneshan et al, 1999]. The research methodologies can be categorized into three areas:

- 1). Concepts and Non-Quantitative Models – research that analyzes that supply chain in an attempt to define, describe, and develop methods for the management of the supply chain without using quantitative models, such as recent research work presented in [Lee, et al, 1997] and [Towill, 1997].
- 2). Case Oriented and Empirical study – research that works with specific firms or industries and uses data collected by the researcher or another qualified source to aid in the management of the supply chain. This type of research are presented in [Bagahana and Cohen, 1998], [Cachon and Fisher, 1997] and others.
- 3). Quantitative Models including optimization, simulation, stochastic model, and heuristics – research that attempts to develop methods for the management of the supply chain using quantifiable models, such as research in [Camm, et al, 1997], [Lederer and Li 1997], [Feigin, et al, 1999], etc.

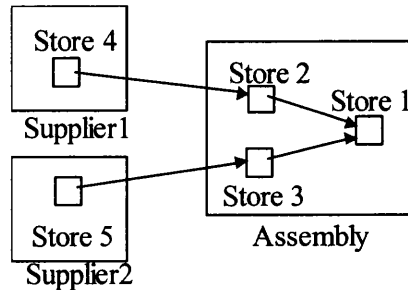
### **2.2.2 Quantitative Models**

Many quantitative models have been developed in order to solve supply chain management problems such as inventory management, supply contracts, product variety, etc. Analytical researches on multi-echelon inventory problem have been considered in which there are multiple tiers in the supply chain, and quantitative methods must be utilized to solve the performance analysis and optimization issues of this kind of complex problems.



In deterministic scenarios, global optimization can be formulated using mixed integer programming [Cohen and Moon, 1990; Newhart, et al, 1993]. In stochastic environment, approximations and optimization are provided to evaluate inventory level and service level [Lee and Billington, 1993]. More recent research has been reported to use network model and non-linear optimization to analyze the supply chain dynamics [Ettl, et al, 1996 and Feigin, 1997]. The profile of this work is described as follows.

A supply chain network model is defined to support decision making in the management of large, complex supply chain. As shown in Figure 2.3, the supply network



**Figure 2.3** Supply Network Topology

consists  $\mathcal{S}$  of stocking locations, or stores, each of which stocks one type of stock keeping unit (s.k.u.). Each site in the network in general has two types of stores: input stores and output stores. Each store  $i \in \mathcal{S}$  has a set of supply stores, denoted by  $\mathcal{S}_{>i}$ , which consists of all those stores which directly supply store  $i$ . If  $i$  is an input store, then  $\mathcal{S}_{>i}$  is a singleton set which can only contain exactly one store. On the other hand, if  $i$  is an output store, then the set  $\mathcal{S}_{>i}$  either is empty or contains one or more stores, which are necessarily input stores at the same site, corresponding to the components in the one-level Bill of Materials (BOM) for the s.k.u. in store  $i$ . Moreover, this one-level BOM also specifies the usage counts,  $u_{ji}$ ,  $j \in \mathcal{S}_{>i}$ , where  $u_{ji}$  denotes the number of s.k.u.'s from store

$j$  needed to produce one s.k.u. at store  $i$ . Each store  $i$  follows a base-stock control policy which means when the inventory position at store  $i$  falls below some specified level,  $R_i$ , a replenishment order must be placed. The shipping time for input store or production time for output store constitutes the nominal lead time of store  $i$ , denoted by  $L_i$ .

Let  $M$  be denoted as the set of all customer classes, then associated with each customer class  $m \in M$  are the end store that supplies the demand, with the transit time  $T_m$ . In addition,  $W_m$  is the waiting time to receive an order for the class  $m$  customer, then service-level requirement is given by

$$\mathbf{P}[W_m \leq \beta_m] \geq \alpha_m, \quad (2.1)$$

where are given parameters:  $\beta_m$  is possibly random due date for class  $m$  order, while  $\alpha_m$  is the fraction of class  $m$  orders that are filled before the due date. There is also demand stream,  $\{D(m,1), D(m,2), \dots\}$ , where the second argument denotes the time period. The demand is translated into the effective demand at each store  $i$ , denoted  $\{D_i(1), D_i(2), \dots\}$ . The offset associated with customer class  $m$  is denoted as  $o_m := E[T_m]$ . Then for each store  $i$ , define the effective demand stream as:

$$D_i(t) := \sum_{m: \text{str}(m)=i} D(m, o_m + t), \quad (2.2)$$

where  $\text{str}(m)$  denotes the end store that supplies the class  $m$ . By preceding recursively moving to upstream for all other stores in the network, Then the effective stream for store  $i \in S$  is:

$$D_i(t) := \sum_{j \in S_{\triangleright i}} u_{ij} D_j(o_j + t) \quad (2.3)$$

The next step is the performance analysis. Each site in the above-defined network is modeled as an inventory-queue. The appropriate queue model is chosen for the arrival

processes, which is crucial in modeling the inventory dynamics at each store. The  $M^X/G/\infty$  model is used where arrivals follows a Poisson process with rate  $\lambda_i$ , and each arrival brings a batch of  $X_i$  units. With equations:

$$E(D_i) = \lambda_i E(X_i) \text{ and } \text{Var}(D_i) = \lambda_i E(X_i^2), \quad (2.4)$$

and let  $\tilde{L}_i$  be the actual lead time at store  $i$ , the total number of jobs  $N_i$  in the queue  $M^X/G/\infty$  is derived as:

$$\begin{aligned} \mu_i &:= E(N_i) = \lambda_i E(X_i) E(\tilde{L}_i) = E(D_i) E(\tilde{L}_i) \\ \sigma_i^2 &:= \text{Var}(N_i) = E(N_i) + \lambda_i [E(X_i^2) - E(X_i)^2] \int_0^\infty \bar{F}_{\tilde{L}_i}^2(y) dy, \end{aligned} \quad (2.5)$$

where  $F_{\tilde{L}_i}(y) = 1 - \bar{F}_{\tilde{L}_i}(y)$  is the distribution function of  $\tilde{L}_i$ .

Now the inventory and service measures can be derived. Let  $I_i$  and  $B_i$  be the level of on-hand inventory and number of backorder at store  $i$ . Then there are relations:

$$I_i = [R_i - N_i]^+, \text{ and } B_i = [N_i - R_i]^+, \text{ where } [x]^+ := \max\{x, 0\}. \quad (2.6)$$

Then:

$$E(B_i) = E[N_i - R_i]^+ = \sigma_i E[Z - k_i]^+ = \sigma_i \int_{k_i}^\infty (z - k_i) \phi(z) dz, \quad (2.7)$$

where  $k_i$  is that safety factor, and  $\phi(z) = \exp(-z^2/2) / \sqrt{(2\pi)}$  is the density function of  $Z$ .

Let  $G(k_i) := \int_{k_i}^\infty (z - k_i) \phi(z) dz$ ,

$$E(B_i) = \sigma_i G(K_i). \quad (2.8)$$

Similarly,

$$E(I_i) = \sigma_i \int_{-\infty}^{k_i} (k_i - z) \phi(z) dz = \sigma_i H(k_i). \quad (2.9)$$

The fill rate at store  $i$ , denoted as  $f_i$ , is the fraction of customer orders that is filled by on-hand inventory. Let  $\bar{f}_i := 1 - f_i$ , making use of the above relations, the expression of the service level is:

$$\begin{aligned}\bar{f}_i &= \mu_i^{-1} E[N_i | N_i > R_i] P[N_i > R_i] \\ &= \mu_i^{-1} [\sigma_i G(K_i) + (\mu_i + k_i \sigma_i) \bar{\Phi}(k_i)] \\ &= \sigma_i \phi(k_i) / \mu_i + \bar{\Phi}(k_i).\end{aligned}\tag{2.10}$$

The objective of optimization is to minimize the total expected inventory capital throughout the network, while satisfying customer service-level requirement as specified in (2.1). Let  $c_i$  denote the inventory capital per s.k.u. at store  $i$ .

$$\hat{c}_i := \frac{1}{2} (c_i + \sum_{j \in S_{>i}} c_j \mu_{ji}).\tag{2.11}$$

Therefore, the objective function takes the following form:

$$C(k) = \sum_{i \in S} [\hat{c}_i \mu_i + c_i \sigma_i H(k_i)].\tag{2.12}$$

The decision variable is the safety factor  $k_i$  for store  $i$ . The gradients of the objective function play a very important role in the optimization. Considering the  $j$ -th and  $i$ -th partial derivatives of (2.12), the partial derivative of  $C(k)$  is:

$$\begin{aligned}\frac{\partial}{\partial k_j} C(k) &= c_j \sigma_j \Phi(k_j) + \sum_{i \in S_{j>} \setminus S_0} [\hat{c}_i \frac{\partial \mu_i}{\partial k_j} + c_i H(k_i) \frac{\partial \sigma_i}{\partial k_j}] \\ &+ \sum_{i \in S_{j>} \cap S_0} \{\hat{c}_i \frac{\partial \mu_i}{\partial k_j} + c_i [H(k_i) \frac{\partial \sigma_i}{\partial k_j} + \sigma_i \Phi(k_i) \frac{\partial k_i}{\partial k_j}]\}\end{aligned}\tag{2.13}$$

Considering (2.10) about  $\bar{f}_i$ , the partial derivative can be rewritten as follows.

$$\frac{\partial}{\partial k_j} C(k) = c_j \sigma_j \Phi(k_j) - \frac{R_j}{\mu_j} \phi(k_j) \cdot \left\{ \sum_{i \in S_{j>}} [\hat{c}_i \frac{\partial \mu_i}{\partial \bar{f}_i} + c_i H(k_i) \frac{\partial \sigma_i}{\partial \bar{f}_i}] \right\}$$

$$+ \sum_{i \in S_j \cap S_0} c_i \sigma_i \Phi(k_i) \frac{\partial k_i}{\partial f_j} \} \quad (2.14)$$

More detailed derivation is shown in [Ettl, et al, 1996]. In this optimization model, gradient formulas are worked out in explicit forms, leading to effective execution of the optimization algorithm. Some industry-based case studies using this model are shown in [Feigin, 1997]. The limitation of this model is that it does not take into the consideration the information flow which is critical in e-Business enabled supply chain network. In addition, supplier selection and routing scheduling are not included in the model.

Many researchers also applied simulation to evaluate the effects of various supply chain strategies and improving performance of the supply chain in terms of objectives such as cost minimization, on-time delivery, and optimal inventory level. Towill, Naim, and Wiker [Towill, et al, 1992] used simulation techniques to evaluate effects of various supply chain strategies on demand amplification. A multi-echelon simulation system operated on a centralized or a decentralized mode is presented in [Swaminathan, et al, 1998]. The simulation-based framework is developed using customized supply chain models from a library of software components which captures generic supply chain processes and concepts. A gradient estimation with respect to the base stock level in a multi-echelon system is performed in [Tzafestas and Kapsiotis, 1994] utilizing a combined analytical and simulation model.

### 2.2.3 Internet and E-Business in Supply Chain

E-Businesses are now providing value through the power of information network while redefining or eliminating activities in the physical network. The growth of Internet has

presented supply chains with many significant opportunities for cost reduction and service improvement. Examples of these opportunities are the ability to track shipments, online catalogs which buyers could select and order items directly from suppliers, or the ability to notify vendors or buyers regarding customer service problems from late delivery or stock outs. In procurement, there are opportunities for more business partners, faster turnaround, and smaller inventories.

Recent nationwide survey [Lancioni, et al, 2000] revealed that the most popular use of the Internet for supply chain is in transportation, followed by order processing, managing vendor relationships, purchasing, procurement, and customer service. Table 2.1 shows the result of the survey.

**Table 2.1** E-Business Application in Supply Chain Management

<b>Application</b>	<b>%Using</b>
Transportation	56
Order processing	50
Purchasing/procurement	45
Relations with vendors	45
Customer service	42
Inventory Management	30
Production scheduling	12

The Internet use in each of these areas is based on the real-time information requirements needed to manage them effectively. The application of the Internet in customer service, inventory management, and production planning and scheduling will become more popular as the technology develops.

Prominent examples of these positive effects include many companies. The Ford Motor Company uses Internet to track small quantities of spare parts shipped to customer on a daily basis. PPG Industries, Inc. utilizes the Internet to monitor the weekly route

performance of carriers from its main production plants and to track long-haul deliveries across country. Dell Corporation, General Electric (GE), Wal-Mart, Digital Equipment Corporation, the personal computer supply chain, and the Hewlett-Packard Corporation are also good examples [Ursula and Herbert, 2001]. Dell computer's inventory controls provide an example of how Internet supplier exchanges function. Dell has lowered its average inventory holdings from 35 days in 1993 to six days today [Laseter, et al, 2000]. The Internet has helped Rollins Leasing Inc. reduce its supply chain costs by 5% to 15% through increased partnering with suppliers. IBM has reduced inventory write-offs by \$800 million, increased on-time delivery from 90% to 98%, and reduced order commit time from two weeks to real time [Cross, 2000]. Since joining the trading process network, the GE Lighting unit has cut its average purchasing cycle time from 14 to 7 days. It has also reduced price paid for materials by 10 to 15 percent [Handfield and Nichols, 1999].

The use of Internet and e-Business technologies in the supply chain management and engineering will increase without any questions. However, there is still lacking of quantitative model as in the traditional SCME area that can catch up the characteristics of the e-supply chain network in terms of information network, flexible routing and supplier selection, as well as dynamic system performances.

### **2.3 Sustainable Development Methodology**

It has become clear that our environment cannot continue to bear an ever-increasing burden. At present, the limits of sustainable development for most environmental effects have been surpassed by a factor 2 to 5 [Goedkoop, 1998]. This is primarily caused by

rapidly increasing problems concerning environmental damages, huge amounts of wastes, occupational health damages, and increasing use of non-renewable resources. These problems will be coupled with expected exponential growth in world population and world consumption during the next 50 years. Nowadays, the concept of sustainable development has been generally accepted, as a famous proverb said “We don’t inherit the earth from our ancestors - we borrow it from our children”.

The need to do something about the environment is undisputed nowadays. Many initiatives have been taken worldwide in recent years to change our present consumption and industrial culture towards sustainability. As a basis for sustainable production, the lifecycle concept or the lifecycle assessment approach has been identified as one of the most important factors [Alting and Jorgensen 1993]. Lifecycle Assessment (LCA) is a systematic method to evaluate the environmental burdens associated with a production system by identifying and quantifying energy and material usage and environmental releases, to assess their impacts, to evaluate and implement opportunities to effect environmental improvement, and finally to achieve the sustainable industry development. LCA has been found useful for examining the design of products and processes to reduce the impact upon human health and the environment and to achieve sustainable development.

LCA has been used in one form or another over the past 30 years in Europe, the United States, and a few other countries by industry, government agencies, and other organizations. Interests in this environmental analysis tool have grown substantially in recent years [Kolluru, 1994]. The history of LCA can be divided into two periods. The first is the early development period from 1960s to the late 1980s. In this period, LCA



calculated energy requirements associated with various production systems or evaluated chemical inputs and outputs involved with different processes or products. The second period started in 1990. In this period, there has been an increasing number of workshops, studies, and evaluations of methodologies and applications of lifecycle work. One of the key drivers of this is recognition of the potential value of lifecycle assessment in addressing environmental issues proactively to prevent pollution instead of having to control it or clean it up. Several organizations, industry associations, and private companies have used LCA to justify claims that marketing strategies used such as “environmentally friendly” products. This has led the U.S. Environmental Protection Agency (EPA), the U.S. Federal Trade Commission (FTC), the European Economic Commission (EEC), the International Standards Organization (ISO), several U.S. state governments, the Society of Environmental Toxicology and Chemistry (SETAC), and others to press for acceptable methodologies upon which process improvements and product advertising claims can reliably be based in order to merit public confidence.

The LCA Methodology is an integrated, holistic and long-term systems concept. It gets an overview of values of resource consumption and loads on environment, material type, production process, method of distribution, way of disposal, and degree of recirculation to evaluate the environmental consequences of the objects. The currently-known technical framework for LCA was originally defined by the Society of Environmental Toxicology and Chemistry (SETAC) in 1991. The methodology is outlined briefly in [ISO, 1996][SETAC, 1991][EPA, 1994].

In the last decade, many researchers and industrialists have been heavily engaged in research and development in the fields of LCA. For example, an approach to identify

and quantify the environmental effects during products lifecycle was introduced [Zust, 1992]; The methodology and guidelines of design for assembly and disassembly were discussed by Boothroyd and Alting [Boothroyd and Alting, 1992], etc. Various methods are in use to assess the environmental effects of objects. Almost all of the methods operate on the assumption that an object's entire lifecycle should be analyzed. The main differences between the methods are the comprehensiveness of the analysis, the type of effect that is included, the degree of quantification of the result, or the interpretation (weighting) method of the environmental impacts identified.

Traditionally, LCA is a cradle-to-grave analysis. Over the last decade, people have also worked on End-Of-Life products and waste streams recovery and reengineering so that they can be put back into valuable feed streams. Based on these initiatives, Multi-lifecycle Engineering (MLCE) methodology was proposed [Caudill, 1997]. MLCE emphasizes a cradle-to-cradle 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 environment, but rather a complex, next generation engineered system that transcends traditional discipline boundaries in search of scientific knowledge, new methodologies and technologies. The structure of MLCE structure includes explicit consideration of demanufacturing, remanufacturing, reengineering and reuse. 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. Comparing to the traditional life-cycle model consisting of four life-cycle stages of material production, 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) A packaging and distribution stage is separated from the production stage to quantify the materials, energy and emissions associated with packaging and transportation processes, 3) The recovery and new life options of a product is the stage of Remanufacturing. 4) The reengineering stages acts as a link that closes the lifecycle loop. 5) Demanufacturing stage is where the parts and subassemblies are disassembled and reused. Generic frameworks of MLCE and some assessment examples are addressed and discussed in a degree thesis [Al-Okush, 1999].

Environmentally conscious design and manufacture of products has been driven by product take-back initiatives in Europe, international certification standards for environmental management, increasingly stringent regulations governing hazardous materials world-wide, requirements for waste stream purity for landfill and incineration, as well as a growing consumer preference for “green” product characteristics. The pioneering work by Graedel and Allenby [Graedel and Allenby, 1995 ] has greatly promoted Design for Environment (DFE) industry-wide. A lifecycle engineering design approach to products including computers and manufacturing systems is reported in [Yan et al., 1998-2000]. Their work is the first one that systematically considers the concurrent optimization of products in terms of their cost, performance, and environmental impact. It, however, applies to only a product without taking into account the multi-layer suppliers. Other developments have focused on the development of life-cycle assessment methods [Graedel and Allenby, 1995] and electronic product disassembly and recovery [Zhou et al., 1999; Zussman and Zhou, 2000]. There is no reported work that explores the concurrent optimization of an e-supply chain in terms of product cost, cycle time, energy

consumption and environmental impact in the context of global and Internet-based manufacturing.

## **2.4 Information Science and Technology in Mechanical and System Engineering**

Information science and technology in mechanical and system engineering is a new research area that examining and developing information models, technologies, and tools to aid design, manufacturing and analysis of products and related systems. The research issues include advanced information models for representing, exchanging, managing and integrating the entire engineering product and process lifecycle; Internet-aided design, manufacturing and commerce; virtual environments and systems; knowledge models and ontologies for engineering applications, etc. The new international journal, *ASME Journal of Computing and Information Science in Engineering*, have pointed out that this new research area has received significant attentions in the research community of mechanical engineering. There are mainly four sub-areas currently in this area:

- 1) Knowledge-based integration for engineering systems;
- 2) Internet-based engineering systems;
- 3) Distributed artificial intelligence;
- 4) Collaborative Product Commerce.

A literature survey on the most recent research progress is carried out in the following directions related to this dissertation.

### **2.4.1 Engineering Information Management and Integration**

Engineering Information Management (EIM) initially dealt with file management for product definition in the form of CAD/CAM/CAE files at a coarse level, and then evolved to managing structured product meta-data, a finer levels of granularity. This trend has now advanced to support business processes such as engineering release, product bill of materials, and has elevated the EIM systems through the entire product development lifecycle where many business processes including production, supply chain fulfillment, and sales configuration, etc. are driven by the structured engineering contents. A survey about industry oriented EIM technologies is presented in [Rangan and Chadha, 2001]. EIM systems can be classified into: CAD/CAM/CAE to manage design, manufacturing and engineering data; Product data Management (PDM) and Enterprise Resource Planning (ERP) to improve internal efficiencies and gain synergistic advantages of size through acquisitions and mergers; Supply Chain Management (SCM) to improve the effectiveness of entire supply nets; Customer Relation Management (CRM) to establish and maintain external customer satisfaction.

As the products being developed have become more complex and are being designed collaboratively by many organizations, the focus of engineering information management has to be broadened to facilitate the “virtual enterprise”, a heterogeneous, dynamic, and evolving environment. According to Gartner Group [Gartner, 2000], leading manufacturers already outsource 78% of their transportation, 54% of their distribution, and 46% of their manufacturing. These numbers are expected to increase. This means that collaboration between different groups will continue to grow in frequency and importance.

The existing EIM systems cannot support to manage the information flow through the multi-organizational circumstance. This has led to some advanced information modeling technologies such as object models [Rambaugh, et al, 1991], Unified Modeling Language (UML) [Fowler and Scott, 1998] and associated methodologies. More importantly, managing information across the enterprise must enable systemic integration approaches.

Enterprise system integrations pay attention to communication between various EIM repositories and typically follow a company implementation-specific business process. There are three levels of integration across the enterprise boundaries, distributed computing level, process level and data level. Distributed computing level is the lowest level in which the issue is accessing data and software from distributed sources over the Internet. There have been significant developments over last ten years in the creation of middleware solutions that provide standardization for communication with distributed software components as well as layers of abstractions that provide more effective ways of programming in distributed environment [Urban, et al, 2001]. The Common Object Request Broker Architecture (CORBA) of the Object Management Group (OMG) emerged in the 1990's is an important standard for access to distributed software components [OMG, 1998]. The CORBA standard has matured significantly since the early 1990's, providing advanced features such as event notification and transaction processing. In parallel with the maturity of the CORBA standard, several different solutions for distributed object computing have also emerged based on the use of JAVA technology [JAVA, 2000]. The Enterprise JavaBean [EJB, 2000] specification from SUN Microsystems provides a sophisticated software component model which can

provide a cleaner separation between business logic and low-level distributed computing issues. Jini Connection Technology [Jini, 1999], unlike CORBA promoting transparency as an advantage of distributed computing, provides a service that allows distributed components to find each other in a distributed space so that they can then directly communicate.

Process level integration is also important because a product lifecycle typically involves many different groups and goes through many processes. RosettaNet model [RosettaNet, 2000] has been developed to achieve integration of this level. RosettaNet is a non-profit industry consortium working to create and implement industry-wide, open e-Business process standards. These standards form a common e-Business language, aligning processes between supply chain partners on a global basis. RosettaNet model is a business process focused, message-based, symmetric e-Business framework in which each trading partner assumes an equal level of control over the relationship. The message-based feature make transaction relatively ease to automate, and back-end integration possible. Further, this automation enables handling of tremendous volumes of e-Business transactions.

RosettaNet focuses on creating Partner Interface Processes (PIPs). PIPs originate as high level business documents describing an important discrete flow of information between two companies to accomplish a business function such as availability of component or a check on price. The PIPs is defined as the standardization of business processes in a manner that allows trading partner's computer systems to align those processes. The clustering of PIPs creates a virtual cross-enterprise workflow in which trading partners can experience a unified process to accomplish a single goal.

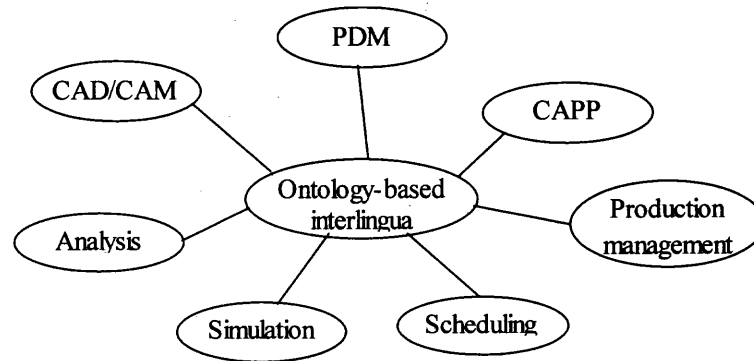
Thus RosettaNet standards allow the partners to communicate effectively and to function, when necessary, as a single virtual system.

Data level integration is intended to deal with the lacking of information interoperability among the various enterprise EIM systems. Especially in manufacturing, the ability to share information among different systems is often hindered because the meaning of information can be drastically affected by the context in which it is viewed and interpreted, especially when the complexity of manufacturing information is growing and the need to exchange this information among various software applications. A solution to this problem is the use of taxonomies or ontologies of manufacturing concepts and terms. Current research and development on ontologies in mechanical engineering applications are reviewed in [Ciocoiu, et al, 2001].

Ontologies can provide a way to make explicit semantics for the concepts used, rather than just rely on the syntax used to encode those concepts. Ontological techniques can be useful for giving unambiguous definitions of product and process capabilities and evolving designs and design requirements, unifying the differences in how knowledge is conceptualized across multiple product and process domains, and translating those definitions into the specialized representation languages of application systems.

Various groups with industry and academia have been developing sharable and reusable ontologies which can support interoperability by providing a common vocabulary with a shared machine-interpretable semantics. The information exchange and integration among applications can use a common ontology as shown in Figure 2.4.





**Figure 2.4** A Common Ontology Reduces the Number of Translators [Ciocoiu, et al, 2001]

#### 2.4.2 Collaborative Product Commerce

Collaborative Product Commerce (CPC) is a new product development strategy that uses Internet to tie together product design, engineering, manufacturing, purchasing, sales, marketing (and other staff functions), services, and customers into a global knowledge network. It is a product-focused e-Business that promises to deliver significant increases in product innovation, productivity and profitability resulting in a competitive advantage that traditional business models simply cannot duplicate.

In today's extremely competitive manufacturing market, enterprises are looking to develop better products more rapidly than their competitors, and to generate a product that is custom-tailored to customers' needs. Meanwhile, manufacturing is now centered on assembling modular components from multiple, external suppliers as opposed to fabricating all elements from scratch internally [Aberdeen Group, 2000]. All of these mean that cross-enterprise collaboration is becoming a necessity for manufacturing success. To meet these needs, enterprises are looking toward collaborative solutions. CPC has been discovered and analyzed by industry analyst such as Aberdeen Group, Gartner

Group since 2000. It is predicted that Collaborative Product Commerce will revolutionize product innovation by effectively utilizing the Internet to manage the entire product commercialization cycle [Gartner, 2001].

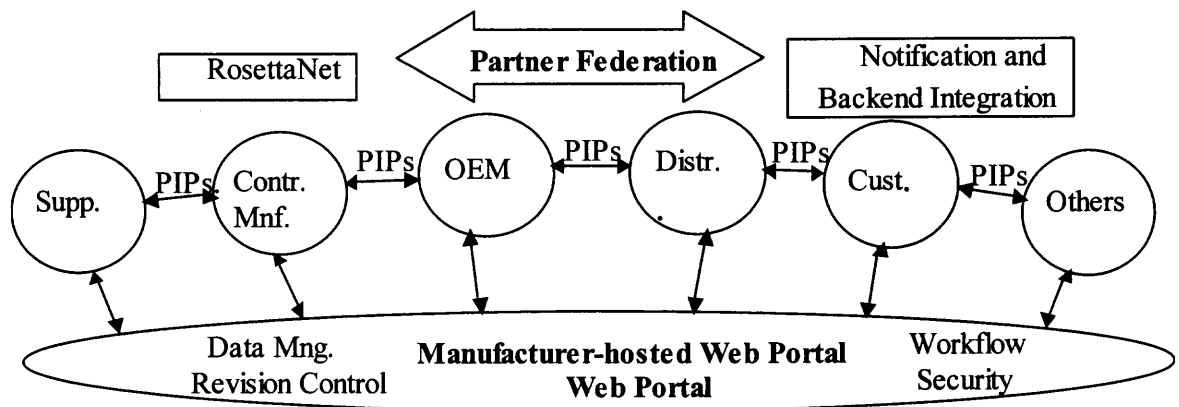
The fundamental concept behind CPC is that manufacturing organizations obtain the greatest competitive advantage by creating better products in less time, at less cost, and with fewer defects than their rivals. To do that, manufacturers need real-time design specifications, cost structure, and production capabilities across the entire product development cycle. CPC solutions are providing the structural building blocks to answer this challenge, allowing multiple organizations frequently involved in the manufacturing of a single product to use the Internet to pull together and share design and production information instantaneously from multiple locations. With CPC, manufacturers can propose and test new design ideas electronically thus vastly reducing time and costs. Essentially, CPC collapses time and distance across the product chain. Such is the appeal of CPC that Aberdeen Group expects the market for CPC-related software, professional services, and Information Technology (IT) infrastructure to top \$20 billion by 2003 [Aberdeen, 2001].

The automotive and aerospace industry has been very aggressive in the adoption of collaborative product development system to tie together geographically distributed groups relative to 3D visualization and simulated assembly walkthroughs [Richardson, 2000, Lundberg, 2000, and Horter, 2000]. Same implementation effort in the electronics industry is presented in Hutchinson Technology Inc. [Tessmer, 2000].

Leading CPC solutions emerging during these two years include Parametric Technology Corporation's Windchill [PTC, 2001], MatrixOne's eMatrix system

[MatrixOne, 2001], Structural Dynamics Research Corporation's Enterprise Collaboration solution [SDRC, 2001], Unigraphics Solutions (UGS)'s eVis [UGS, 2001], and Autodesk's Connectivity Strategy [Autodesk, 2001]. Using the Windchill system of PTC [PTC, 2001] as an example, system architecture, main components, functions, and key technical issues of CPC are described as follows.

Windchill allows customers, partners, and suppliers to collaborate in a Web environment to create innovative new products, deliver those products to market faster, and manage the complexities of an evolving supply chain. It does this through its unique web-centric approach and federated architecture as depicted in Figure 2.5.



**Figure 2.5** PTC Windchill Architecture

In Windchill architecture, a manufacturer-hosted Web portal exploits the web to unite every member of the extended virtual organization to collaborate on design, manufacturing, procurement, marketing, service throughout a product's development cycle. The web portal offers complete networks of product and process knowledge that can be leveraged as a strategic enterprise asset to drive innovation and expand revenue and market opportunities.

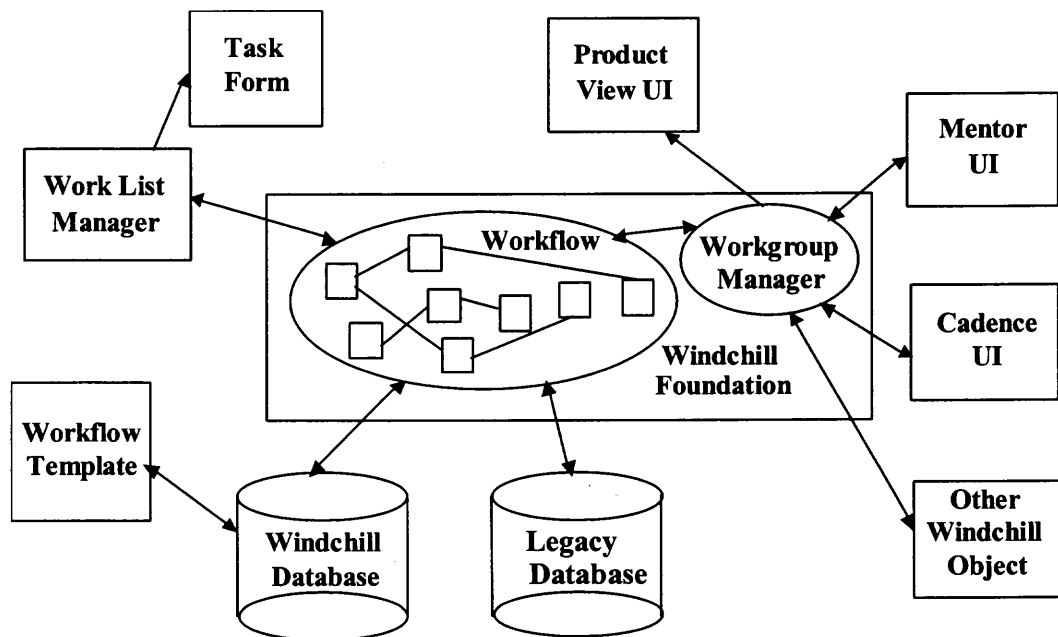
At the same time, Windchill also support symmetric e-Business through RosettaNet model. This is called federation. As a result, users can automate symmetric RosettaNet processes within current internal and external processes. As described in the last section, the power of RosettaNet comes with process integration. Windchill provides external and internal workflow integration, blending external and internal workflow into a seamless e-Business environment. In this environment, for example, one OEM could initiate PIP to notify distributors of a stage change of a product, or customers can notify manufacturer of a demand change of a product.

The architecture of Windchill balances Web-portal structure with federated process integration. The web native feature is scalable across the globe, and the federation environment can only allow those relevant data to be accessed by other partners outside the firewall domain. Therefore, Windchill system can deliver a full-featured e-Business environment for collaborative product development including data management, revision control, automatic notification, security, workflow and back-end integration.

The Windchill CPC addresses three problems that e-Business is inherently able to tackle over traditional business model: process integration, data management, and collaborative design environment. The main components of the Windchill CPC in the Windchill collaborative Design Environment are shown in Figure 2.6 which is adapted from the Windchill white paper [PTC, 2001].

The windchill CPC is built upon a set of core functionality called Windchill Foundation in which Workflow is the key element. The Workflow is a process definition and management software engine designed to capture and drive organization behavior. It is coupled with product data across the development cycle, and provides both structured and ad-hoc method for tasks and events. Automatic notification, via a specific Windchill Work list Manager, deliver the right information at the right time in the right format to the right participant.

The Workflow module is supported by a Windchill database which is connected to a Workflow Process Template module. The Workflow can also access Legacy databases residing on numerous local servers and individual PCs across the organization. The data and document management are enabled by Workgroup Manager. The end user only needs to subscribe specific Windchill Objects for certain tasks. The Workgroup



**Figure 2.6** The Windchill Collaborative Design Environment

Manager associates data files to the appropriate Windchill Objects. As a result, relevant product data is visible throughout the enterprise to any appropriate participants.

## **2.5 System Analysis and Decision-making**

Systems analysis provides a variety of analytical tools, design methods and evaluative techniques to aid in decision-making processes. In science and engineering, reducing complex real-world systems into precise mathematical models is always the main trend.

Analytical approaches using deterministic model became one of the most important fields in science and engineering in the last century. Unfortunately, real world situation are often not so deterministic. To deal with imprecision and uncertainty, concepts and techniques of probability theory was developed and employed. Around the same time as the development of chaos theory to handle non-linear dynamic systems in physics and mathematics, fuzzy set theory was developed in 1965 by Zadeh [Zadeh, 1965]. Since then it has been applied to the field of system analysis, engineering design, management science, control theory, statistics and many other fields. In this section, a brief review about the theoretical bases and applications about the fuzzy decision-making in the system analysis is given. Note that fuzzy set theory is a theory of graded concepts (a matter of degree), but not a theory of chance. Therefore, figures and numerical tables are considered paramount in the study in fuzzy set theory.

Making decision is often very important in engineering design and system analysis. A major concern is that almost all decision problems have multiple, usually conflicting, criteria. Research on how to solve such problems has been enormous. Methodologies appear in professional journals of different disciplines. A comprehensive literature survey

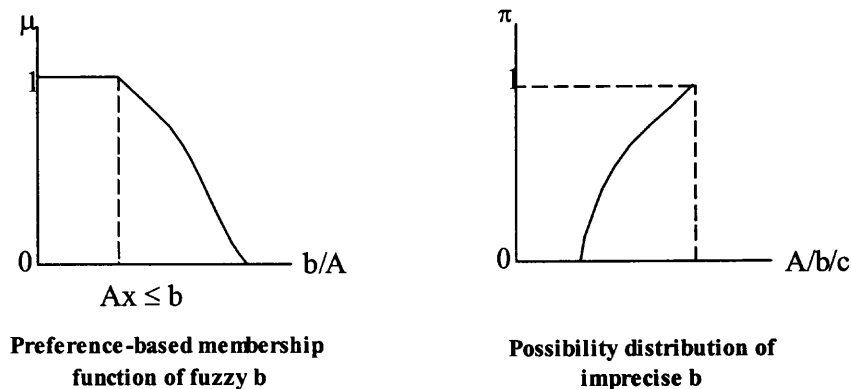
on this area is shown in [Lai and Hwang, 1994]. Multiple Objective Decision Making (MODM) is dealing with problems not associated with predetermined alternatives. The Decision maker's primary concern is to design a "most" promising alternative with respect to limited resource.

Symbolically, a general linear MODM problem with  $K$  objectives may be stated as:

$$\begin{aligned} \text{Max/min } f_k(C_k, \mathbf{x}) &= C_k \mathbf{x}, k = 1, 2, \dots, K \\ \text{s.t. } g(A, \mathbf{x}) &= A\mathbf{x} \leq \mathbf{b} \text{ and } \mathbf{x} \geq 0 \end{aligned} \quad (2.15)$$

where  $C_k = (c_{k1}, c_{k2}, \dots, c_{kn})$  is the vector of cost coefficients of  $k$ -th objective function and  $\mathbf{b} = (b_1, b_2, \dots, b_m)^T$  is the vector of total resource available. The  $\mathbf{x} = (x_1, x_2, \dots, x_n)^T$  is the vector of decision variables, and  $A = [a_{ij}]_{m \times n}$  is the matrix of technical coefficients.

If the input data (of  $C$ ,  $\mathbf{b}$  and  $A$ ) are fuzzy or imprecise because of incomplete or non-obtainable information, the conventional probability theory may not be a correct way to model these imprecision. For example, with the assumption of normal distribution, negative values of  $b_i/a_{ij}$  become probable, which is counter-intuitive and incorrect. Fuzzy set theory, on the other hand, provides better tools to represent those fuzzy imprecise data. To formulate these fuzzy/imprecise numbers, membership functions or possibility



**Figure 2.7** Membership Function and Possibility Function

distributions (depend on specific problems) can be used. Figure 2.7 is a form of membership function and possibility function.

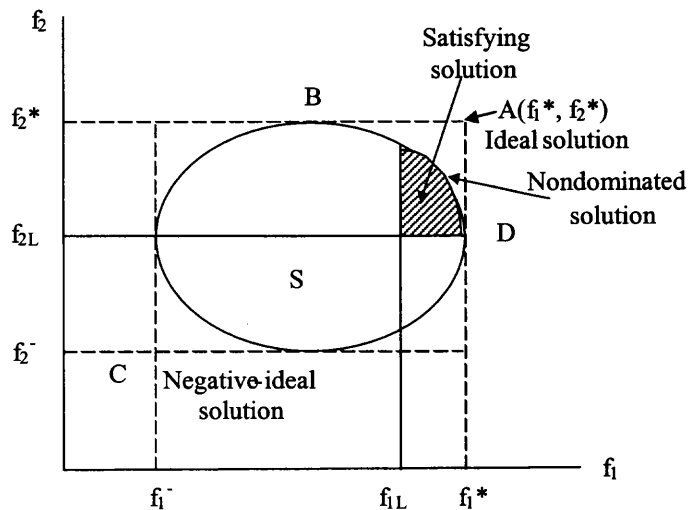
Usually the grade of membership function indicates a subjective degree of satisfaction within given tolerances. On the other hand, the grade of possibility indicates the subjective or objective degree of the occurrence of an event. It is important to realize this distinction. Non-linear functions such as exponential, power, hyperbolic, inverse hyperbolic may be also adopted as membership functions.

The solutions to MODM include optimal solution, positive-ideal solution, negative-ideal solution, and non-dominated solution. For a general form of MODM problem as shown in (2.15), The MODM solutions are classified as follows (see Figure 2.8).

$$\max/\min [f_1(x), f_2(x), \dots, f_k(x)]$$

$$\text{s.t. } x \in X = \{x \mid g_s(x) \{ \geq, =, \leq \} 0, s = 1, 2, \dots, m\}$$

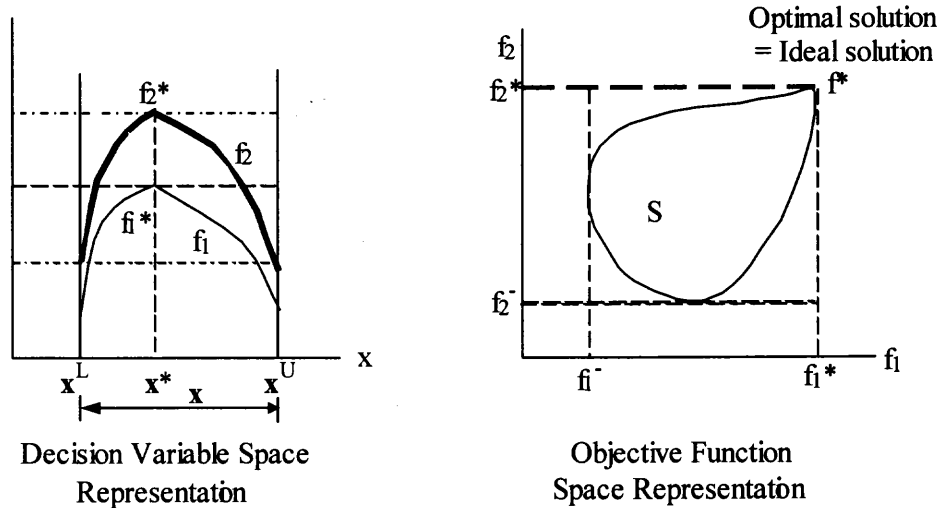
Note: all functions  $f_k(x)$  and  $g_s(x)$  can be linear or non-linear. (2.15)



**Figure 2.8** MODM Solutions in the Objective Function Space



An Optimal Solution to a MODM is one which results in the optimal value of each objective functions simultaneously. Figure 2.9 illustrates an optimal solution for the case of one decision variable and two objective functions. In the decision variable space representation, the feasible space is between the upper limit  $x^U$  and the lower limit  $x^L$ . The two objectives,  $f_1(x)$  and  $f_2(x)$ , are at the maximum simultaneously when  $x = x^*$ . In objective function space representation, the optimal solution is located within the boundary of the feasible space  $S$ . There is usually no optimal solution to a MODM problem because of conflicting objectives.



**Figure 2.9** An Optimal Solution of a Maximum Problem

A Positive-Ideal Solution is one that optimizes each objective function simultaneously, like the point A in Figure 2.6. A Negative-Ideal Solution is one that results the negative optimization value simultaneously. The Nondominated Solution is a feasible solution that there exists no other feasible solution that will yield an improvement in one objective without causing a degradation in at least one other objective. In general, the

number of nondominated solution is quite large, so the decision maker must make a final selection of a preferred solution or satisfying solution by using other criteria.

Methods for solving MODM problems have been systematically reviewed in [Hwang and Masud, 1979]. There are goal programming, utility function method, adaptive search method, etc. For fuzzy MODM problems, many fuzzy programming techniques have been developed in the last decades. The methods include Max-Min approach [Zimmermann, 1978], parametric approach [Chanas, 1989], weighted additive model [Lai and Hwang, 1992], etc.

## **CHAPTER 3**

### **RESEARCH ISSUES AND APPROACHES**

#### **3.1 Initial Lifecycle Environmental Study of the Impact of E-Business**

E-Business is still in its infancy and its impact on the environment is uncertain and difficult to quantify with any degree of rigor or level of confidence — the data is incomplete and the vision is still evolving. To overcome some of these limitations, the first step is based on lifecycle concept, and draws information from a variety of sources and case studies and attempts to examine the environmental impacts of e-Business by constructing bounding scenarios and concentrating on a specific product. The lifecycle environmental study identifies specific changes that may occur to each of the product lifecycle stages and quantifies these impacts using traditional lifecycle assessment tools and methodologies.

Since the real scope and depth of future changes are uncertain, two scenarios are postulated and modeled. The first scenario envisions only modest changes with limited impact primarily on the packaging, distribution and delivery stages—typical of today's B2C commerce. The second one is more aggressive encompassing significant changes to traditional production systems, supply-chain relationships, retail outlets, consumer behavior, reverse logistics, and recovery/reuse/recycling infrastructure and resale marketing. It accounts for extensive B2B commerce approaching a virtual enterprise operation and coordinating end-of-life product management and recovery strategies within the enterprise. Comparisons are made using the traditional business model as a baseline.

Following the traditional Society of Environmental Toxicology and Chemistry (SETAC) methodology, the product lifecycle includes several stages from raw material extraction and feedstock synthesis to production, packaging, distribution, use, and end-of-life disposition. The lifecycle study identifies and evaluates product material usage, energy consumption, and environmental burdens during each stage of the product lifecycle. For the purpose of comparison, the design of the product remains fixed as the baseline for each scenario, and the study focuses on the process and business practice changes associated with e-Business and their impact on the environment.

The baseline is the traditional commerce model for desktop computers. The manufacturer predicts demand based upon previous sales data, works with a loosely integrated supply chain to build large lot sizes of “typical” machine configurations, and warehouses finished products waiting to ship on order to an intermediary’s warehouse who then ships to the retailer’s store. Traditional purchasers are assumed to do comparative shopping at a couple of standard electronics/computer retail stores, buy an available computer that most closely fits their needs, and bring the computer home in their automobile. The total warehousing time along the value chain to final purchase is approximately two months [Wyckoff and Colecchia, 1999].

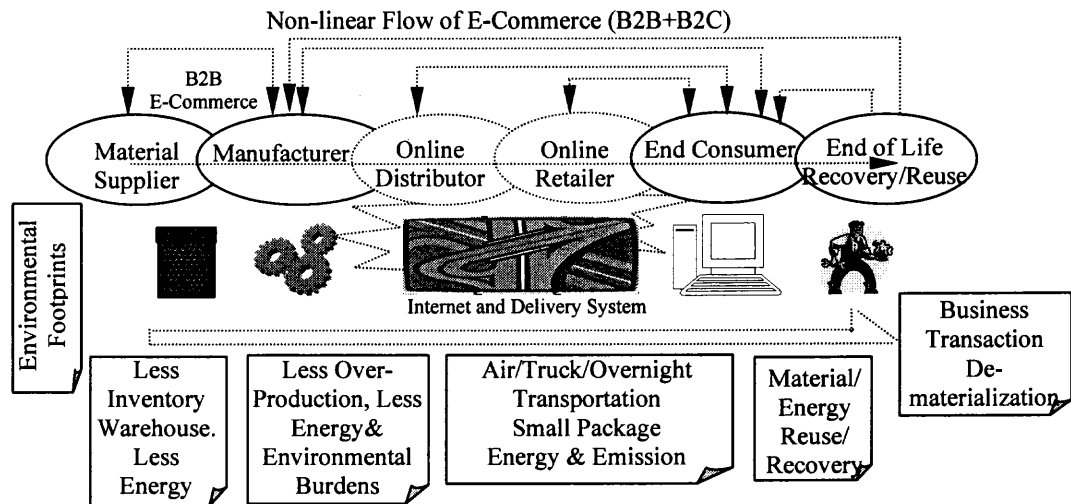
The *moderate scenario* reflects modest changes to traditional customer/business patterns representing those typical of today’s B2C commerce. The buyer visits a merchant web site, configures the desktop computer as desired, makes the purchase via electronic payment (i.e., credit card), and specifies shipping preference by air express or surface delivery (both delivery options are modeled). A back-end database keeps track of customer information and routes the order to the manufacturer (note: manufacturer and

merchant could be same organization), traditional production and procurement procedures are followed to produce the “built-to-order” product. The finished product is then shipped to the distribution (or intermediary’s) warehouse by truck then drop shipped directly to the customer according to the delivery option specified.

The *aggressive scenario* uses the same web-based B2C buyer front-end and delivery stage as the first scenario, but utilizes the customer information and product configuration data to drive a web-enabled B2B system to procure materials and components, expedite production, assure order correctness, and coordinate shipment to the customer using a well-planned, efficient delivery system. During the product usage stage, customers can logon to the company’s web site to find service information or technical support. In addition, end-of-life management of the product is integrated into the system. When the product becomes out-dated or obsolete, the customer can either resell it online using one of the existing auction sites or contact the manufacturer or a local demanufacturing facility. The use of electronic product tags and “garage sale” web sites will greatly facilitate reuse and resale [Riley and Thomas, 2000]. Collecting discarded products from the consumer may be coordinated with existing package delivery operations to improve collection efficiency and reduce energy usage. This scenario assumes recovery and reuse of all components and basic materials through disassembly and shredder operations.

The lifecycle of a product begins from material extraction/synthesize and product design. The product design and feedstock materials are assumed to remain the same even though e-Business technology may allow for more efficient product innovation through closer collaboration of value chain [Margherio, 1998]. Figure 3.1 illustrates the

interconnected nature of the e-Business process and its direct impact on product lifecycle stages.



**Figure 3.1** Illustration of Impacts of E-Business on Product Lifecycle Stages

#### *A. Material Extraction and Synthesis*

This stage refers to the order of raw material and components from suppliers. E-Business technology can facilitate a company to put its supply chain onto the Internet using advanced supply chain management software. The so-called “streamlining purchases via the Internet” could save the company a lot and can bring about environmental benefits.

The impacts come from five factors:

- Reduced inventory saving energy (and associated electric power generation emissions) required for warehouse construction and operation.
- Reduced mistaken orders and over-production saving material, energy and environmental burdens.
- Reduced materials such as office paper, catalogs, and manuals saving material consumption.

- Reduced transportation efficiency due to just-in-time supply increasing energy and associated environmental burden. Well-planned logistics and “spot marketing” of underutilized freight space may reduce this negative impact.
- Improved utilization of production capacity for suppliers leading to reduce production space with associated savings in construction and operation.

E-Business can reduce inventory, storage space and energy, and potential waste of over-purchased materials. The energy consumption for commercial warehouse is 6.4 KWh per square foot [EIA, 1998].

#### *B. Production: Component Suppliers & Assembly*

With e-Business, manufacturers can adjust production cycles to match fluctuations in consumer demand and inventory levels. In a “build-to-order” process, trade-offs exist between production efficiency of mass production lines and flexible, just-in-time techniques. The environmental impact of these production techniques is difficult to quantify and is omitted in this initial study. The environmental impact included in this stage is similar to that for raw material suppliers:

- Reduced mistaken orders and over production saving material, energy and transportation.
- Reduced inventory and warehouse space saving energy and construction.
- Reduced transportation efficiency due to just-in-time delivery of components thereby increasing energy and associated environmental burden.
- Improved utilization of production space.

### *C. Package and distribution*

In this stage, products are typically packaged and placed in lot sizes, skidded and wrapped for warehousing onsite or at an intermediate distribution facility. If individual products are shipped directly to the customer, secondary packaging should not be needed, thereby, saving materials such as cardboard paper and plastic. Shippers themselves have an incentive to reduce one of their principal costs, post-consumer recycled shipping materials and reusable package will be vastly used [Romm, 1999]. If there is a significant growth in the delivery of packages to residences, it seems likely that more retailers and shippers will explore reusable packaging.

The most significant consideration affecting environmental impact at this lifecycle stage is the transportation mode selected to the product from the manufacturer to the customer. An earlier LCA study of textile products has shown that if overnight air express is used as opposed to standard trucking, then transportation energy becomes a significant portion of the lifecycle energy consumption of the product. In general, however, some of the distribution impact is offset if the product is shipped directly from the manufacturer to the customer bypassing at least one stage of bulk shipment to the retailer's warehouse.

### *D. Marketing and Sale*

While not typically considered in LCA as one of the lifecycle stages of the product, marketing and sales becomes important for two primary reasons: (1) Web-based marketing of products reduces or even eliminates the need for printed catalogs and traditional advertising materials. This will save consumption of paper, printing cost and distribution costs. It is estimated that e-Business may lead to 15% reduction in paper for



catalogs [Young and Vanderburg, 1994]. (2) Shopping on the web may lead to a reduced need for retail store space for display and inventory. Some estimate that the potential exists for significant changes in future land-use for malls and shopping centers, predicting future commercial retail building will decline to 12.5% [Cohen, 1999]. Both of which can bring about large resource and energy savings.

#### *E. Product delivery*

Although a non-traditional lifecycle stage, product delivery will be directly affected by e-Business. This stage is the final transportation link delivering the product from an intermediate warehouse or transfer point (for air express or small package shipments) to the customer. If more efficient package delivery by truck could replace at least in part the inefficient personal driving to malls, supermarkets, bookstores and the like, then the environmental impact of small package direct delivery would be offset.

#### *F. Use*

The product is the same for each of the e-Business scenarios; consequently, the use stage generates no difference. However, there may be significant changes in the web-based technical support and maintenance services offered to customers. The cyber-home with intranets and major appliances connected to the web are now being developed and may have major impact in the future.

#### *G. End-of-Life Recovery & Reuse for Multi-lifecycle*

Considerable attention has been given to recovery and reuse of discarded products through demanufacturing. The potential exists to expand the collection infrastructure and extend the secondary markets for reuse and material recovery through various Internet-enabled outlets. Today, many demanufacturers are web-active conducting resale via their

own sites and commercial auction sites. In addition, e-Business can help manufacturers track the location and condition of the products. Through coordination of delivery, the logistics system can also function as reverse logistics, making discarded product collection more efficient. Frequently, high collection costs prohibit recycling and reuse of materials; consequently, e-Business may lead to greater recovery at lower cost.

A typical desktop computer system is used as an example to do a lifecycle environmental study. Table 3.1 gives the material inventory for the product and the energy intensity associated with raw material extraction and synthesis. The two future scenarios are used to establish the type of changes which are expected to occur in selling, producing and delivering the desktop computer to an individual customer. Various sources of data, many not sector or product specific, were used to study the material, energy and environmental impact of these scenarios and are referenced in this and previous sections of the paper. In addition, several assumptions, as stated in previous texts, have been made in order to quantify and help to understand which lifecycle stages are most important and need further detailed consideration and evaluation.

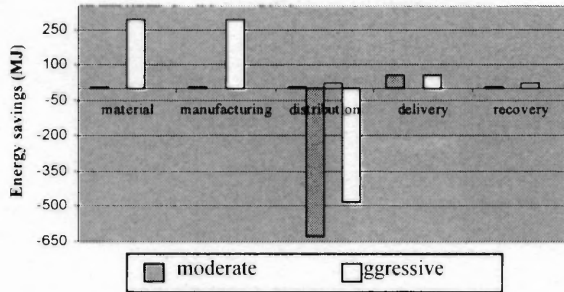
**Table 3.1** Material/Energy Inventory of  
Desktop Computer, Monitor, Keyboard & Mouse

Material	Weight (kg)	Energy Intensity (MJ/kg)	Energy (MJ)
Plastic	7.3	120	876
CRT Glass	9.9	15	148
Aluminum	4.5	300	1350
Steel	6.5	23	149
Copper	2.2	150	330
Circuit Boards	0.5	120	60
Other	<1		
<b>Total</b>			<b>2913</b>

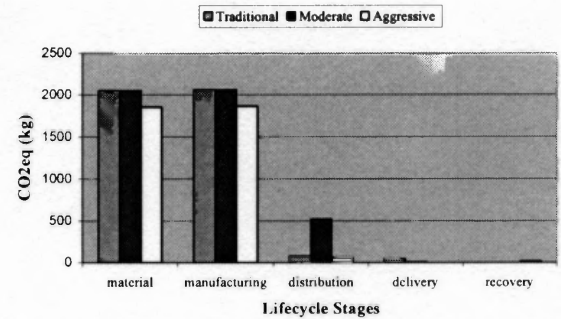
Table 3.2 gives the detailed analysis assumptions and results in terms of energy savings due to e-Business over lifecycle stages. Figure 3.2 indicates the energy saving and Figure 3.3 is the CO<sub>2</sub> equivalent emission saving over lifecycle stages.

**Table 3.2 Energy Saving due to E-Business over Product Lifecycle**

	Traditional Model Energy Consumption (MJ)	Major Assumption	Energy Saving in Aggressive Scenario (MJ)		Energy Saving in Moderate Scenario (MJ)	
<b>Material</b>	2913	20% reduction of over/mistaken production, 50% of which can be reused. The material saving is 10%.	291		0	
<b>Manufacturing</b>	Energy use for warehouse floor space for one product .2	1. 20% reduction of inventory warehouse 2. Energy intensity is 6.4kWh/ft <sup>2</sup> for warehouse 3. 1 unit of computer is 3*2*2 ft <sup>3</sup> , 1 stack 6*6*6 ft <sup>3</sup> contains 18 units, 4 levels high of stack in one column. Warehouse turnover is 6 times/year. The warehouse floor space for one computer is 0.083ft <sup>2</sup> /unit-year.	0.4		0	
	Production energy 2920	20% reduction of mistaken/over production due to mistaken order, 50% of which can be reused. The production energy saving is 10%.	292		0	
<b>Distribution</b>	Transportation energy from manufacturer to distributor, and from distributor to retailer 105	1. Transportation from manufacturer to distributor 1000 miles, from distributor to retailer 100 miles. 2. Energy intensity for truck transportation is 3MJ/ton-mile. 3. Energy intensity for air transportation is 21MJ/ton-mile. 4. 20% energy saving in aggressive scenario due to reduction of mistaken order. 5. Traditional model always uses truck, but e-commerce has 2 modes, air (overnight) and truck.	Air -482	Truck 21	Air -629	Truck 0
	Energy use in retail building for one unit 4	1. There is 12.5% reduction of wholesale and retail building. 2. Energy intensity for retail building 12 kWh/ft <sup>2</sup> .	0.5		0.5	
<b>Delivery</b>	Transportation energy from retail building to home, one round-trip-shopping 60	1. There is 20% transportation energy saving in aggressive scenario due to reduction of mistaken order. 2. Average shopping length is 11.2 mile. 3. Car energy intensity is 5.4 MJ/mile. 4. 20 miles from local delivery site to home.	58		57	
<b>Reuse/recovery</b>	No energy is recovered 0	1. 50% of End-Of-Life(EOL) computers can be reused. 2. 50% of EOL computers can be recovered. 3. Part shredding needs 24 MJ/kg for typical electronic products. 4. Plastics contain significant amount of embedded energy, 111MJ/kg energy.	21		0	
<b>Total Energy and Saving</b>	6004		181	684	-572	58
<b>Energy Saving Percentage</b>			3%	11%	-9%	1%



**Figure 3.2** Energy Savings over Lifecycle



**Figure 3.3** CO2 Equivalent Emission Savings

The environmental lifecycle study shows that the emerging e-Business does have environmental impact in terms of resource, energy and environmental burdens. The study indicates that just selling products over the Internet in a single B2C practice will result in negative impact on the environment up to 10%, especially if packages are shipped air express. However, if the full power of web-enabled commerce is implemented, by integrating B2B and B2C, then energy savings and environment benefits, exceeding 10% improvement over today's business practices, are achievable. The detailed results should be considered as approximations and insights for further study as opposed to definitive conclusions; however, it is necessary to begin to quantify these impacts in order to begin to ask the right questions and guide future business practice along a pathway towards sustainability.

### 3.2 Research Issues and Approaches

The initial study looks into the impact of e-Business by combining product lifecycle assessment and business scenario assumption. The per-product-based analysis and comparison on different business scenarios have given insights of environmental impacts

of e-Business and tradeoffs between business objectives and environment issues. It is demonstrated that fully-integrated B2B+B2C system and seamlessly connected supply chain are the key to achieve sustainability as well as obtain better business goals.

In order to integrate the e-Business strategy into multi-lifecycle production systems, a number of **research issues** are being addressed and explored. They are:

- Major environmental impacts of e-Business and methods for quantitatively analyzing these impacts have to be identified. The environmental impacts of e-Business are influenced by energy consumption, paper use, de-materialization, networked supply chain, changed logistic, etc. Environmental lifecycle based systematic approaches are needed to quantify the impacts.
- An appropriate sustainability metric is needed to measure the environmental aspects of business processes and supply chains.
- Suitable mathematical methods need to be studied and applied to deal with the incomplete and uncertain nature of data associated with e-Business processes.
- Network modeling methods of e-supply chain must be examined. Based on the observation of our previous study, the significant change e-Business brings to the traditional production system is that the supply chain relationship is being transferred from sequential to networked structure. In addition, the information network plays an important role in data sharing, partner selection, supply chain cost, time, and environmental performance. The e-Business network model will be established to analyze the system performance. An optimization solution method will also be provided to determine the “best” product supply chain system and to guide the design

and optimization. The dynamics and robustness of the system also need to be investigated.

- An e-Business application for virtual enterprise environmental management through out the multi-lifecycle production system deserves to be developed and prepared to integrated e-Business technology to bring together supply chain partners and collaboratively manage environment-related data across the enterprise boundary and finally achieve sustainable improvement.

To deal with the above research issues, the corresponding **research approaches** are:

- Scenario development. Discover the major influences and constraints e-Business system potentially imposes to the multi-lifecycle and environmental performance of individual product. Draw the boundary of the problems within product multi-lifecycle perspective and e-Business strategies.
- Analytical modeling and analysis. Mathematical formulation of hyper-network structure of e-Business production systems will be established. The characteristics and relationships of network nodes and links will be formulated to provide a theoretical model of the e-Business process.
- Fuzzy multi-objective optimization: fuzzy logic theory will be extended and applied to solve the multi-objective optimization problem based on the network model.
- System simulation: Discrete event simulation will be used to numerically study the robustness of the system.
- Case study verification: The results will be verified by case studies to check the performance of the established theoretical model.
- Ontology based knowledge management methodology.

- E-Business system architecture and implementation methods.

### **3.3 Research and Development Tasks**

Initial research in this dissertation showed that e-Business does have environmental impact in terms of resource, energy and environmental burdens as well as cost, productivity, efficiency, and other business parameters to production systems. This dissertation is aimed to provide a novel framework to evaluate, design, analyze, and deploy e-Business integrated multi-lifecycle production systems. The framework addresses four characteristics including environmental performance metric; modeling and analyzing methodology for the sustainable e-Business integrated production systems; Solution methodology for the generic model; and a system prototype to leverage currently developing technologies to achieve scalable sustainable management. There is growing consensus that in the future all sustainability decisions in product design, packaging, labeling, supplier selection, transportation carrier selection, etc. must be made collaboratively across the virtual enterprises boundaries on a Internet web-enable platform.

The major research and development tasks involved in this dissertation include:

- Environmental performance metric evaluation and implementation to justify the scientific base, usability, availability and applicability of major environmental performance metrics;
- Analytical modeling and analysis methodology for the e-supply chain network to provide a generic frame work for the e-Business integrated production systems;

- Develop an optimization method and simulation model for the e-Business integrated production systems to solve problems of partner selection, performance tradeoff, network configuration and dynamic performance distribution.
- Design and prototype a Scalable Enterprise Environmental Management System, a configurable web-enabled portal, to integrate sustainability seamlessly into everyday corporate business practices and strategic decision-making.



## **CHAPTER 4**

### **ENVIRONMENTAL PERFORMANCE METRICS**

In the context of design for environment (DFE) tools, it is extremely important to utilize an impact assessment technique that is unambiguous, robust, simple to use, requires minimal environmental knowledge, and yields a quantitative result. Qualitatively it is possible to comment on the seriousness of the impacts on the basis of the impact table. However, the expertise and sometimes the intuition of environment expert carrying out the evaluation play an important role. Designers and other non-experts cannot generally offer or make sense of such comments. In recent years much attention has been given to build scientific basis to environmental assessment method and to standardize environmental performance metrics. In this chapter, the well-known Eco-indicator method is introduced and applied to evaluate the environmental performance of manufacturing processes. Then a new environmental metric – the target-based universal environmental metric, Lucent Sustainability Target Metric, which is being implemented in MERC at NJIT in collaboration with the Lucent Technologies, is introduced. Then four major environmental metrics are compared and evaluated including Eco-indicator and Lucent Sustainability Target Metric. The intention of this chapter is to select an appropriate metric that can be used in our overall framework to understand and assess the environmental performance of e-Business enabled production system.

## **4.1 Application of Eco-indicator Method in Evaluating Environmental Performance of Manufacturing Processes**

The Eco-indicator 95 approach, developed by the National Reuse of Waste Research Programme and Pre Consultants of the Netherlands, is one of the most widely used environmental performance assessment tools. The work was intended to give fundamental and in-depth considerations of how people should evaluate the consequences of impairment of the environment, and how designers can search for more environmentally friendly design alternatives. In this section, the Eco-indicator approach is to be applied to evaluate the environmental performance of an evolving waste-free manufacturing process called Solid Freeform Manufacturing.

### **4.1.1 Eco-indicator Lifecycle Model for Solid Freeform Manufacturing**

Solid Freeform Manufacturing (SFM), or often referred to as Rapid Prototyping and Manufacturing (RPM), can be used not only to generate rapid prototypes for design optimization and verification but also to create production tools or directly fabricate products. This new manufacturing technology has been experiencing tremendous development and growth since its introduction a little over one decade ago. SFM has been widely adopted in aerospace and automotive industries, and is quickly becoming an important production process in electronics industry.

In view of the fast growth and wide adoption of various SFM processes, it is important to study the lifecycle performance of SFM processes, including consumption of natural resources and energy, and impact on human health and the environment, together with other process attributes such as cost, accuracy, productivity, and functionality, so that the SFM technology can become more sustainable. SFM processes have many

good environmental characteristics. The material utilization rate is much more higher (almost 100%) in material additive process adopted in SFM than in material removal process used in machining process. The waste streams are less in SFM processes than in conventional manufacturing processes such as machining. Worn tools and scraps seldom occur in SFM processes and equipment. Cutting fluids, which are the major source of hazard in machining [Sheng 1998 and Hows 1991], are not used in SFM processes. Comparing with conventional manufacturing processes, SFM processes have distinguishing features in process mechanisms, materials, energy use, etc. It is essential to look into these processes, investigating how the process variables influence the environmental consequences, and apply a systematic method to assess the process environmental performance so that these processes can be optimized with consideration of their environmental properties.

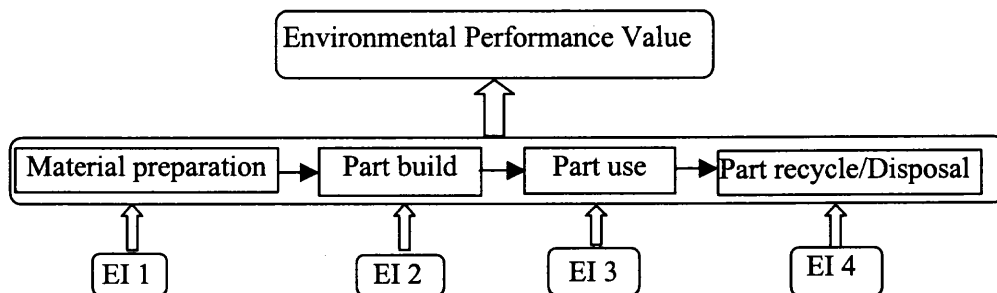
In order to assess SFM processes, the Lifecycle Analysis (LCA) Methodology is adopted, which is also the basis of Eco-indicator approach. The LCA method holistically incorporates the entire process lifecycle, including material extraction, pattern fabrication, shape replication, post processing, and material disposal. The environmental performance is evaluated, based on LCA principle and with the Eco-indicator metric.

From the lifecycle point of view, a part produced with a SFM process generally goes through the following stages: (a) inputting the building material into the system, (b) building the part layer by layer, (c) shape replication and sintering or burning (for tooling processes) and (d) post-processing. When the user finishes using the part fabricated by SFM, the part goes to the disposal stage: to be landfilled, incinerated, or recycled. While the material, part usage and part disposal are not exactly part of a process, their inclusion

provides a holistic view of the environmental performance of an SFM process. Thus, factors taken into account in process environmental performance should include the material extraction stage, energy consumption and process wastes in the fabrication and replication stages, and the disposal stage.

To evaluate the environmental performance, a process model is presented based on lifecycle concept. The steps of an SFM process can be viewed as the process lifecycle stages, and thus the environmental impact factors in all process stages can be included in this model. The model is then extended for assessment of SFM based Rapid Tooling (RT) processes.

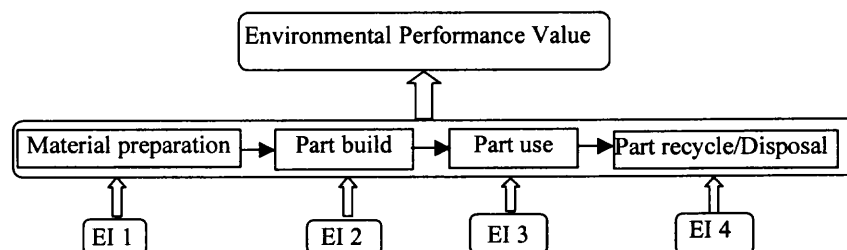
The environmental performance process model is shown in Figure 6.1. In the process model, the overall environmental performance value is the sum of the environmental performance values of the various life stages, each of which has one or more corresponding environmental impacts. The environmental performance of a process is evaluated by defining the lifecycle stages of the process, identifying the individual environmental impact factors, obtaining the environmental impact values, and summing these values.



**Figure 4.1** Lifecycle Model of SFM Process

Figure 4.1 shows that the lifecycle of a process can be divided into  $n$  stages. For SFM process, there are generally four lifecycle stages: 1) material preparation, 2) part build, 3) part use, and 4) part disposal. Environmental impacts that occur in each lifecycle stage are identified as follows. In the material preparation stage, the environmental impact is material extraction & production. During the part building stage, the main environmental impact is energy consumption. Process residues, such as cutting fluids, which exist and have severe environmental consequences in the part cutting stage of machining process, are rare in most of SFM processes, and can be ignored in evaluation. Material toxicity may cause negative impact to human health in the part use stage. Finally in the disposal stage, the part can be landfilled, incinerated or recycled. Different disposal methods have different environmental impacts.

The model presented above is the basic process model for SFM processes. It can be extended to SFM based Rapid Tooling (RT) processes. Here indirect RT processes is considered, in these processes, a few additional steps are needed to duplicate the shape of the pattern made by SFM, and then sintering or burning the duplicate part is needed to get the tool. These steps are needed for the mold creation, and they can be seen in, for example, 3D Keltool [Raetz ,1998] and the rapid tooling process that integrates SFM with electroforming [Yang and Leu, 1999]. The extended process model for indirect RT



**Figure 4.2** Lifecycle Environmental Performance Model of Indirect RT Process

processes is shown in Figure 4.2. The environmental impacts corresponding to every lifecycle stage need to be identified. In the Figure 4.2, EI1 is for material extraction & production. EI2 is for energy consumption. EI3 includes material consumption, energy consumption and process residue. And EI4 results from the tool disposal stage where the tool can be landfilled, incinerated or recycled.

To summarize, the process model deals with the process complexity by dividing a process into several life stages. The environmental impact index provides a quantitative measure of environmental impact for each stage of the process. The implementation of this evaluation method can be carried out as follows. First, every process stage and the elements of its associated environmental impact factors are identified. Then, the value of eco-indicator is obtained for each environmental impact factor. Finally, the environmental index values for all process stages are summed up to generate the total environmental performance value.

#### **4.1.2 Eco-indicator 95 Assessment of SLA Process and Tooling Process**

Eco-indicator method is used to assess the StereoLithography (SLA) process and two rapid tooling processes that utilize SLA to build patterns: 3D System's Keltool process [Raetz, 1999] and an SFM based electroforming process [Yang and Leu, 1999]. SLA is one of the most widely used SFM processes today. It is a fabrication process that builds a part by controlling a laser beam to selectively cure liquid photo-polymer layer by layer. 3DKeltool and electroforming tooling processes are two rapid tooling processes that utilize SLA to quickly create highly detailed and accurate patterns.

For the SLA process, the process parameters that influence the environmental performance are identified as follows:

M: Material used (cm<sup>3</sup>),

V: Scanning speed (mm/sec),

W: Line width (mm),

T: Layer thickness (mm),

P: Power rate of the equipment (kW),

k: Process time delay between layers.

The scanning speed can be estimated using the following equation [4]:

$$V = \sqrt{\frac{2}{\pi} \left[ \frac{P_L}{W_0 E_c} \right]} \exp \left[ -\frac{T}{D} \right] \quad (4.1)$$

in which  $P_L$  is the laser power,  $W_0$  is the half line width,  $E_c$  is the critical laser exposure, and  $D$  is a material constant of the polymer. The Process Productivity (PP) and the Energy Consumption Rate (ECR) for each unit volume of material processed can be calculated as follows:

$$PP \text{ (cm}^3/\text{h)} = V \times W \times T \times k \times 3600 / 10^3 \quad (4.2)$$

and

$$ECR \text{ (kWh/cm}^3\text{)} = P / PP \quad (4.3)$$

### ***Assessment of SLA Process***

The building material in the SLA process is photopolymeric resin. The process is evaluated with three models of the equipment, SLA-250, SLA-3500, and SLA-5000. The manufacturer's recommended process parameter values are used in the assessment. First the environmental impact due to energy consumption in the process needs to be obtained. Here equation (4.1) is used to calculate the process scanning speed  $V$ , then equation (4.2)

and (4.3) are used to estimate the process energy consumption rate (ECR). Finally the environmental impact of energy consumption is obtained. Table 4.1 shows the result representing the environmental impact of the energy used to process one  $\text{cm}^3$  of epoxy resin. Because SLA-5000 has the highest laser power, resulting in the highest scanning speed, and the least ECR. While for SLA-3500 and SLA-250, the former one has higher scanning speed but also higher power rate of equipment than the later one. The result gives that the SLA-250 has less ECR than SLA-3500.

Table 4.2 shows the environmental indicators of the environmental impact occurring in each lifecycle stage of the process, and the environmental performance value representing the total environmental impact. The environmental impacts in various lifecycle stage are identified and the corresponding index values are obtained from the Eco-indicator database, and converted to the values representing effect of one  $\text{cm}^3$  of specific material. Since there are usually two alternatives of disposal, two values are given for the disposal stage. The value before “/” is for disposal using landfill and the one after “/” is for disposal using incineration.

**Table 4.1** Environmental Impact Due to Energy Use of SLA Process

	<i>SLA-250</i>	<i>SLA-3500</i>	<i>SLA-5000</i>
<i>V (mm/sec)</i>	340	1000	2000
<i>W (mm)</i>	0.25	0.25	0.25
<i>T (mm)</i>	0.15	0.1	0.1
<i>k</i>	0.7	0.7	0.7
<i>P (kW)</i>	1.2	3	3
<i>PP (cm<sup>3</sup>/h)</i>	32.13	63.00	126.00
<i>ECR (kWh/cm<sup>3</sup>)</i>	0.037	0.048	0.024
<i>Eco-indicator (kWh) [8]</i>	0.57	0.57	0.57
<i>Environmental Impact</i>	0.021	0.027	0.014

$$\text{Environmental Impact} = \text{ECR} \times \text{Eco-indicator}$$



**Table 4.2** Environmental Impact of SLA Process

<i>Process</i> <i>SLA</i>	<i>Project</i> <i>Environmental effect for 1 cm<sup>3</sup> material processed</i>		
<i>Equipment</i> <i>SLA-250, SLA-3500, SLA-5000</i>	<i>Environmental impact index</i> <i>Eco-indicator</i>		
	<i>SLA-250</i>	<i>SLA-3500</i>	<i>SLA-5000</i>
<b>Material preparation</b>			
• <i>SLA 5170 Epoxy resin</i>	0.0104	0.0104	0.0104
<b>Part build</b>			
• <i>Energy use</i>	0.021	0.027	0.014
<b>Disposal</b>			
• <i>Landfill/Incineration</i>	4.03e-5/0.0021	4.03e-5/0.0021	4.03e-5/0.0021
<b>Total Impact</b>	0.0314/0.0344	0.0374/0.0404	0.0244/0.0265

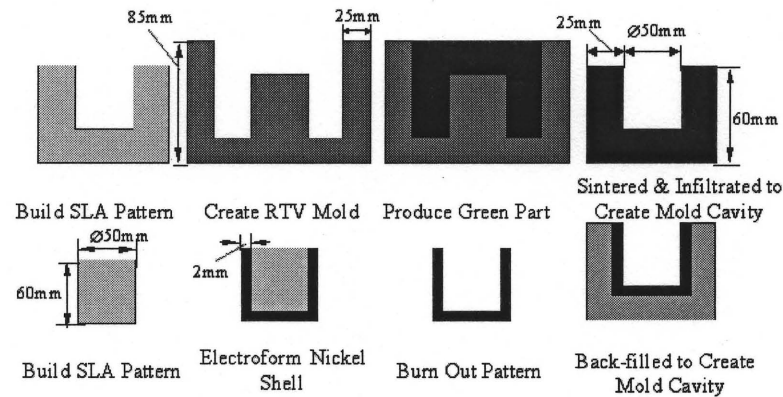
### ***Assessment of Two Rapid Tooling Processes***

3D KelTool and the SFM based electroforming process are two indirect rapid tooling processes. Indirect tooling requires a master pattern built by SFM process. At least one intermediate step is needed. The intermediate steps may include shape replication and sintering or burning in the manufacture of the production tool.

3D Keltool process can be used to rapidly create injection molds or die casting inserts. It begins with an SLA master pattern. The pattern is used to produce an RTV silicone rubber mold. Once the RTV mold is produced, it is then filled with a mix of tooling steel powder, tungsten carbide powder and epoxy binder. After this material has cured in the mold, this “green part” is sintered in a hydrogen-reduction furnace and the binder material is burning off. The final step is to infiltrate the sintered part with copper.

The SFM based electroforming process can be used to produce EDM electrodes, molds and dies. First, an SLA pattern is fabricated. Then the pattern is metalized and electroformed in nickel or copper solution. When the desired thickness of metal shell is reached, the SLA pattern is removed by burning out. Finally, the metal shell is backed with other materials to form the production tool. Figure 4.3 illustrates the concepts of

these two indirect tooling processes. When a cylindrical metal mold cavity is required to be manufactured, both 3D Keltool and SFM-Electroforming processes have this function, although they differ from each other in the type and amount of materials use and specific intermediate steps.



**Figure 4.3** Indirect Tooling Process

Unlike the assessment of SFM process in which only unit volume of material is considered, In evaluating indirect RT processes, the volume of final tool should be accounted in order to estimate the amount of intermediate material consumed. In the following assessment, the cylindrical mold cavity in figure 6.3 is used as an example with dimensions of diameter 50mm and height 60mm.

In the pattern building stage, the assessment result for the SLA process is used. Assume the two RT processes both use SLA 250 to fabricate the master pattern. The environmental impact for unit volume ( $\text{cm}^3$ ) SLA material consumed is 0.0104. Since 3D Keltool uses the negative pattern and SFM-Electroforming uses positive pattern, different volumes of materials used yield different impact values for this stage. Here it is assumed that the dimensions of the mold is 100mm diameter and 90mm height. The volume of material used by the 3D Keltool process to build the pattern is  $589.4\text{cm}^3$  and that used by

the SFM-Electroforming process is  $117.2\text{cm}^3$ . In the mold creation stage, material consumption, and energy consumption during the sintering or burning step should be considered. In this stage, 3D Keltool typically consumes silicone rubber to build an RTV mold, uses mixed steel powder and epoxy binder to create the green part, and uses copper infiltration to create the final solid mold. The environmental indices for unit volume ( $\text{cm}^3$ ) of silicone rubber, mixed steel, epoxy binder and copper are 0.0101, 0.133, 0.0104 and 0.757 respectively. The volumes of RTV mold can be calculated. The volumes of steel and epoxy binder are 70% of 30% of the mold volume respectively. Since the void volume of mold after sintering is 30% [13], the volume of infiltrated copper should be 30% of the mold volume. Therefore the material consumption impact in this stage can be estimated based on eco-indicators and the volume of materials used in this stage. Similarly, the SFM-Electroforming process usually uses nickel to electroplate certain thickness of metal shell, and then backfills the shell with aluminum. For unit volume ( $\text{cm}^3$ ) of nickel and aluminum, the environmental indices are 0.757 and 0.0486, respectively. The nickel shell thickness is typically 2mm. So the volume of nickel and aluminum used also can be calculated. Hence the material consumption impact can be obtained in this stage for SFM-Electroforming process. The results can be seen in table 4.3.

Sintering & infiltration in the 3D Keltool process and burning off in the electroforming tooling process require energy. The energy consumption is estimated based on the melting point or burning point, the specific heat and the assumed furnace efficiency.

In the disposal stage, the 3D Keltool process produces wastes such as SLA material and silicone. The SFM-electroforming tooling process only has residue of SLA

material. If the process residues are all disposed to landfill, the environmental impact can be assessed by considering the impact indices and the volume disposed. The results are shown in table 4.3. In addition, the disposed tools can be recycled by material recovering. The mixed metal of the tool made by 3D Keltool is less preferable than laminated nickel and aluminum used in the electroforming tooling process. The impact indices for recycling unit volume ( $\text{cm}^3$ ) of mixed steel, nickel, and aluminum are -0.0226, -0.312,

**Table 4.3 Environmental Performance of RT Process**

<b>Process</b> 3D KelTool SFF based Electroforming Tooling	<b>Project</b> Environmental effect for RT processes	
<b>Base SFF process</b> SLA	<b>Environmental impact index</b> Eco-indicator	
	3D KelTool	SFF-Electroforming
<b>Pattern build</b>		
• Material use	6.13 (epoxy resin)	1.22 (epoxy resin)
• Energy use	12.38 (energy used in pattern building)	2.46 (energy used in pattern building)
<b>Mold creation</b>		
• Material use	193.7 (silicon rubber + mixed steel powder + epoxy binder + infiltrated copper)	46.21 (nickel + aluminum)
• Energy use	0.707 (energy used in sintering and infiltration processes)	0.0191 (energy used in burning off process)
<b>Disposal</b>		
• Process residues landfill	0.088 (epoxy resin + silicon rubber)	0.033 (epoxy resin)
• Material recovery	-64.49 (mixed steel + copper)	-26.67 (nickel + aluminum)
<b>Total impact</b>	148.52	23.24

and -0.035 respectively. Table 6.3 shows the assessment results for the above two indirect RT processes.

From the above assessment, it is seen that the environmental performance of a rapid tooling process depends on several factors. First, the selection of the base SFM process is an important factor. It is desirable to select an SFM process that has good environmental performance Secondly, the tooling materials, and process residues can further impact on the environmental performance due to the use of natural resources and

possible generation of process residues. Finally, the method of disposal or recovery of tool material will also influence the total environmental performance of a process.

In this section, a specific example is used to show how Eco-indicator method can be used in evaluating environmental performance. It is concluded that Eco-indicator methodology is suitable to be used to compare different product or process in terms of their environmental friendliness. It embeds lifecycle concept and gives a simple and easy-to-use tool for environmental assessment. The drawback of this metric is that it is a relative measurement, and there are always data gaps when no suitable value can be found in the Eco-indicator database.

#### **4.2 A Universal Environmental Metric Using Target-based Methodology**

Sustainability will require that products and services not be evaluated using environmental metrics that are very subjective or that allow only relative comparisons, but rather based on their relationship to the carrying capacity of the environment. It is not enough to know that reduced energy use and material content, for example, will move the economy toward sustainability; It must also be known at what level of energy and material use a specific product or service reasonably can be characterized on an absolute basis as sustainable. These are principles of the “*target*” method developed by Lucent Technologies Bell Laboratories [Dickinson, D.A., 1999]. This method provides a practical way for businesses to assess and communicate environmental performance and sustainability. Carrying capacity estimates are converted to “aspect reference levels” that are used to determine the relative indicator Resource Productivity (RP) for environmental impact and the absolute indicator Eco-Efficiency (EE) for sustainability. Most

importantly, by linking the economic contribution of a business with its effect on carrying capacity, this method provides a practical sustainability target at the firm and product level ( $EE = 100\%$ ). When achieved by individual businesses, this essentially will result in a sustainable overall economy. This approach replaces the traditional economy vs. ecology conflict with a synergy that will drive to sustainability.

#### **4.2.1 Lucent Sustainability Target Metric Methodology**

Lucent Sustainability Target Metric is a universal environmental metric developed at Lucent Technologies in collaboration with MERC at NJIT. It can be used to assess environmental performance and provide a clear indication of progress towards sustainability. It is “universal” in the sense that it possesses numerous necessary attributes, including applicability to the entire product lifecycle, compatibility with LCA methods and databases, and means for communicating with both suppliers and customers. Importantly, it provides both a relative indicator for environmental impact and an absolute indicator for sustainability. The latter links environmental and economic performance to provide a practical *target* for sustainability at the firm and product levels that will result in a sustainable economy. A brief summary and simple example of the method is included also in a previous IEEE ISEE paper on competitive advantage and sustainability [Dickinson, Mosovsky, Moribito, 2000].

Environmental Impact (*EI*) resulting from an activity, such as manufacturing a product or providing a service, is quantified by adding normalized environmental aspect levels to obtain an aggregated and dimensionless value (for selected scope: supply line, factory, customer use, full life cycle, etc.), according to the following equation:

$$EI = (A_1/A_{R1} + A_2/A_{R2} + A_3/A_{R3} + \dots + A_N/A_{RN}) \quad (4.4)$$

where:

$A_{1,2,3,\dots,N}$  = the level of each aspect, e.g., kWh/year for energy, lb/year for material consumption or waste,

$A_{R1,2,3,\dots,RN}$  = the aspect “reference level” indicating the level at which the aspect would have a “significant” environmental impact, i.e., the level at which it would become non-sustainable for an activity of given size (specified in terms of its rate of value generation).

Resource Productivity ( $RP$ ), the production rate achieved per unit of environmental impact, is then:

$$RP = \frac{P}{EI} \quad (4.5)$$

where:

$P$  = production rate, units/year

$RP$  serves as a relative indicator of environmental performance that allows for direct comparison, such as between products or alternative product designs.

Eco-Efficiency ( $EE$ ) is then defined as:

$$EE = \frac{\beta}{EI} \quad (4.6)$$

where:

$\beta$  =  $V/V_R$  (value ratio)

$V$  = value creation, e.g., revenue, the value of the product or service as established by the market.

$V_R$  = the value reference level corresponding to the aspect reference levels

$EE$  serves as an absolute indicator of sustainability. It is essentially the actual rate of value generation,  $V$ , normalized to the rate that is sustainable at the actual level of environmental impact ( $V_R \times EI$ ). It can be viewed also as the ratio of sustainable to actual impact. The product value,  $V$ , can be further adjusted to account for various social considerations.

Production rate and revenue may not yet be estimated or may be very uncertain when a product design is still in progress, and LCA databases typically do not present data in terms of rates.  $RP$  and  $EE$  can be expressed alternatively, in terms of per-product-unit quantities, by dividing numerator and denominator by production rate  $P$ :

$$RP = 1 / (A_1^*/A_{R1} + A_2^*/A_{R2} + \dots + A_N^*/A_{RN}) \quad (4.7)$$

and

$$EE = \text{Price} \times RP / V_R \quad (4.8)$$

where:  $A^* = A / P$ , the aspect quantity per product unit (e.g., kWh/unit)

Price =  $V / P$ , the revenue per product unit (market price) or value added per unit (\$/unit)

For each aspect, the reference level  $A_R$  depends on the environmental impacts (or “effects”) created by the aspect, the associated carrying capacities, and the relationship of  $V_R$  to total economic output. For each impact, the “natural carrying capacity”,  $NCC$ , minus the natural burden,  $NB$ , is the “economic carrying capacity”,  $ECC$ , i.e., that portion available to industry and commerce to support the needs of society. For each impact, part of  $ECC$  can be associated with the reference firm in the same proportion as the ratio of  $V_R$  to total global or regional economic output, depending on the geographical scale of the impact (see as Figure 4.4). This is the “Impact Reference Level”,  $I_R$ :



$$I_R (\text{Global}) = \text{ECC} (\text{Global}) \times V_R / \text{GGP} \quad (4.9)$$

or

$$I_R (\text{Regional}) = \text{ECC} (\text{Regional}) \times V_R / \text{GDP} \quad (4.10)$$

where GGP and GDP are total global and regional (e.g., national) economic product (\$/year), respectively. (Regional Impact Reference Levels can be adjusted further for specific local issues based on local conditions, e.g., air and water quality or rainfall compared to the regional average.)  $I_R$  is defined as the maximum level at which the impact is sustainable for the reference firm, i.e., the level at which its environmental impact is the same in proportion to carrying capacity as the contribution of its value generation  $V_R$  to total economic output.

The Impact Reference Levels are combined to produce the Aspect Reference Level. Each Impact Reference Level first is converted to an Aspect Equivalence Level,  $A_{EQ}$  (e.g., for the electrical energy consumption aspect and the global warming impact,  $A_{EQ}$  would be the rate of energy generation that produces  $\text{CO}_2$  at the rate  $I_R$ ). Then for each aspect the following equation must be satisfied:

$$A/A_R = A/A_{EQ1} + A/A_{EQ2} + \dots + A/A_{EQn} \quad (4.11)$$

where:  $A$  = the Aspect Level

$A_R$  = the Aspect Reference Level to be determined

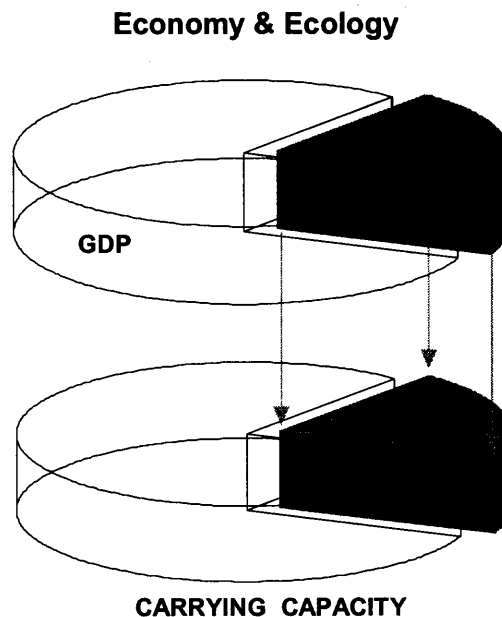
$A_{EQ1, 2, \dots, n}$  = the Aspect Equivalence Level for each impact associated with the aspect.

The Aspect Reference Level is then

$$A_R = 1 / (1/A_{EQ1} + 1/A_{EQ2} + \dots + 1/A_{EQn}) \quad (4.12)$$

If  $A_{EQ}$  for any one of the impacts is much smaller than the others, this identifies the primary or “limiting” impact. This  $A_{EQ}$  can be denoted  $A_L$ . Then  $A_R \approx A_L$ .

Using the above approach, EI as shown in (4.4) is really the sum of the normalized Impact Levels. In practice, operating data is collected and maintained and objectives generally will be set on the basis of aspects (e.g., goals to reduce energy or material consumption), so the above approach allows direct use of such data. However, LCA databases typically present LCA inventory data in terms of impacts. Since impact reference levels have been determined in the above approach, the elements EI, RP, and EE also can be calculated using such data when necessary.



**Figure 4.4** Linking Value Generation and Environmental Impact  
As a Target For Sustainability

Resource Productivity, RP, depends on the  $V_R$  selected and the associated  $A_R$  quantities, but this is consistent with its use as a relative indicator only. The choice is arbitrary as long as the same  $V_R$  and  $A_R$  are used within a given comparison. Further, since each  $A_R$  is linearly proportional to  $V_R$ , Eco-Efficiency, EE is independent of  $V_R$ . This is consistent with its use as an absolute indicator. Most importantly,  $EE \geq 1$  (100%)

indicates that the value provided by the product meets or exceeds that necessary given the level of environmental impact it causes, i.e., the product is sustainable. The relationship between value generation and environmental impact in the Lucent Sustainability Target methodology are represented in Figure 4.4.

Carrying capacities have been estimated using various data sources and have been applied according to the Lucent Sustainability Target methodology described above to calculate Economic Carrying Capacity (ECC), Impact Reference Levels ( $I_R$ ), Aspect Equivalence Levels ( $A_{EQ}$ ), and Aspect Reference Levels ( $A_R$ ). In the following section, carrying capacity is estimated for two environmental impacts related to electrical energy consumption.

#### **4.2.2 Carrying Capacity Estimates for Electrical Energy Consumption**

Commercial and industrial activities once assumed to be insignificant with respect to natural ecological systems are now being found to have significant environmental effects, including global warming, ozone depletion, acid rain, loss of species, depletion of non-renewable resources, and scarcity of fresh water. As business activities expand with the global economy, it is increasingly important to be able to evaluate the environmental aspects of these activities in relation to the earth's "carrying capacity". Environmental performance of products and services should not be compared on a relative basis using subjective environmentally-related criteria, but rather based on carrying capacity. Further, it is not enough to know that reduced energy use and material content, for example, will move the economy toward sustainability; it also important to know at what level of

energy and material use a specific product or service reasonably can be characterized on an absolute basis as sustainable.

In Lucent Sustainability Target Methodology, a set of the environmental aspects most commonly linked with business activities and their associated impacts are identified in Table 4.4. The aspects include energy and water consumption, air emissions, wastewater discharge, and hazardous waste generation; and the associated impacts include global warming and resource depletion.

**Table 4.4** Lucent Sustainability Target Metric – Aspects and Impacts

Aspect	Impact								
	Global Warming	Ozone Depletion	Resource Depletion	Acidification	Eutrofication	Human Health	Eco Health	Bio-diversity	Others
1. Energy Consumption	*		*	*	*	*			*
2. Material Consumption			*					*	
3. Water Consumption			*				*	*	
4. Air Emissions	*	*		*	*	*			
5. Waste Generation						*			*
6. Wastewater Discharge					*	*	*	*	

**\* : Impact Carrying Capacity (ton mass/year)**

“Carrying Capacity” is defined as the capacity of a region (or the earth as the global scale) to absorb or tolerate the imparted burdens, that is, to accommodate the stresses without showing damage. A carrying capacity is considered individually with each associated impact. For example, carrying capacity for greenhouse gas emissions (global warming impact) can be determined based on the stabilization of global temperature, although the values may change as models become more refined. For obtaining the

carrying capacity of non-renewable fossil fuels (resource depletion impact), existing reserves are considered over a specified time horizon needed for availability and use of the resource.

The energy consumption aspect (electrical) can impact the environment through use of fossil fuels and generation of air emissions, water discharges, and wastes. Impacts include global warming due to CO<sub>2</sub> and other greenhouse gases, resource depletion, acid rain due to SO<sub>2</sub> and NO<sub>x</sub> emissions, cooling water discharges, steam emission, and fly ash generation. The two major impacts considered here are global warming, resource depletion.

**1) Global Warming Impact.** Increased atmospheric levels of carbon dioxide and other greenhouse gases lead to global warming with significant contributions resulting from fossil fuel usage. Climate models predict that the global temperature will rise 1-3.5°C by the year 2100 based on the current emission trends [IPCC, 1996]. The total carbon emission from use of fossil fuels in 1995 was approximately 6.0 GTCE (Giga Tons of Carbon Equivalent) [UNEP/IUC, 2000]. A reduction factor of 2.5 from recent carbon dioxide emission levels is perceived as being needed to contain global warming [Goedkoop, 1998]. This reduction will sustain a temperature increase of 0.2°C per decade and maintain ecosystem impairment below 5%. Therefore, based on this determination of tolerable global ecosystem change, the estimated carrying capacity for the global warming impact is air emissions of 2.4 GTCE/yr (8.8 GTCO<sub>2</sub>-E/yr).

**2) Resource Depletion Impact.** The resource depletion impact is considered at both global and regional (U.S.) scales. Electric power generation involves different resources. Sources used to supply a given electric power grid vary according to macro-factors like

resource availability and technological infrastructure. For this analysis, the current mixes of power sources for the U.S. [Young, 1996] and the world grids [World Coal Institute, 1998] are used. Among all the primary energy resources, fossil fuels (coal, gas, and oil) constitute 67.7% and 62% in the U.S. and world power grids, respectively. In the U.S., coal is the primary source of fossil fuel used to generate electric power, and it is by far the most plentiful in the world. As of 1996, one thousand billion tons of total coal reserves have been estimated to be economically accessible using current mining technology. According to the World Coal Institute, coal reserves are sufficient to last over 210 years at 1997 levels of production [EIA, 2000]. Note that this figure does not take into account that coal resources may increase through exploration, or will become accessible, as mining technology improves. If coal is the primary source of the energy generation in the future, the time horizon for its availability is estimated to be in the range of 200 to 2,000 years. Considering current coal production capability, 200 years is selected as the time horizon.

Note that when a sustainable level for resource use is associated with a time horizon, one of two possible assumptions is at work. Either there is faith that at the end of the of the time horizon selected, an alternative resource will have been identified to meet the need, or there will be periodic recalculation of the amount of the current resource available so that the time horizon of availability is always constant. The latter implies that the rate of use will decrease each year to assure a continuous 200 year supply, using the numbers in this example, unless increased supplies of the resource are identified. The world's recoverable coal reserves were approximately 986,294 million tons in 1997 [EIA, 2000]. When extended to 200 years, the estimated carrying capacity of coal reserves at

the global level is then 4,931 million tons/yr. The U.S. recoverable coal reserves were approximately 249,610 million tons in 1997 [EIA, 1999], so the estimated carrying capacity at the U.S. scale is 1,248 million tons/yr.

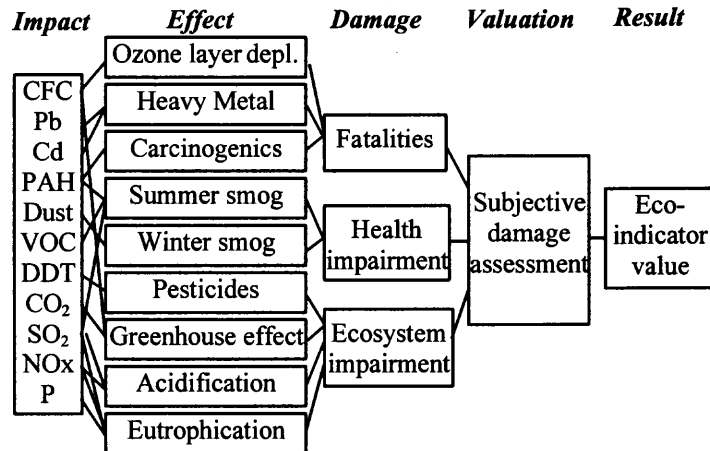
#### **4.3 Comparison and Discussion of Major Environmental Performance Metrics**

Few would disagree with the underlying principles of and goals for sustainability or question the value of strong product stewardship programs. In addition, environmental awareness is fast becoming a part of everyday consciousness. However, very little agreement exists as to how to measure progress towards sustainability or the eco-efficiency of our products and processes. Consequently, an array of environmental performance metrics and assessment techniques has been devised with little consensus or broad based acceptance in the environmental community. This section begins to compare four major environmental impact assessment methods that are comprehensive in nature and generate a single numerical value reflecting the composite magnitude of global impact associated with a specific product.

In this section, four techniques have been selected for comparison and validation purpose: Eco-indicator 95, Eco-indicator 99, Ecological Footprints, and Lucent Sustainability Target Metric. Before comparison, brief overviews of first three metrics are given. The fourth metric, the Lucent Sustainability Target Metric, has already been described in last section. Comparison of each metric is given in terms of conceptual methodological base, weighting techniques, usability, and extensibility. Finally three case studies are used to illustrate each methodology and compare results.

### 4.3.1 Comparison of Four Major Environmental Performance Metrics

1) **Eco-indicator 95** The Eco-indicator 95 approach, developed by the National Reuse of Waste Research Programme and Pre Consultants of the Netherlands, is one of the most



**Figure 4.5** Eco-indicator 95 Methodology [Goedkoop,1998].

widely used environmental performance assessment tools. The work was intended to give fundamental and in-depth considerations of how people should evaluate the consequences of impairment of the environment, and how designers can search for more environmentally friendly design alternatives. Detailed information on Eco-indicator 95 can be found in reference [Goedkoop, 1998]. The methodology is depicted as Figure 4.5 as follows

The Eco-indicator 95 method classifies, characterizes and normalizes the environmental impacts based upon their effects. The environmental burdens associated with a product are first aggregated into a number of environmental effects caused. Then the effects are characterized according to the degree to which they contribute to ecosystem damage. The characterized effect scores can then be normalized compared with reference values. The result is an environmental profile with standardized effect



```

graph LR
    subgraph Resource_analysis [Resource analysis]
        direction TB
        R1[Extraction of minerals and fossil fuels]
        R2[Land-use: occupation and transformation]
        R3[NOx  
SOx  
NH3  
Pesticide  
Heavy metal  
CO2  
HCFC  
Nuclides  
SPM  
VOC's  
PAH's]
    end

    subgraph Exposure_and_Effect_analysis [Exposure and Effect analysis]
        direction TB
        E1[Concentration minerals]
        E2[Fossil fuel availability]
        E3[Change in habitat size]
        E4[Changed pH and nutrient]
        E5[Concentr. Urban, agri, nat. soil]
        E6[Concentration greenh. gas]
        E7[Concentr. Ozone depl.]
        E8[Concentr. radionuclides]
        E9[Concentr. SPM and VOC's]
        E10[Concentr. in air, water, food]
    end

    subgraph Damage_analysis [Damage analysis]
        direction TB
        D1[Surplus energy for future extraction]
        D2[Surplus energy for future extraction]
        D3[Regional effect on vascular plant]
        D4[Local effect on vascular plant]
        D5[Acidif/eutr.]
        D6[Ecotoxicity: toxic stress]
        D7[Climate change (diseases and displacem.)]
        D8[Ozone layer depl. (cancer and cataract)]
        D9[Ioniz. radiation]
        D10[Respiratory effect (cases and type)]
        D11[Carcinogenesis]
    end

    subgraph Normalization_and_Weighting [Normalization and Weighting]
        direction TB
        N1[Damage to mineral and fossil resources [MJ surplus energy]]
        N2[Damage to ecosystem quality [% vasc. Plant species * Km2*yr]]
        N3[Damage to Human health [disability Adjusted life Years DALY]]
    end

    Indicator[Indicator]

    R1 --> E1
    R1 --> E2
    R2 --> E3
    R3 --> E4
    R3 --> E5
    R3 --> E6
    R3 --> E7
    R3 --> E8
    R3 --> E9
    R3 --> E10
    E1 --> D1
    E2 --> D2
    E3 --> D3
    E3 --> D4
    E4 --> D5
    E5 --> D6
    E6 --> D7
    E7 --> D8
    E8 --> D9
    E9 --> D10
    E10 --> D11
    D1 --> N1
    D2 --> N1
    D3 --> N2
    D4 --> N2
    D5 --> N2
    D6 --> N2
    D7 --> N2
    D8 --> N3
    D9 --> N3
    D10 --> N3
    D11 --> N3
    N1 --> Indicator
    N2 --> Indicator
    N3 --> Indicator
  
```

**Resource analysis**

- Land-use analysis
- Fate analysis

**Exposure and Effect analysis**

**Damage analysis**

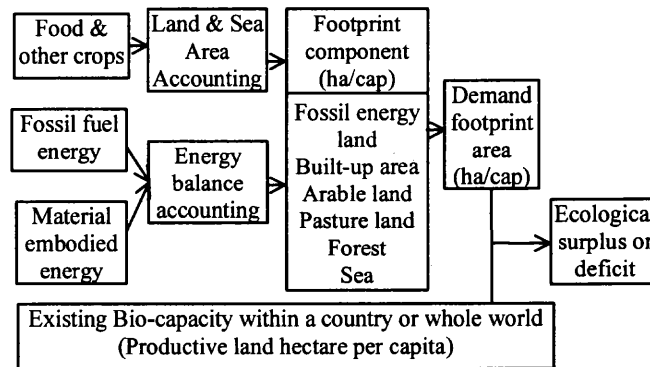
**Normalization and Weighting**

**Indicator**

95 methodology. Eco-indicator 99 is based on a damage-oriented methodology. Three types of environmental damages: human health, ecosystem quality and resource depletion

have been taken into consideration. Figure 4.6 shows the Eco-indicator 99 methodology. Damage models have been established to link these damage categories with the inventory results. Damages to human health are expressed as DALY (Disability Adjusted Life Years). Models have been developed for respiratory and carcinogenic effects, climate change impacts, ozone layer depletion and ionizing radiation. Damages to Ecosystem Quality are expressed as PAF (Potentially Affected Fraction), the percentage of species that have disappeared in a certain area due to the environmental load. Resource extraction damage in Eco-indicator 99 only models mineral resources and fossil fuels. The unit of the resources damage is the “surplus energy” in MJ per kg extracted material. The extraction of resources will result in higher energy requirements for future extraction. It should be noted the damage assessed here is not absolute or actual damage, but rather the incremental or marginal damage. After damage assessment, the normalization step and weighting step are needed to obtain a single score from damage values with different units. Due to model and data uncertainty, it is thought that natural science alone cannot be used to determine how serious the discussed damage is perceived. The concept of culture theory is adopted to model societal subjectivity and alternative basic value systems. For further information on Eco-indicator 99 readers are referred to reference [Goedkoop and Spriensma, 2000].

**3) Ecological Footprint** The concept of the Ecological Footprint is based on the premise that sustainability depends on maintaining natural capital, and, that human consumption



**Figure 4.7** Ecological Footprint Methodology

and emission must not exceed the natural carrying capacity. This framework, developed by Wackernagel [Wackernagel et al., 1999], is intended to track national economy's energy and resource throughput and translate them into biologically productive areas necessary to produce these flows. The approach estimates, not only, industrial and commercial usage, but overall human consumption of resources, including food and shelter. The Ecological Footprint represents the critical natural capital requirements of a defined economy or population in terms of the corresponding biologically productive areas. In order to calculate the ecological footprint, resources consumed and wastes generated have to be estimated. Then, these resource and waste flow are converted to a biologically productive area necessary to provide these functions. If the footprint area calculated for a region exceeds that available from within its boundaries, the region is deemed to be drawing excessively from the global carrying capacity. To represent the carrying capacity of contamination, footprints can only be estimated through a proxy calculation by assessing the biophysical resources necessary to rectify the damage. Figure

4.7 depicts the methodology and framework for the Ecological Footprint approach. The ecological footprints for 52 countries and the world as a whole have been calculated. The basic indication drawn from these calculations is that human consumption has a footprint larger than the ecological carrying capacity of the world. Using this basic concept, the footprint of a single product can be modeled and analyzed in terms of its energy balance. The fossil fuel land footprint reflects the environmental impact of the product.

The four environmental performance metrics are examined in terms of their methodological basis, usability and extensibility.

### **1) Theoretical Base Comparison**

All four of the techniques are comprehensive, estimating impact on the global ecosystem and human health. Eco-indicator 99 and Lucent Metric extend the impacts to include resource depletion while the Ecological Footprint includes overall human consumption. In addition, with the exception of Eco-indicator 99, the methodologies are based on estimates of the earth's carrying capacities, i.e., a sustainability level as reflected in the earth's ability to cleanse or absorb the burden in perpetuity. Eco-indicator 95 and 99 are product and process focused, use damage-oriented methods and are based on "less is better" approach. The difference is that, Eco-indicator 95 assesses the potential impact, and a low damage level at which demonstrable but limited damage occurs is set as the target level, while Eco-indicator 99 assesses the impacts on their possible marginal damage, that is to say, no explicit target is defined. Ecological Footprint and Lucent Metric are similar in their basic premise that consumption and pollution must not exceed natural carrying capacity in order to be sustainable. However, the Ecological Footprint approach is primarily focused on macroscopic assessment of national or regional impacts

rather than individual products or facilities. The Lucent Sustainability Target methodology is unique in that it explicitly considers economic or market value and is equally applicable to analyzing products/processes, services or facilities. By directly considering economic value, resource productivity measures can be generated, and, comparisons can be drawn between products or services that are not necessarily “functionally equivalent” but are instead economically equivalent. In addition, the structure and terminology of Lucent Sustainability Target Metric is consistent with ISO14000 standards.

## **2) Weighting Techniques**

Perhaps, the most controversial step in developing composite, singled valued environmental performance metrics is the weighting step. Eco-indicator 95 and 99 employ explicit weighting methods, while Ecological Footprint and Lucent Metric use an implicit weighting method. Eco-indicator 95 uses a Euclidean distance-to-target weighting method to give rank to the seriousness of an effect. The larger the difference between the current and target level value, the higher the weighting factor for the effect. Eco-indicator 99 methodology has more sophisticated weighting method where damage models instead measures the seriousness associated with the environmental effect. Also, the concept of alternative culture theory is applied to differentiate subjectivity in applying different basic value systems. In contrast to the Eco-indicator approaches, Ecological Footprint and Lucent Metric integrate the weighting concept implicitly in carrying capacity determination. The Footprint framework reflects the weighting in its estimate for yield data. If the yield rate for a natural product is smaller, then consumption of this product will bring about bigger footprint to the environment. Lucent Sustainability Target

Metric uses the relative magnitudes of the normalized impacts as inherent weighting factors.

### **3) Usability**

From a user perspective, Eco-indicator 95 and 99 consists of a set of tables containing intensity-based indicator values stratified by lifecycle stage, characterizing individual contributions by specific material, production processes, transport processes, energy utilization, and disposal scenarios. Underlying data for these methods is European based. Eco-indicator 95 contains approximately 100 separate indicators, while Eco-indicator 99 provides about 180 indicators. Missing indicator values for a material or process can be either substituted with a similar known one, or estimated independently by the user. These techniques are straightforward, easy to use, and require minimal lifecycle information, provided the materials and processes being studied are included in the Eco-indicator database.

While formulated at the macroscopic level, the Ecological Footprint framework can be used to evaluate product level footprint, provided that yield (assimilation) data for solid wastes, liquid effluents, and toxic emissions can be developed. For material processing and production stages, the methodology is based on energy content and process energy. Data is provided on a national level; consequently, analyses can be location specific. Like Eco-indicator, provided the basic footprint data is available, the technique is straightforward. From a usability perspective Lucent metric is interesting in that the methodology is applicable to the facility level as well as the product level, applies equally well to services, and can be calculated along the supply and summed to get the overall impact values. Given the aspect reference values (derived from the carrying

capacities) and aspect loads, calculations are very simple. In addition to environmental impact, it is easy to quantify resource productivity and eco-efficiency using the Lucent Metric framework.

#### **4) Structure Extensibility**

As sustainability and environmental concerns evolve, priorities shift, and technologies advance, the structure and methodologies need to be adaptable and extendable to adjust to the changing situation. In the Eco-indicator approaches, the structure and interrelationship between loads, impacts, and effects are fixed. If additional environmental issues arise or changes in relative importance between the effects occur, then essentially each indicator value has to be recalculated. The Ecological Footprint and Lucent Metric frameworks are structurally open. If additional environmental aspects are to be included in the analysis, a corresponding carrying capacity value needs to be determined. However, this does not affect other reference values or the methodological framework.

#### **4.3.2 Case Studies**

Three types of electronic products are used to illustrate the implementation procedure for the four techniques and to compare and contrast their ability to estimate environmental performance. The first case study examines laptop computers from two different manufacturers. These machines have similar material contents but different designs. The second case study is a comparison for two generations of office telephones. These two phones have substantially different energy usage and economic value. The third case

study looks at alternative designs of functionally equivalent product subassembly where the primary different is choice of material and associated processing.

### **A. Laptop Computers**

Two laptop computers, 95Laptop (2.8 kg, Year 1995) and 91Laptop (3.6 kg, Year 1991) are studied. The material contents of the products are similar however the design and weights differ. Four lifecycle stages are considered: material processing, production, use, and disposal. The material inventory and process data was collected by disassembling the laptops at the MERC lab. The use data was extracted from work at the University of Tennessee [Socolof, 2000].

#### ***Eco-Indicator 95 Calculations***

For each phase in the life cycle, the relevant Eco-indicator intensity values were found in the Eco-indicator data tables, and multiplied by the appropriate material weight or energy value then summed to yield the overall indicator value for each product. The results indicate that 91Laptop has an indicator value of 320 while the 95Laptop has an indicator value of 169. This suggests that the 91Laptop has a higher environmental impact than the 95Laptop. The ratio of these two results is 1.9.

#### ***Eco-Indicator 99 Calculations***

The calculation steps are the same as with the Eco-indicator 95. The changes are only the specific indicator values given in the Eco-indicator 99 data tables and the hierarchical perspective on culture theory is represented. The Eco-indicator 99 value for 95Laptop is 5,399, while 91Laptop's value is 8,126. While the specific values from Eco-indicator 95 and 99 cannot be compared, they give a similar indication that 95Laptop has lower environmental impact and the ratio is 1.5.



### ***Lucent Sustainability Target Metric Calculation***

Three environmental aspects are considered in this case: electricity energy consumption, air emissions, and solid waste. Using the material inventory and process data, the energy, CO<sub>2</sub> emission, and solid waste generated from the materials and processes are calculated. The value of the product and production rate, V=\$2,000 and P=2,000,000 units per year are assumed. Each aspect reference ( $A_R$ ) level is taken from reference [Yossapol, et al., 2001]. Table 4.5 shows the environmental impact (EI), resource productivity (RP), and eco-efficiency (EE) results for the two laptops. Similar to the results from Eco-indicator 95 and 99, Lucent/MERC's EI values indicate that 95Laptop performs better than 91Laptop; however, the difference is lower than that calculated by the Eco-Indicator approach.

**Table 4.5** Lucent Metric Assessment for Two laptop Computers

		95Laptop		91Laptop	
		$A_1$	$A_{R1}$	$A_2$	$A_{R2}$
Energy	( $10^6$ kWh)	432.4	795	456.7	795
CO <sub>2</sub> Emission	( $10^6$ kg)	2.54	1230	2.72	1230
Solid waste	( $10^6$ kg)	0.47	1.88	0.57	1.88
EI	Sum( $A/A_R$ )	0.79		0.88	
RP	( $P/EI$ )	2,531,645		2,272,727	
EE	( $B/EI$ )	126%		113%	

### ***Ecological Footprint***

Energy embodied in the material contents and consumed in processes needs to be calculated for Ecological Footprint study. The total global average energy yield data expressed as a land ratio is calculated assuming a global-average electricity generation mix with a global average yield data from reference [Wackernagal, 1999], results in a

carrying capacity value of 237.4 GJ/ha/yr. Ecological Footprint is then calculated by dividing the energy consumed by each laptop by the total global average energy to land ratio (yield) and multiplied by the equivalence factor. The equivalence factor is used to scale the area of each ecological category in proportion to their productivity. The results indicate that the 95Laptop has a smaller ecological footprint value, 0.0039 ha, than 91Laptop, 0.0042 ha, implying that 1995 laptop consumes less hectares of biologically productive space than the 1991 model.

## **B. Office Telephones**

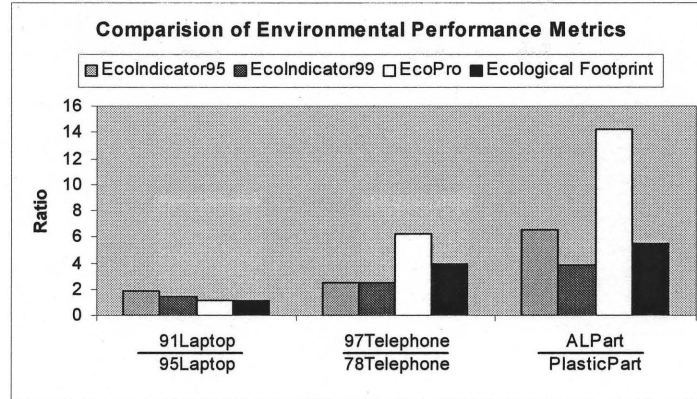
In this case study, two generations of business telephones is examined, a 1978 model (78Telephone) and a 1997 model (97Telephone). The steps in calculations for each technique are the same as above. The main differences in these telephones are the significantly higher energy consumption during the use stage and the lower economic value for the 1997 model compared with the 1978 phone. The 1997 telephone has a stand-by mode in which it consumes 14 times more energy than the in-use mode over the telephone lifetime while the 1978 does not have memory cells. Also, the ratio of economic value to gross domestic product for the 1997 model is significantly lower than that for the 1978 phone. Reference [Al-Okush, 1999] provides a material, environmental burden, and energy inventory for these two telephones. All four methods are consistent in suggesting that the 1997 telephone has higher environmental impact than the 1978 phone. The second set of bar charts in Fig 4.8 gives the ratio of metric results for the 1997 phone to the 1987 phone. Note that the ratio for the Lucent Metric value is higher

than the others because the direct consideration of economic value in the formulation of aspect reference values.

### **C. Alternative Part Designs**

The focus of this case study is on two parts which serve the same purpose but are designed using different materials: ALPart is die cast from aluminum while PlasticPart is injection molded from plastic. The results from all four metrics are similar, indicating that the plastic part has better environmental performance than the aluminum part. The third set of bar charts in Figure 4.8 illustrates the overall results. The Lucent Metric value is relatively higher than the others due to the higher solid waste associated with aluminum and the die cast process.

In above examples, four comprehensive environmental performance metrics are examined focusing on demonstrating the variation in results calculated to specific product characteristics. Two laptop computers are used to examine how the metrics respond to two fairly similar products. The telephone example illustrates the variations to significant energy consumption economic value differences. While, the last case study focused on two parts with equivalent functionally but constructed of different materials. In each case, all four metrics are consistent in selecting which alternative product is environmentally superior. The inherent consideration of economic value in the methodology and formulation of Lucent Sustainability Target Metric is evident in its assessment of products where value to the economy differs.



**Figure 4.8** Results from Metrics Application Comparison

#### 4.4 Summary

This chapter introduces four metrics representing a set of comprehensive environmental performance metrics that are based on estimates of the earth's carrying capacities; consequently, as further study gives insights into quantifying these values, these techniques will become more fully accepted and utilized within the industrial and environmental communities as sustainability and eco-efficiency metrics.

The aim of this study is to evaluate and select one methodology with associated metric which can model and measure environmental performance of complex system such as Internet-based production system. The Eco-indicator and Ecological Footprint methodologies have limitations. They are mainly used to assess product level environmental impact. The indicator value has only relative sense and cannot show at what level the product is towards the sustainability. The Lucent Metric metric, promisingly, has the ability to assess environmental impact of product, service,

manufacturing facility, and supply chain all of which are critical elements in the multi-lifecycle production system.

The reasons that Lucent Sustainability Target Metric is chosen are four folds.

- It has universal scope. In reality, upstream suppliers are not reluctant to reveal information about their product and process if there is no standard inquiry approach, which make the full scale LCA infeasible if not impossible. The same situation is faced to the manufacturers too. The Lucent Sustainability Target Metric provides a common framework for every partner along the product lifecycle to evaluate the environmental performance.
- It provides an absolute quantified measure of eco-efficiency, along with resource productivity value, to businesses as practical guideline.
- It has simple framework for business to use and interpret, and eliminates the burden of each business to explain the “environmental impact” using different languages.
- It is the best metric so far for enterprise environmental management and has potential to be accepted as a standard.

## **CHAPTER 5**

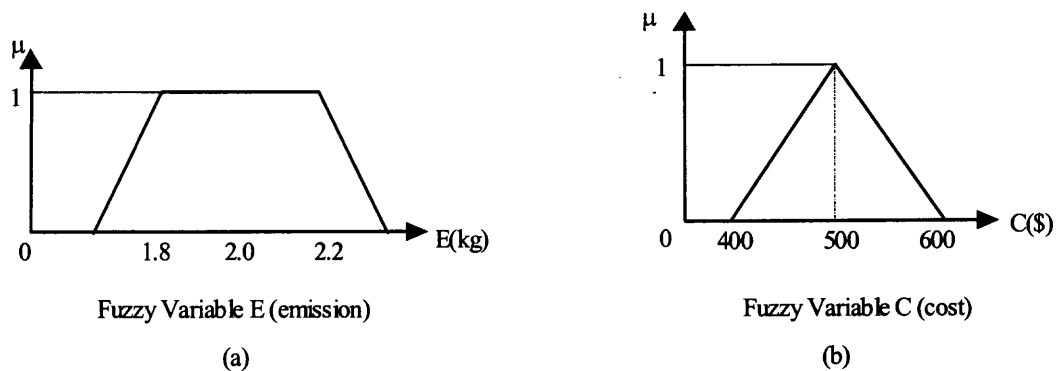
### **SUSTAINABLE E-SUPPLY CHAIN MODEL**

Based on the initial study on the lifecycle environmental performance of e-Business, it can be seen that there are environmental impacts of e-Business on the production system in terms of material use, energy consumption and other aspects. Further research has been conducted to seek a more systematic model with associated approaches and explore system performances of e-Business integrated multi-lifecycle production system. In this chapter, fuzzy logic-based methods is introduced to handle the data gap and information uncertainty. A generic model for Integrated E-Supply Chain Network (IESC) is further addressed. For this model, a fuzzy multi-objective optimization method is constructed, and a discrete-event simulation approach is provided. A comprehensive case study is then used to illustrate the application procedure.

#### **5.1 Fuzzy Logic-based Approach on Exploring Environmental Impacts of E-Business**

In a comprehensive assessment, the inputs, outputs, goals, and constraints cannot always be defined precisely. In practice, information is incomplete or sometimes non-existent, and the goal is frequently unclear and vague. For instance, total processing time may be “around 10” hours and a facility’s environmental burden such as toxic emission may be “substantially less than 2000lb per year”. Moreover, imprecise information is sometimes described by linguistic terms. For example, the reliability of a system is “excellent, good, fair, poor”, or, the goal of system optimization is “to achieve sustainability”. Fuzzy logic, or interchangeably referred to as fuzzy set theory, provides a better tool to represent

fuzzy information by formulating it using membership functions. The concept and techniques of the fuzzy set are often used to deal quantitatively with uncertainty or imprecision which come from fuzziness nature and could not be represented using probability theory [Li and Yen, 1995]. Some prevailing forms of membership functions are depicted in Figure 5.1, in which (a) is trapezoid function that can be used to model fuzzy variable E (emission), and (b) shows triangle function formulating fuzzy variable C (cost). The grade of a member function  $\mu$  indicates a subjective degree of satisfaction with given tolerance. It is noted that nonlinear functions such as piece-wise linear, exponential, power, hyperbolic, inverse hyperbolic, etc., may also be adopted as member functions. Fuzzy logic theory has been widely used in automatic controls, data processing, systems analysis, optimizations, etc.



**Figure 5.1** Membership Functions of Fuzzy Variables

Fuzzy multi-criteria assessment (FMA) is to provide a synthetic evaluation of an object in a fuzzy decision environment with many criteria. Let  $U$  be a set of objects for assessment, let  $\pi = \{c_1, c_2, \dots, c_m\}$  be the set of basic criteria in the assessment system, and let  $E = \{e_1, e_2, \dots, e_p\}$  be a set of grades or qualitative classes used in the assessment.

For the object set  $U$ , there are  $m \times p$  objective functions. And for every object  $u \in U$ , there are  $m \times p$  values of objective functions:

$$\varphi_j^{(k)}(f_j(u)), k = 1, 2, \dots, p; j = 1, 2, \dots, m.$$

If let  $r_{ij}(u) = \varphi_j^{(k)}(f_j(u))$ , the  $m \times p$  values is expressed in the matrix form as:

$$R^{(u)} = \begin{bmatrix} r_{11}(u) & r_{12}(u) & \cdots & r_{1p}(u) \\ r_{21}(u) & r_{22}(u) & \cdots & r_{2p}(u) \\ \vdots & \vdots & \cdots & \vdots \\ r_{m1}(u) & r_{m2}(u) & \cdots & r_{mp}(u) \end{bmatrix},$$

which can be viewed as a fuzzy relation between  $\pi$  and  $E$ .

Let  $W = (w_1, w_2, \dots, w_m)$  be a weight vector, then the decision vector or evaluation vector of  $u$  is defined as:

$$D^{(u)} = W \bullet R^{(u)}.$$

If there exists an index  $k_0 \in \{1, 2, \dots, p\}$  such that

$$D^{(u)}(e_{k_0}) = \max\{D^{(u)}(e_1), D^{(u)}(e_2), \dots, D^{(u)}(e_p)\},$$

then according to the principle of the highest membership,  $u$  is recognized as belonging to grade  $e_{k_0}$  with degree of satisfaction  $D^{(u)}(e_{k_0})$ .

FMA method is applied on the same scenario description and example used in the initial study in chapter 3. Five scenarios are under assessment: traditional business scenario, two moderate eCommerce scenarios and two aggressive eCommerce scenarios. Three criteria are taken into consideration: cost, energy use, and CO<sub>2</sub> emission. The Lucent Sustainability Target Metric is used to calculate the energy metric value and CO<sub>2</sub> emission metric. Energy use is the total energy consumption throughout the lifecycle. The reference level is determined from the sustainable level multiplied by the ratio of the product's value compared to the GDP. CO<sub>2</sub> emission adds up emissions from the



production stage (includes raw material extraction and synthesis, manufacturing, and reuse/recovery) and the transportation stage (distribution and delivery) throughout the lifecycle. The reference level is determined by the same method as above by using the US information of CO<sub>2</sub> emission from commercial and industrial and CO<sub>2</sub> emission due to transportation of commodities.

A simplified activity-based cost analysis is performed to estimate the lifecycle cost for this product. The total revenue of a desktop computer is assumed as \$1500. 80% of the revenue is the cost [Dell, 2000]. The information is obtained from typical computer vendors and delivery agencies. The result is shown in Table 5.1.

**Table 5.1** Lifecycle Cost Analysis (in US Dollars)

	Traditional Model	Aggressive Scenario		Moderate Scenario		Major Assumption
<b>Material</b>	\$600	\$540		\$600		50% of total cost is for materials, components and assemblies. 20% reduction of over/mistaken production. The material saving is 10%.
<b>Manufacturing</b>	Warehouse \$60	\$48		\$60		20% reduction of inventory warehouse. Warehouse cost is 10% of the manufacturing and distribution cost.
	Production cost \$430	\$387		\$430		20% reduction of mistaken/over production due to mistaken order, 50% of which can be reused. The production energy saving is 10%.
<b>Distribution</b>	Transportation cost from manufacturer to distributor, and from distributor to retailer \$50	Air \$160	Truck \$95	Air \$160	Truck \$95	1. Transportation from manufacturer to distributor 1000 miles, from distributor to retailer 100 miles. 2. 20% energy saving in aggressive scenario due to reduction of mistaken order. 3. Traditional model always uses truck, but e-commerce has 2 modes, air (overnight) and truck. 4. Transportation from manufacturer to distributor costs \$45 and from distributor to retailer costs \$5.
	Cost for storing one unit in retail building \$60	\$0		\$0		1. There is 12.5% reduction of wholesale and retail building.
<b>Delivery</b>	Transportation cost from retail building to home, one round-trip-shopping \$3	-		-		1. There is 20% transportation energy saving in aggressive scenario due to reduction of mistaken order. 2. Average shopping length is 11.2 mile. 3. cost for car and gasoline is 25 cents per mile.
<b>Reuse/recovery</b>	No recovery \$0	-\$75		\$0		1. 50% of End-Of-Life(EOL) computers can be reused. 2. 50% of EOL computers can be recovered.
<b>Total Cost</b>	<b>\$1,203</b>	<b>\$1060</b>	<b>\$995</b>	<b>\$1,250</b>	<b>\$1,185</b>	

The Lucent sustainability target metric calculations are shown in the following Table 5.2 and Table 5.3.

**Table 5.2** Lucent Sustainability Metric EI for Lifecycle Energy

	Traditional	Aggressive Scenario		Moderate Scenario	
		Air	Truck	Air	Truck
$A_{\text{lifecycle energy}}$ (MJ)	6,004	5,823	5,320	6,576	5,946
$A_{R\text{lifecycle energy}}$ (MJ)	547	547	547	547	547
$EI_{\text{energy}}$	11.0	10.6	9.7	12.0	10.9

**Table 5.3** Lucent Sustainability Metric EI for CO<sub>2</sub> Emission

	Traditional	Aggressive Scenario		Moderate Scenario	
		Air	Truck	Air	Truck
$A_{\text{production}}$ (Kg)	4,120	3,729	3,729	4,117.9	4,117.9
$A_{R\text{production}}$ (Kg)	47.5	47.5	47.5	47.5	47.5
$EI_{\text{production}}$	86.7	78.5	78.5	86.6	86.6
$A_{\text{transportation}}$ (Kg)	6.45	58.08	4.89	72.6	6.12
$A_{R\text{transportaion}}$ (Kg)	23.5	23.5	23.5	23.5	23.5
$EI_{\text{transportation}}$	0.27	2.47	0.21	3.09	0.26
$EI_{\text{CO}_2\text{emission}}$ ( $\Sigma EI$ )	87.0	80.9	78.7	89.7	86.9

Fuzzy multi-criteria assessment is applied to evaluate five business scenarios. The set of the objects U as  $U = \{TD, AA, AT, MA, MT\}$ , in which TD is traditional model, AA and MA are the aggressive scenario and moderate scenario respectively, under which the major transportation mode is by air (usually referring to over night delivery), AT and MT are the aggressive scenario and moderate scenario respectively, under which the major transportation mode is by truck (usually referring to ground delivery).

Let  $\pi = \{c_1, c_2, c_3\} = \{\text{Energy use, CO}_2 \text{ emission, Cost}\}$  be the set of basic criteria for the assessment. And let  $E = \{e_1, e_2, e_3, e_4\} = \{4, 3, 2, 1\}$  be a set of grades in the

assessment. The higher grades indicate better performance. The grades can be also explained as excellent, good, fair, and poor in terms of the assessed performance.

Table 5.4 shows the values of the objects with respect to energy use, CO<sub>2</sub> emission and cost. For energy use and CO<sub>2</sub> emission, the values are dimensionless Eco-pro index values. And the cost uses the US dollar value. Table 5.5 is the relation between assessment criteria and the grades.

**Table 5.4** Lucent Sustainability Metric EI Value for Energy Use and CO<sub>2</sub> Emission with Costs

		Energy Use	CO <sub>2</sub> Emission	Cost (US\$)
Traditional		11	87	1,203
Aggressive	Air	10.6	80.9	1,060
	Truck	9.7	78.7	995
Moderate	Air	12	89.7	1,250
	Truck	10.9	86.9	1,185

**Table 5.5** Relationships Between Fuzzy Assessment Criteria and Grades

	Energy	CO <sub>2</sub> Emission	Cost (US\$)
4	0-9.5	0-75	0-900
3	9.5-10.5	75-80	900-1,000
2	10.5-11.5	80-85	1,000-1,100
1	11.5-12.5	85-90	1,100-1,300

All together, twelve (3×4) membership functions are constructed. For each object, a fuzzy decision matrix is derived based on membership functions. One example of fuzzy decision matrix for MT is shown as:

$$\begin{array}{lcl}
 \text{Grades} & 4 & 3 & 2 & 1 \\
 \text{Energy} & 0 & \left( \begin{array}{ccc} 0.6 & 1 & 0.4 \end{array} \right) \\
 \text{CO}_2 & 0 & \left( \begin{array}{ccc} 0 & 0.62 & 1 \end{array} \right) \\
 \text{Cost} & 0 & \left( \begin{array}{ccc} 0 & 0.58 & 1 \end{array} \right)
 \end{array}$$

Three different weighting vectors are used. They are  $w1=[1/3,1/3,1/3]^T$ ,  $w2=[1/4,1/4,1/2]^T$ , and  $w3=[1/2,1/2,0]^T$ . Decision vectors and the final decision are shown in the following tables. The final decision consists of two elements, grade and degree of membership and is shown in Table 5.6.

**Table 5.6** Fuzzy Decision-making Results

Weight $[1/3, 1/3, 1/3]^T$		Grades				Decision
		4	3	2	1	
The Traditional		[ 0	0.17	0.70	0.83 ]	(1, 0.83)
Aggressive	Air	[ 0	0.71	1	0.29 ]	(2, 1.0)
	Truck	[ 0.37	1	0.63	0 ]	(3, 1.0)
Moderate	Air	[ 0	0	0.27	1 ]	(1, 1.0)
	Truck	[ 0	0.2	0.73	0.8 ]	(1, 0.8)

Weight $[1/4, 1/4, 1/2]^T$		Grades				Decision
		4	3	2	1	
The Traditional		[ 0	0.13	0.64	0.88 ]	(1, 0.88)
Aggressive	Air	[ 0	0.63	1	0.37 ]	(2, 1.0)
	Truck	[ 0.29	1	0.71	0 ]	(3, 1.0)
Moderate	Air	[ 0	0	0.265	1 ]	(1, 1.0)
	Truck	[ 0	0.15	0.69	0.85 ]	(1, 0.8)

Weight $[1/2, 1/2, 0]^T$		Grades				Decision
		4	3	2	1	
The Traditional		[ 0	0.25	0.80	0.75 ]	(2, 0.8)
Aggressive	Air	[ 0	0.86	1	0.14 ]	(2, 1.0)
	Truck	[ 0.53	1	0.47	0 ]	(3, 1.0)
Moderate	Air	[ 0	0	0.28	1 ]	(1, 1.0)
	Truck	[ 0	0.3	0.81	0.7 ]	(2, 0.8)

This is the first study to incorporate fuzzy decision theory with traditional lifecycle assessment to evaluate the environmental impact of e-Business. The analysis shows that the aggressive scenario using ground transport (AT) is the best among all objects and B2C moderate scenario with air freight (MA) is always the worst strategy, regardless of the weighting factors. And AA is the second best. If only considering

environmental factors and disregard cost considerations, then TD, AA, MT are about in the same level.

## **5.2 Hyper-network Modeling of Integrated E-Supply Chain System**

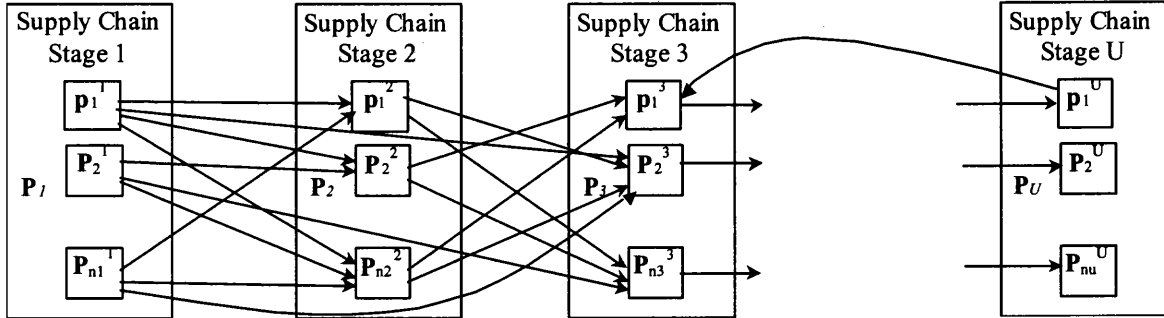
The previous studies indicate that improved environmental performance of e-Business comes from system efficiency of interconnected e-supply chain network. E-supply chain is an emerging business strategy that incorporates the power of e-Business to streamline the manufacturing processes, speed the product cycles, integrate the supply chains, and better respond to the customers. Integrated e-supply chain system has more complex structure than traditional supply chain system in that it embraces e-Business strategy to establish information links and integrates end-of-life processes into the entire supply chain structure. Many changes will take place in product lifecycle stages and environmental implications. Advanced methodologies and approaches are needed to model and analyze these changes.

### **5.2.1 Generic Framework of IESC**

The methodology presented herein represents a novel approach to model and optimize the integrated e-supply chain network structure. Supply chain parameters and system strategies are represented as a mathematical model of the network structure. Interaction and tradeoffs that occur between the components and parameters in the network are analyzed and optimized using fuzzy multi-objective optimization approach. The result is an optimal product supply chain under e-Business strategy for Internet-based manufacturing.

An Integrated E-Supply Chain (IESC) network is defined as a hyper-network of material flows overlaid with an e-Business information network. A generic framework for IESC can be defined as follows.

- Product supply chain system: A network contains  $U$  consecutive supply chain stages;



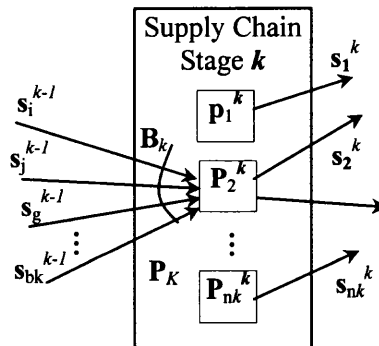
**Figure 5.2** A Product's Generic Supply Chain System

- Supply chain stage  $k$ : Stage Partner set  $\mathbf{P}_k = \{p_1^k, p_2^k, p_3^k, \dots, p_{nk}^k\}$ ;

Stage  $k-i$  is called **upstream stages** of  $k$ , and Stage  $k+i$  **downstream stages** of  $k$ ,  $i > 0$ .

Stock Keeping Unit (SKU) set  $\mathbf{S}_i^k$  is the finished products set of  $p_i^k$ ;

Bill of Material (BOM) set  $\mathbf{B}_k$  of stage  $k$ ,  $\mathbf{B}_k \subseteq \cup_i \mathbf{S}_i^{k-1}$ ,  $\mathbf{B}_1 = \Phi$  (since the first layer is either raw material supply or an aggregate stage including raw material supply). The BOM of stage  $k$  is a list of materials and components required for processes in this stage as shown in Figure 5.3.



**Figure 5.3** Stage Partner, Bill of Material (BOM) and Stock Keeping Unit (SKU) of a Supply Chain Stage

- Supply chain Partner **P**:  $\mathbf{P} = \{\mathbf{P}_1 \cup \mathbf{P}_2 \cup \dots \cup \mathbf{P}_k \cup \dots \cup \mathbf{P}_U\}$ ;
- Material flow link, or m-link of stage  $k$ : Link set  $\mathbf{L}_{mk} = (\mathbf{P}_k \rightarrow \mathbf{P}_{k+j})$ , i.e. all existing physical directed links from a  $k^{\text{th}}$  stage partner to a  $(k+j)^{\text{th}}$  stage partner. Multiply links are allowed between two partners.
- Set of m-links,  $\mathbf{L}_m = \cup \mathbf{L}_{mk}$ ;
- Material flow network (MFN):  $\mathbf{MFN} = (\mathbf{P}, \mathbf{L}_m)$ , with node set **P** and link set  $\mathbf{L}_m$ ;
- Supply chain information link, or e-link  $\mathbf{L}_e$  of stage  $k$ : Link set  $\mathbf{L}_{ek} = (\mathbf{P}_k \text{ --- } \mathbf{P}_{k+j})$ , i.e. all existing e-Business information non-directed links between a  $k^{\text{th}}$  stage partner to a  $(k+j)^{\text{th}}$  stage partner. These links affect the characteristics of the corresponding material flow network.
- Set of e-links,  $\mathbf{L}_e = \cup \mathbf{L}_{ek}$ ;
- E-Business information network (EIN):  $\mathbf{EIN} = (\mathbf{P}, \mathbf{L}_e)$ , with node set **P**, link set  $\mathbf{L}_e$ ;
- Integrated supply chain network (IESC): Two over-laid network i.e.  $\mathbf{IESC} = \mathbf{MFN} + \mathbf{EIN}$ ;
- A product's supply chain (PSC):  $\mathbf{PSC} \subseteq (\mathbf{P} \cup \mathbf{L}_m)$ , a subset of appropriate partners (nodes) and links from  $\mathbf{P} \cup \mathbf{L}_m$ ; Obviously, product supply chain is a sub-net of IESC consisting of connected nodes and links through and along which products travel from original supplier to the consumer, then to end-of-life processor. There must be at least one manufacturer node and one customer/consumer node in the pathway.
- General performance vector  $\mathbf{m} = (m_1, \dots, m_i, \dots, m_a)^T$ ;
- Performance vector for stage  $k$ :  $\mathbf{m}_k = \mathbf{m}(\mathbf{P}_k)$ ;
- Performance vector for material link  $\mathbf{L}_{mk}$ :  $\mathbf{m}_{mk} = \mathbf{m}(\mathbf{L}_{mk})$ ;

- Performance matrix  $\mathbf{M} = (\mathbf{m}_1, \mathbf{m}_{m1}, \dots, \mathbf{m}_k, \mathbf{m}_{mk}, \dots, \mathbf{m}_U, \mathbf{m}_{mU})$ ;
- Most of the concerned issues can be addressed as:

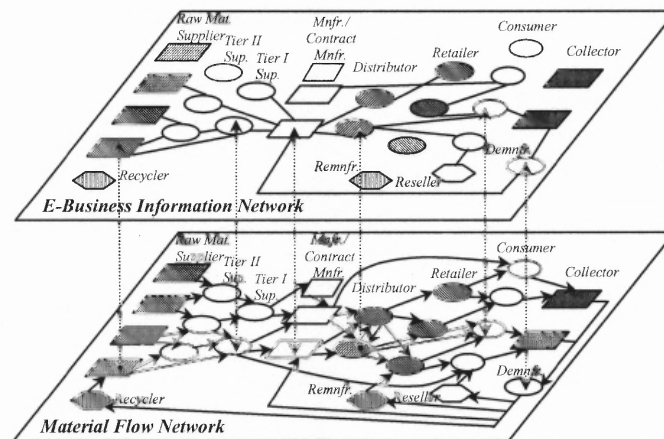
Given  $\mathbf{M}$  or transform of  $\mathbf{M}$ ,

find a PSC,

such that  $\mathbf{M}$  or transform of  $\mathbf{M}$  is optimized.

### 5.2.2 Basic Concept of IESC

An example of IESC is shown as Figure 5.4. It contains 8 supply chain stages: raw material supply, tier II supply, tier I supply, manufacture, distribution, retail, customer use, and demanufacture. After demanufacture stage, recovered material or components



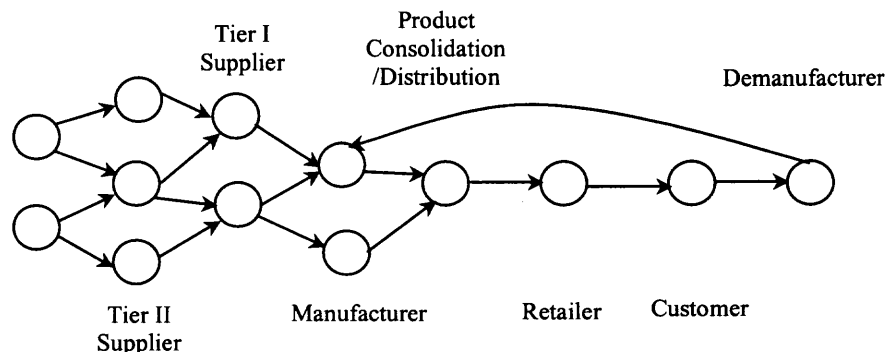
**Figure 5.4** Integrated E-Supply Chain Network

will feedback to suitable supply chain stages. This structure extends the traditional supply chain to an integrated, more sustainable system. The focal point is still the manufacturer, but the upstream and downstream parts cover the entire product value-added chain. In the IESC structure, partners contain autonomous or semi-autonomous business entities collectively responsible for the full lifecycle of a product. M-link represent the



transportation link between two partners, multiple m-links are allowed between two nodes to model different transportation modes. E-links represent e-Business relationship between business entities for streamlining the material flow efficiently and effectively. E-links can speed up the communication process and thus reduce the response time. It can also be used by a company to select its suppliers and service providers.

E-supply chains can bring about a more cooperative business environment, especially between manufacturer and service providers. Some modular components of the product, such as the monitor and keyboard, can be shipped directly from the supplier to the consumer without passing through the manufacturer. The elements in IESC network are involved in production, communication, warehousing and transportation activities. Placement and selection of these elements are related to the supply chain configuration and e-Business scenario developed. The above-defined framework depicts two overlaid, interconnected networks representing the physical material flows and the e-Business information network, as shown in Figure 5.4. Figure 5.5 gives an example of a product's supply chain after IESC optimization and configuration are done.



**Figure 5.5** A Product's Supply Chain Network

### 5.2.3 Application Procedure of IESC Methodology

The IESC methodology is aimed to model and optimize an e-supply chain system from product perspective and with focus on the manufacturers. The application steps involved in this methodology consists of the following:

1. Identify supply chain stages for a target product and manufacturer.
2. Set up the material flow network where the links represent transportation links between two partners.
3. Set up the E-Business information link beyond material network, where an e-link is the e-Business relationship between two partners for sharing the information, aligning the manufacturing planning, and better forecasting the demand.
4. Identify sets of interesting characteristics for partners, and links, and represent them as performance indices. They may be product cost, productivity, cycle time, quality, energy use, and environmental impact.
5. Apply an optimization algorithm, and search in IESC a suitable product supply chain having best overall performance.

While most of performance indices can be well quantified, charactering the environmental impact is a relatively difficult task to be discussed next.

The Lucent Target Metric is integrated in this framework as a sustainability metric that can be used to assess environmental performance and provide a clear indication of progress towards sustainability. The metric possesses numerous necessary attributes, including applicability to the entire product lifecycle, compatibility with LCA methods and databases, and means for communicating with both suppliers and customers. Importantly, it provides both a relative indicator for environmental impact and an

absolute indicator for sustainability. The latter links environmental and economic performance to provide a practical target for sustainability at the firm and product levels that will result in a sustainable economy.

The detailed formulas of this metric are discussed in chapter 4. The framework comprehensively embraces the concept of sustainability with principle that ecological protection and economic development should be considered together. It is also able to give suggestion to products or firms the distance towards sustainability. All these characteristics make it a suitable metric to measure the environmental performance for IESC model.

### **5.3 Fuzzy Multi-objective Optimization of IESC Model**

For IESC model, the optimization goal is to find a best sub-net such that multiple goals must be met. Since the supply chain data may be uncertain or information vague or imprecise, the optimization goals may not be reached exactly. Moreover, imprecise information is sometimes described in linguistic terms. In the previous work, fuzzy decision theory is successfully used in evaluating predetermined e-Business scenarios and their lifecycle environmental performance. In this proposed methodology, fuzzy logic theory is further applied to solve a more complicated network optimization problem.

#### **5.3.1 Fuzzy Multi-Objective Optimization**

Based on the IESC model, an integrated e-supply chain network, denoting as  $IESC=(P, L_m)$  with node set  $P$  and link set  $L_m$ , has variables and parameters defined as follows,

Decision variable  $x_i$ : network link in MFN with its origin node,  $\forall i \in L_m$ ,  $x_i = 1$  if

$$\text{link } i \text{ is used, } x_i = 0 \text{ otherwise;} \quad (5.1)$$

$$\mathbf{x}: \text{vector variable of network links.} \quad (5.2)$$

The objective functions are  $f_k(\mathbf{x})$ ,  $k = 1, 2, \dots, n$ . They are  $n$  objectives.

The  $k$ th objective function is corresponding to one specific performance, such as cost or cycle time, and is a function of links and their overlaid e-links. Then the fuzzy multi-objective optimization problem is formulated as follows:

Find  $\mathbf{x}$ ,

$$\text{such that } f_k(\mathbf{x}) \text{ is minimized, where } f_k(\mathbf{x}) \forall k, \text{ are corresponding fuzzy goals.} \quad (5.3)$$

If the tolerance of fuzzy constraints is given, then the membership function of the fuzzy objectives can be established as,  $\mu_k(\mathbf{x})$ ,  $\forall k$ . To solve this problem, the maximin-operator [Bellman and Zadeh, 1970] is used, and the fuzzy programming method [Zimmermann, 1978] is applied. The feasible solution set is defined by interaction of the fuzzy objective set and characterized by its membership function  $\mu_D(\mathbf{x})$  which is:

$$\mu_D(\mathbf{x}) = \max (\mu_1(\mathbf{x}), \dots, \mu_k(\mathbf{x})). \quad (5.4)$$

Furthermore, since the optimization is a minimization problem, a chosen solution is obtained by solving:

$$\min [\max \mu_k(\mathbf{x})] \text{ s.t. } \mathbf{x} \in (0,1). \quad (5.5)$$

Let  $\alpha = \max \mu_k(\mathbf{x})$  be the overall satisfactory level of compromise. The equivalent model is,

$$\begin{aligned} &\min \alpha, \\ &\text{s.t. } \alpha \leq \mu_k(\mathbf{x}), \forall k. \end{aligned} \quad (5.6)$$

To establish membership function of objective functions, the payoff table (Table 5.7) is first obtained for positive ideal solutions which optimize each objective function independently.

**Table 5.7** The Payoff Table

	f1	f2	...	fk	x
min f1	$f1^*$	$f2(x^1)$	...	$fk(x^1)$	$x^1$
min f2	$f1(x^2)$	$f2^*$	...	$fk(x^2)$	$x^2$
...	...	...	...	...	...
min fk	$f1(x^k)$	$f2(x^k)$	...	$fk^*$	$x^k$
	$f1'$	$f2'$	...	$fk'$	

In the payoff table  $f_k^*$  is the feasible and optimal value for the k-th objective, and  $f_k'$  is the maximum (worst) value in each column. The membership functions are assumed to be linear and non-increasing between  $f_k'$  and  $f_k^*$ ,  $\forall k$ , as given below:

$$\mu_k(x) = \begin{cases} 1 & f_k(x) < f_k^* \\ [f_k' - f_k(x)]/[f_k' - f_k^*], & f_k^* \leq f_k(x) \leq f_k' \\ 0 & f_k(x) > f_k' \end{cases} \quad (5.7)$$

The solution method introduced above applies fuzzy multi-objective programming approach in optimizing the networks. Its zero-one property is suitable for numerical computing.

The solution  $x$  is an optimized sub-net of the originally defined IESC network that meets multiple-goals, e.g., minimal cost and minimal environmental impact within the satisfactory degree  $\alpha$ .

The optimal solution can be compared and validated with a base case supply chain defined using known values of parameters. This base model can be traditional business practices and can be used as a reference against which the performances of other scenarios are compared.

### 5.3.2 Example

The case study product is a typical personal computer system consisting of the computer, monitor, keyboard and mouse. An integrated e-supply chain network is shown as Figure 5.6. Although it is a simplified model with only a single tier of suppliers by assuming that the performance of each tier one supplier as the aggregated performance of upstream suppliers, interactions of supply chain partners, use of recovered materials from discarded products, and new relationships occurring because of e-Business strategies can be modeled. Supply chain data of cost, time, energy, and CO2 emission are adapted from the initial work and based on industry experience, scenario definitions and assumptions and reflects the potential of e-Business strategies to reduce cost, over-production, mistaken orders, inventories and business processing time. Transportation distances and transportation modes are also assigned to the network structure. Transportation distances and modes are also assigned to the network structure. The data sheet for this example is shown in Appendix A.

The Bill of Material (BOM) of stage 2, or manufacturing stage is  $B_2 = \{\text{Computer (C), Hard-disk-driver (H), Monitor (M), Keyboard/mouse (K)}\}$ . The Stock Keeping Unit (SKU) sets for each partner in stage 1 are,  $S_1^1 = \{C, H\}$ ,  $S_2^1 = \{C, M, H\}$ ,  $S_3^1 = \{M, H, K\}$ ,  $S_4^1 = \{M, K\}$ . The performance measure of each m-link is also affected by whether there is an overlaid e-link and reflects the potential that e-Business strategies are able to reduce cost, over-production, mistaken orders, inventories and business processing time.

Four objective functions are modeled: f1 cost, f2 cycle time, f3 energy consumption and f4 CO2 emission. The optimization model is,

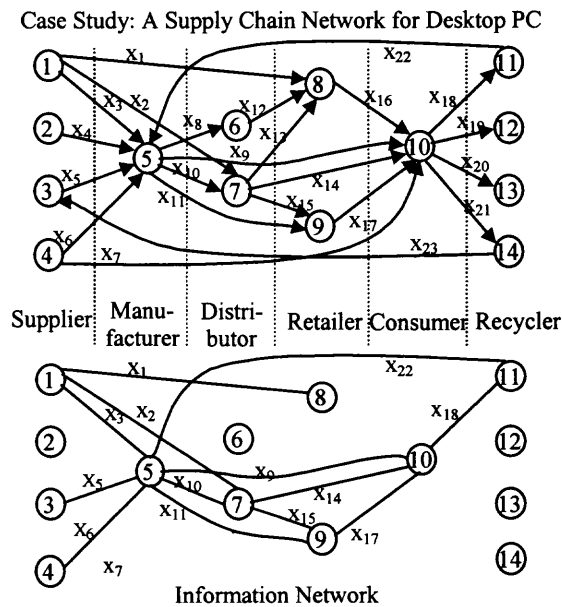
Find  $x$ , such that

$$\begin{bmatrix} C_1 & C_2 & \dots & C_i & \dots & C_N \\ T_1 & T_2 & \dots & T_i & \dots & T_N \\ E_1 & E_2 & \dots & E_i & \dots & E_N \\ A_1 & A_2 & \dots & A_i & \dots & A_N \end{bmatrix} \bullet X$$

is minimized within certain satisfactory degree  $\alpha$ .

There are  $N$  links in the network, and  $C_i$ ,  $T_i$ ,  $E_i$ ,  $A_i$ , are the cost, time, energy, and CO2 emission respectively associated with link  $x_i$  and its origin node including material, production, operation and transportation.

In Figure 5.6, the model has 14 nodes and 23 links. Note that node 1 to 4 are suppliers, node 5 is the manufacturer, node 6 and 7 are distributors, node 8 and 9 are retailers, node 9 also runs a “e-store” so that consumers can order products in a B2C mode with products shipped from a nearest warehouse. Node 10 represents a consumer group, node 11 to 14 are recyclers, among which node 11 is demanufacturer, and node 14



**Figure 5.6** A Simple Example of IESC Model

is a material recoverer. The model also reflects the growing e-Business practice in which

modularized components of electronics products can be shipped directly from supplier to distributors or to consumers. Link 1, 2, and 7 represent this situation.

The fuzzy multi-objective optimization method is applied to this model. Figure 5.7 shows the base case, network solutions of positive ideal solutions and optimization result. Table 5.8 contains optimization parameters and the improvement realized compared to the base case. The satisfactory degree for the optimization is  $\alpha=0.69$ . The Lucent metric EI (Environmental Impact) index is calculated for each scenario.

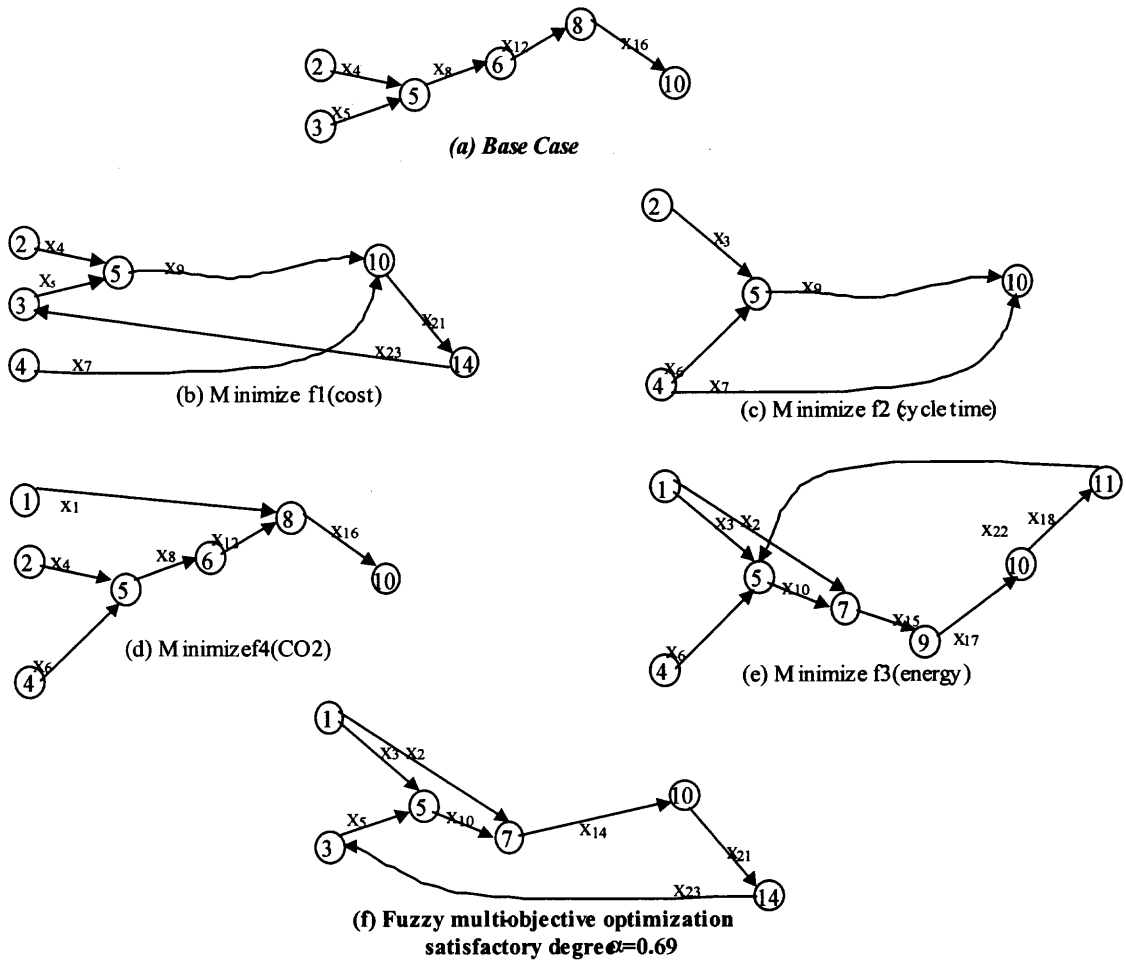
**Table 5.8 Optimization Result for the Simple Example**

	f1 (\$)	f2 hr	f3 MJ	f4 KgCE	EI	Link #
Min f1	<b>951</b>	22	7225	332	9.9	4,5,7,9,21,23
Min f2	998	<b>16.7</b>	6899	330	9.5	3,6,7,9
Min f3	1031	193	<b>6112</b>	85	6.7	2,3,6,10,15,17,18,22
Min f4	1130	279	7266	<b>14.1</b>	7.2	1,4,6,8,12,16
f	1130	279	7266	330		
<b>Optimal</b>	<b>958</b>	<b>96</b>	<b>6122</b>	<b>15</b>	<b>6.1</b>	<b>2,3,5,10,14,21,23</b>
Base case	1009	277	7037	16	7.0	4,5,8,12,16
<b>Improvement</b>	<b>5%</b>	<b>65%</b>	<b>13%</b>	<b>6%</b>	<b>13%</b>	

The solutions yield some interesting insights regarding performance tradeoffs in e-supply chain networks. Scenarios of cost and time optimization suggest to work with partners located close to your facilities and to eliminate intermediate agents between manufacturer and consumers, while energy and emission optimizations seek more environmentally efficient ways to conduct production and logistic. The balanced optimal result implies that a win-win solution is to have a closely connected and well-coordinated e-Business practice using environmentally efficient transportation logistics, integrated with a demanufacturing strategy. In this case study, the optimized solution yields 65%



improvement in time reduction, 5% improvement in cost reduction, and 13% environmental improvement as indicated by the Lucent metric EI value.



**Figure 5.7** Optimization Result for the Simple Example

## 5.4 Discrete-event Simulation of IESC Model

### 5.4.1 Discrete-event Simulation

Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system or evaluating various strategies for the operation of the system. It is used to ask “what if” questions about the real system. Its popularity is the ability to deal with very complicated models of correspondingly complicated systems.

The use of simulation as a vehicle for understanding issues of organizational decision-making has gain considerable attention in recent years. The basic principles are simple. An analyst builds a model of the system, writes computer program which embodies the model and uses a computer to imitate the system’s behavior [Piddm, 1984]. The model is built based on set of assumptions expressed in mathematical, logical, and symbolic relationships between the entities, or object of interest, of the system. Once developed and validated, the model can be used to investigate a wide variety of “what if” questions about the simulated system. Simulation modeling can be used to as an analysis tool to describe the behavior of a system, predicting the effect of changes in the system to existing systems, and as a design tool to predict the performance of new systems under varying sets of circumstances.

There are several concepts underlying simulation. The following are key concepts and their definitions of simulation [Law and Kelton, 1991].

*System:* A collection of entities, e.g. people or machines, that interact together to accomplish some stated objective.

*Model:* A representation of a group of objects or ideas in some form other than that of the entity itself. It usually contains logical and/or mathematical relationships which describe a system in terms of states, entities and their attributes, events, delays, and activities.

*Entity:* Entity represents an object that requires explicit definition. It can be any person, objects, or things whose movement through the system causes changes in the state of system.

*Attribute:* A characteristic of all entities but with a specific value in which can differ from entity to entity.

*System State:* The collection of all information needed to define what is happening within the system to a sufficient level at a given point in time.

*Variable:* A piece of information that reflects some characteristics of the system, regardless of how many of what kinds of entities might be around.

*Delays:* A delay is an indefinite duration that is caused by some combination of system conditions. When an entity joins a queue for a resource, the time that it will remain in the queue may be unknown initially since it may depend on other events that may occur.

Simulation models can be classified in a number of different ways. These classification refers to differences in the model and not to differences in the real system they represent.

- Static vs. Dynamic

A static simulation model is a representation of a system at a particular time or a system hat time plays no role. On the other hand, a dynamic simulation model represents a system as it evolves over time.

- Deterministic vs. Stochastic

Model that does not contain any probabilistic (i.e. random) components is called deterministic. If any random variables are present, the model can be classified as a stochastic model.

- Continuous vs. Discrete

In a continuous model, the state of the system can change continuously over time; in a discrete model, change can occur only at separate points.

Simulation is a widely used and increasingly popular method for studying complex systems. Advantages of simulation that may account for its wide spread appeal are the following.

- Simulation allows one to estimate performance of an existing system under some projected set of operating conditions.
- Simulation enables the study of, and experimentation with, the internal interactions of a complex system which cannot be accurately described by a mathematical model that can be evaluated analytically.
- Requires fewer simplifying assumptions and thereby capture more of the true characteristics of the real system.
- By compressing or expanding time, simulation allows the operation to slow down or speed up, and thus the simulated activity could be thoroughly investigated.
- By using simulation to perform bottleneck analysis, the causes of the delays in work-in-process, information, materials, or other processes can be discovered.
- The typical cost of a simulation study is substantially less than 1% of the total amount being expended for the implementation of a design or redesign.

- Insight can be gained about which variables are most important to performance and how these variables interact.

#### **5.4.2 IESC Simulation Model**

Network optimization techniques only provide a single “snapshot” of the supply chain. In order to understand and analyze dynamics in IESC network, A discrete-event simulation approach based on the IESC network model is applied. IESC structure has complex interactions between difference entities, simulation is thus a practical way to conduct experiments with designed model for understanding the dynamic behavior of the system and evaluating various strategies for the operation of the system. In this study, Arena [Kelton, 1998] simulation software is selected because of its object oriented approach, user defined customized templates, and integration with Windows application. The simulation model is established based on IESC definition and captures the complex dynamics of an e-supply and reflects the impact of Internet on supply chain properties in terms of cost, utilization, inventory level and supply chain environmental performance.

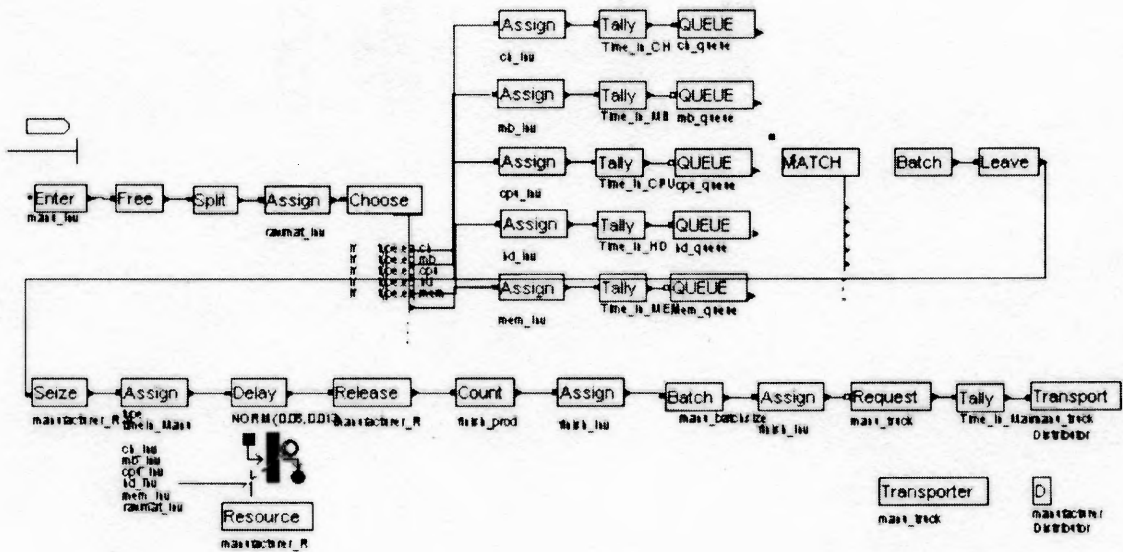
The simulation model is built according to the IESC model for performance analysis. The model captures the complex dynamics of a supply chain and thus far not focusing too much attention on each operational issue. Internet has been identified as important technological that effects supply chain performance in a significant manner. Thus two models are studied, traditional supply chain model for computer manufacturer and e-supply chain model. E-supply chain implements the Internet effects into the model.

The simulation model consists of modules for supply chain partners, and is constructed based on the supply chain activities by utilizing the existing modules in the

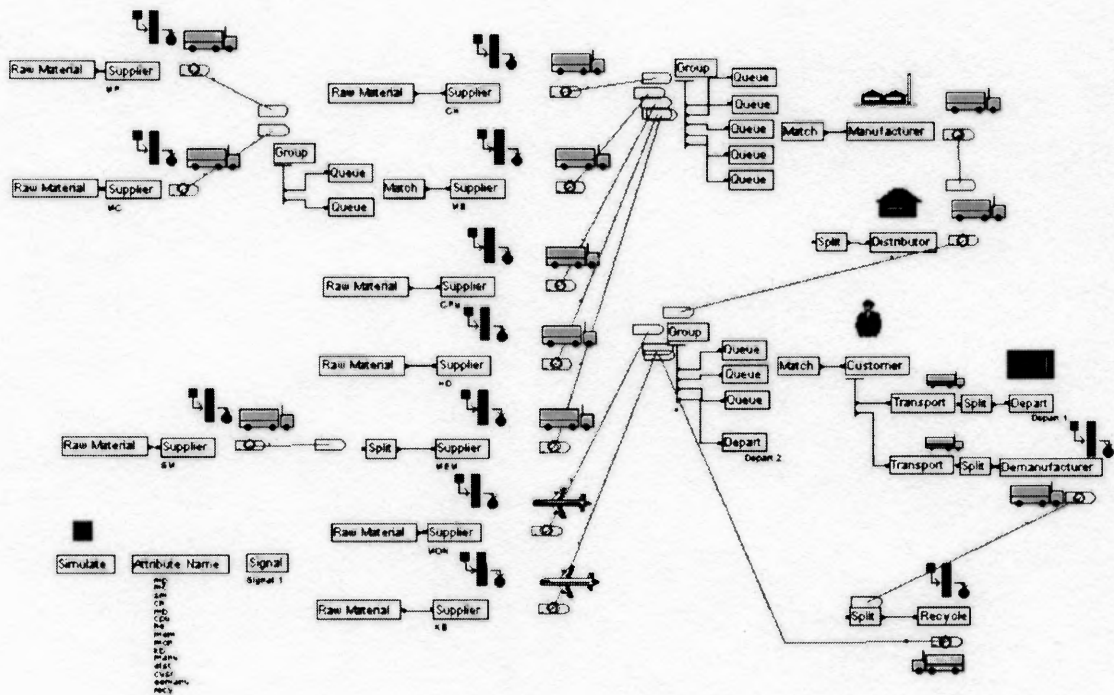
Arena. Modules for supply chain partners include Supplier, Manufacturer, Distributor, Retailer, Customer, Depart and Demanufacturer. Additional modules developed to improve the flexibility of the simulation are Raw material, Group, Queue, Match, Split, Depart, Signal, Attribute Names, Simulate, and Transport.

Manufacturer module (Figure 5.8) is an example to show how this module is built from basic Arena Temples. Parts from supplier enter the manufacturer in batches, separated into individual parts and placed in inventory (Enter, Split, Choose). Before entering the manufacturer parts are matched according to their BOM (Match, Batch). Parts are processed for a specific time and released from the manufacturer to finished product inventory (Seize, Delay, Release). Finished products are kept in inventory until a requested for product occurs (Wait). Once the manufacturer receives request, the products are then batch according to the requested batch size (Batch) and request for transporter (Request). Then the product is sent to the next operation unit (Transport). The Distance model identifies the destination and the distances. Assign module is used for updating inventory level. Other modules for the supply chain model are developed in the same manner.

Figure 5.9 shows that when all the necessary modules are put together, the structure of Integrated E-Supply Chain is built. After input parameters for every module, the model can be simulated for a specified duration of time or number of products.



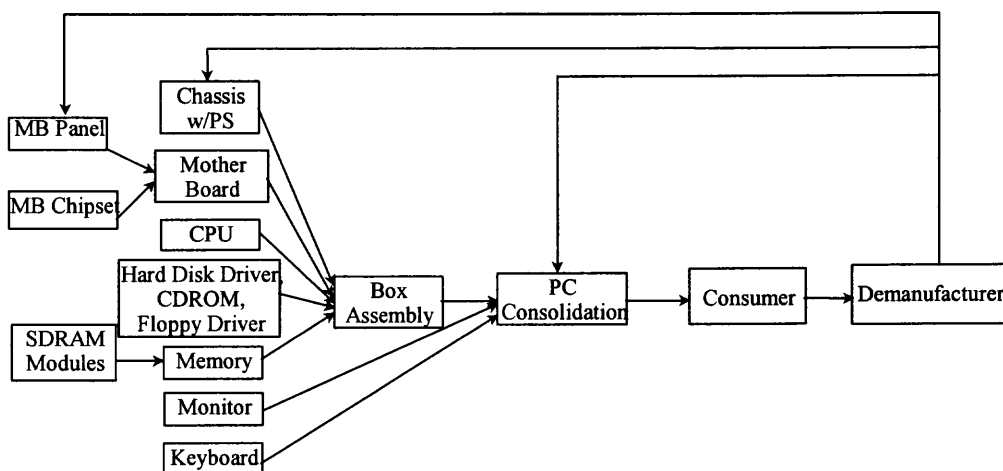
**Figure 5.8** Simulation Module for Manufacturer



**Figure 5.9** A Picture of Simulation Model

### 5.5 Case Study and Discussion

The case study is a supply chain network with two tiers of suppliers. The products are desktop computers. The model is adapted from study of real supply chain data from reference [Feigin, 1998], and extended to demanufacturing stage. The data of material inventory and energy intensity associated with material and production are from LCA study performed in MERC at NJIT. The Table contains data of energy consumption for each part/component is listed in Appendix B. An integrated supply chain model is shown in Figure 5.10.



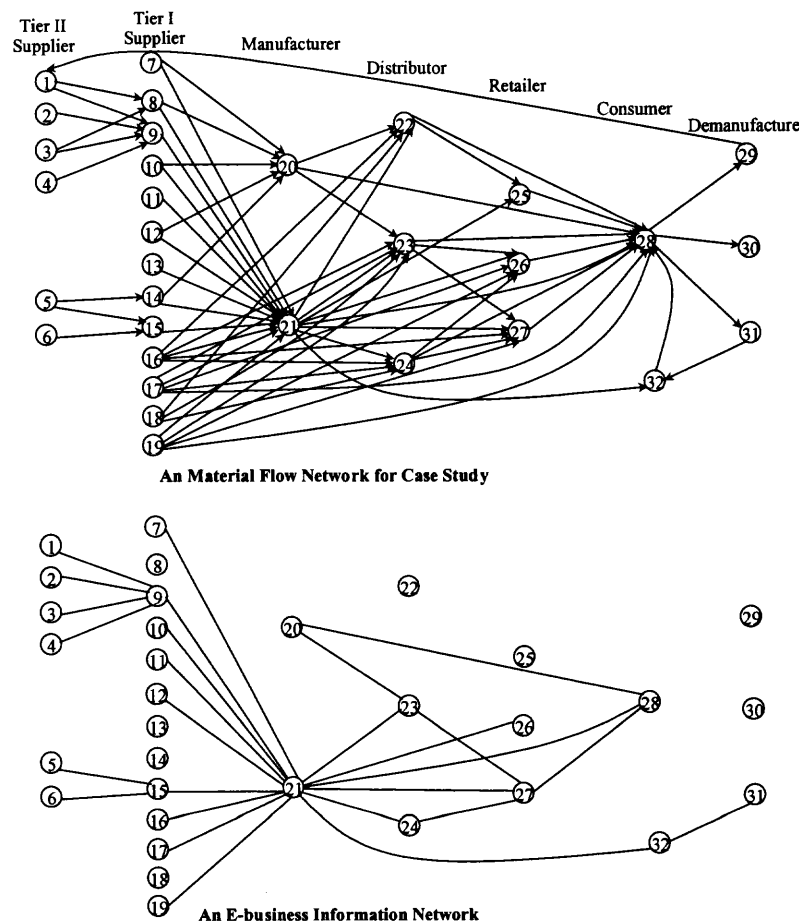
**Figure 5.10** Integrated Supply Chain Model for Desktop Computer

An IESC network model is built and depicted in Figure 5.11. It is a model with two tiers of suppliers by assuming that the performance of each first tier supplier as the aggregated performance of upstream suppliers. Interactions of supply chain partners, use of recovered materials from discarded products, and new relationships occurring because of e-Business strategies can be modeled. Supply chain data of cost, time, energy, and CO<sub>2</sub> emission are based on industry experience [Feigin, 1998], and scenario definitions reflecting the potential of e-Business strategies to reduce cost, over-production, mistaken



orders, inventories and business processing time. Transportation distances and transportation modes are also assigned to the network structure.

In Figure 5.11, the model has 32 nodes and 69 links. Note that nodes 1 to 6 are tier II suppliers, nodes 7 to 19 are tier I suppliers. Nodes 20 and 21 are manufacturers, nodes 22, 23, 24 are distributors, nodes 25, 26, 27 are retailers. Node 28 represents a consumer group, nodes 29 to 31 are recyclers, among which node 31 is a demanufacturer, and node 29 is a material recoverer. Node 32 is a maintenance service provider who obtains parts or components from either manufacturers or demanufacturers and send them to customer. The model also reflects the growing e-Business practice in which



**Figure 5.11** Case Study – A Desktop Computer IESC Network

modularized components of electronics products can be shipped directly from supplier to distributors or to consumers.

### 5.5.1 Supply Chain Network Optimization

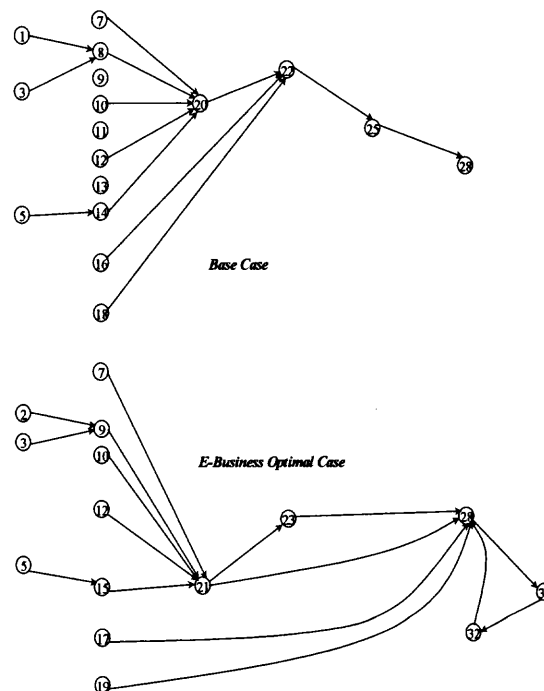
Four objective functions to be minimized are  $f_1$ , cost,  $f_2$ , cycle time,  $f_3$ , energy consumption and  $f_4$ , CO2 emission. Hence, the optimization is to:

Find  $x$  such that

$$\begin{bmatrix} C_1 & C_2 & \dots & C_i & \dots & C_N \\ T_1 & T_2 & \dots & T_i & \dots & T_N \\ E_1 & E_2 & \dots & E_i & \dots & E_N \\ A_1 & A_2 & \dots & A_i & \dots & A_N \end{bmatrix} \bullet x$$

is minimized within certain satisfactory degree  $\alpha$

where  $N=69$ , and  $C_i$ ,  $T_i$ ,  $E_i$ , and  $A_i$ , are the cost, time, energy, and CO2 emission respectively associated with both link  $x_i$  and its origin node including material, production, operation, and transportation considerations.



**Figure 5.12** Base case and Optimized E-Business Network

The fuzzy multi-objective optimization method is applied to this model. A computer program is written to solve this problem according to the optimization algorithm.

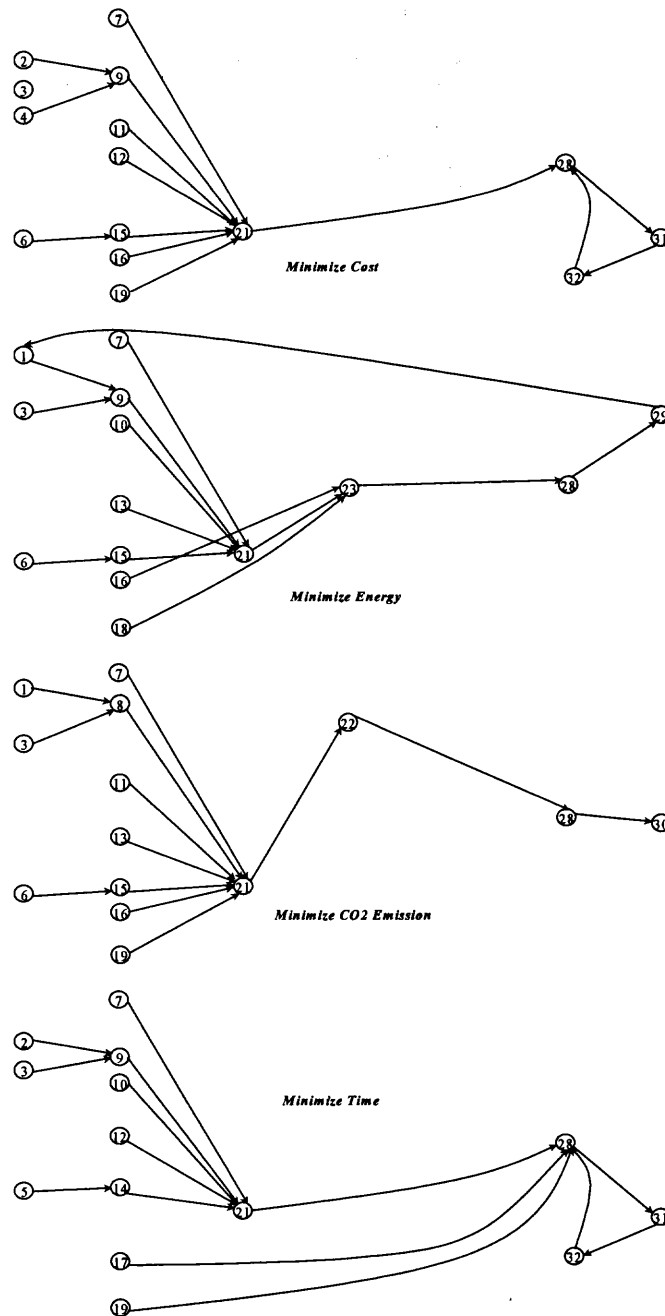
Figure 5.12 shows the base case and the optimized e-Business solution. Figure 5.13 shows four positive ideal solutions or single objective optimization solution. Table 5.9 contains optimization parameters and the improvement realized compared to the base case. The satisfactory degree for the optimization is  $\alpha=0.81$ . The Lucent sustainability EI (Environmental Impact) metric is calculated for each scenario.

**Table 5.9 Optimization Result**

	$f_1$ (\$)	$f_2$ MJ	$f_3$ KgCE	$f_4$ Hr.	EI
Min $f_1$ (Cost)	<b>1058</b>	5653	155	26	2.54
Min $f_2$ (Energy)	1164	<b>5314</b>	24	40	2.05
Min $f_3$ (CO2)	1232	5411	<b>22</b>	38	2.08
Min $f_4$ (Time)	1209	5933	268	<b>18</b>	2.83
<b>Optimal case</b>	<b>1089</b>	<b>5640</b>	<b>23</b>	<b>38</b>	<b>2.18</b>
Base case	1484	6377	28	39	2.47
<b>Improvement</b>	<b>27%</b>	<b>12%</b>	<b>18%</b>	<b>3%</b>	<b>12%</b>

The solutions indicate some interesting insights regarding performance tradeoffs in e-supply chain networks. Scenarios of cost and time optimization suggest to work with partners located close to your facilities and to eliminate intermediate agents between manufacturer and consumers, while energy and emission optimizations seek more environmentally efficient ways to conduct production and logistic. The balanced optimal result implies that a win-win solution is to have a closely connected and well-coordinated e-Business practice using environmentally efficient transportation logistics, integrated with a demanufacturing strategy. In this case study, the optimized solution yields 27%

improvement in cost reduction, 3% improvement in time reduction, and 12% environmental improvement as indicated by the EI value.



**Figure 5.13** Network Optimization Result

The results also show the change of the product consolidation points in different cases and its impact to the system performance. In the base case, the product is consolidated in distribution center, whereas, in the optimal case, the product is consolidated in customer location. Minimal cost case and minimal CO2 emission case both suggest that product be consolidated in manufacture site; but minimal energy case requires the consolidation point in distribution site for this specific example. These results imply that the product consolidation point can affect the transportation routes, modes, and supply chain partner selection, thus impact the overall system and environmental performance.

### 5.5.2 System Simulation

The simulation models are constructed for four cases: base case model assuming traditional business practices, multi-objective optimal case, cost optimal case and energy optimal case. The manufacturing lead times for each components and processes is assumed to follow normal distribution.

**Table 5.10** Time for Components and Processes

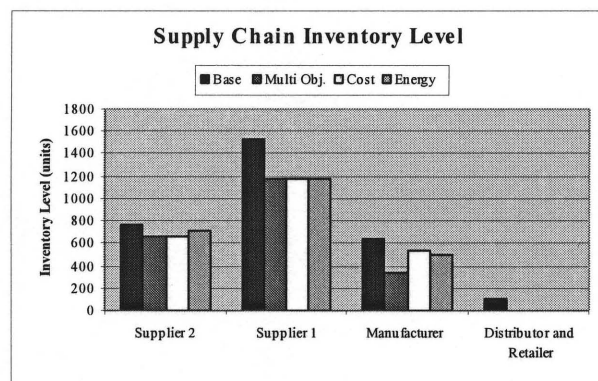
Process	Time		Process	Time	
	Mean	Std.Dev.		Mean	Std.Dev.
MB Panel (MP)	8	0.7	Hard disk (HD)	25	1.7
MB Chipset (MC)	25	1.7	Memory (MEM)	5	0.7
SDRAM (SM)	20	0.7	Monitor (MON)	13	1.0
Chassis (CH)	25	1.7	Keyboard (KB)	5	0.3
Mother board (MB)	3	0.3	Manufacturer	1	0.2
CPU	25	1.0	Distributor	1	0

The times, units in day, are shown in Table 5.10 (Feigin, 1998). Manufacturer has capacity for producing 25,000 units per month. Each model was run for ten independent replications with simulation time 120 time-units or six months production in each replication.

The simulation results show that the average time in system reduced from 30 days in base case to approximately 10-15 days in optimized cases indicating improvement in system performance. Supplier inventory reduced approximately 20% in the optimized cases compared to the base case.

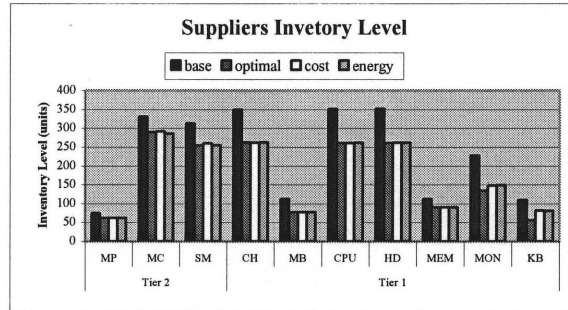
Manufacturing inventory reduction is various for each case. In multi-objective optimized case, the final product is consolidated at customer, and the inventory reduces 46% compared to the base case. For optimal cost and energy cases, the structures are similar to base case in terms of the consolidation point. However, with information links or e-supply chain network, manufacturer's inventory is reduced approximately 20%. Inventory level in distribution and retailer are reduced 100% resulting from built to order concept in the optimized cases.

The supply chain partners' inventory level comparison is shown in Figure 5.14. For more detail inventory distribution, Figure 5.15 shows the inventory level for each individual



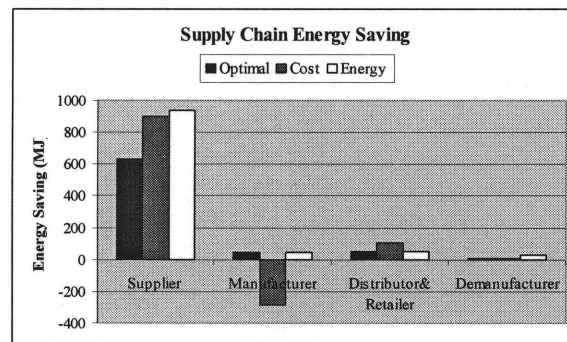
**Figure 5.14** Supply Chain Inventory Level

supplier in both tier I and tier II. The name abbreviation is indicated in Table 5.10. It is seen that, for each supplier, inventory level can be reduced if e-Business optimal structure is applied.



**Figure 5.15 Suppliers Inventory Level**

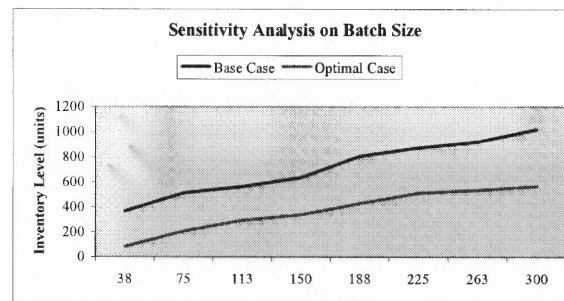
Assuming energy consumption for warehouse floor space is 2 MJ/PC [Caudill et al, 2000a], reduction in inventory results in reduction in associated energy consumption. Taking base case supply chain energy consumption as baseline, Figure 5.16 shows the energy saving for the optimal cases. Note that the energy consumption includes material, process, transportation and inventory energy uses. The energy saving results also show that the multi-objective optimization result is a compromised solution because there are several contradicting objectives and they cannot be optimized at the same time.



**Figure 5.16 Energy Saving of Optimal Cases**

For a given model, sensitivity analysis is used to access the impact of changes of input data on the results. In this case study, change in standard deviation for processing time and change of batch size are analyzed.

The standard deviation for processing time is increased from 25% to 100% and decreased from 25% to 75%. The inventory levels remain relatively stable for different standard deviation value, which indicates that changes in standard deviation do not have significant impact on the simulation result. The change of batch size will have impact on the individual results, as shown in Figure 5.17. But in terms of ratios of results, such as ratios of optimal base over base case, they remain in the same range.



**Figure 5.17** Sensitivity of Batch Size to Inventory Level

### 5.5.3 Discussion

The integrated e-supply chain network model is presented in this chapter to explore the environmental impact of emerging e-Business on production supply chains. The study indicates that the changing relationship in the e-supply chain will have significant impact on system performance in terms of basic characteristics such as cost, cycle time, and inventory level, as well as environmental performance of each supply chain partner and the overall supply chain. A novel approach is presented which combines fuzzy logic decision theory with a hyper-network formulation of e-Business strategies using an



integrated physical material flow supply chain structure overlaid with the internet-based communication network. A fuzzy multi-objective programming method is presented to solve the network optimization problem. The optimized network is also simulated using discrete-event simulation techniques to analyze the robustness of the network to dynamic operational variables and stochastic parameter variations. The study indicates that networked e-supply chain has many interesting characteristics over conventional sequential supply chain. An optimized e-supply chain network for a desktop personal computer product has the potential to yield significantly better performance in terms of business goals and environmental goals than traditional practices.

### 5.6 Summary

The IESC model and methodology is novel in that firstly, it extends the traditional supply chain structure to an integrated and more sustainable supply chain system; secondly it combines two overlaid and interconnected network to model the e-Business strategy, information flows, as well as material flow network; Thirdly, fuzzy logic theory is applied and extended to deal with the data uncertainty and information gaps, and to optimize the network configuration under multiple goals.

The present model opens a rich field for the e-supply-chain model improvement, efficient algorithm development, and benchmark studies. Base on this study, the following research directions should enrich the design theory and practice of the environmentally conscious e-Business systems:

1. Solution methods need to be refined in order to deal with other types of problems, such as optimal selection of both nodes and links or optimizing two networks, material and information ones, at the same time;
2. Algorithm complexity and efficiency is another problem to be explored. Generally, the larger the network, the more the decision variables, hence, the more complex the algorithm. The complexity of the present algorithm grows exponentially with the network size. The intelligent agents such as rules and knowledge bases are being considered to integrate with the method in order to guide the search procedure and improve the algorithm efficiency;
3. The impact of e-links on a material flow network is worth to be further investigated. Not only can they affect the corresponding m-links' performance, as illustrated in the case study, but also the configurations of two overlaid networks through e-link's performance such as degree of e-connection and degree of e-corroboration. Different e-Business strategies can be reflected by the selection of different e-links, leading to an interesting theoretical and practical research area; and
4. Fuzzy modeling techniques can also be used to model fuzzy data to characterize nodes and links. Weighted fuzzy utility function can be used in this case, and more research issues need to be addressed to design agile and environmentally conscious Internet-based manufacturing systems

## **CHAPTER 6**

### **SCALABLE ENTERPRISE ENVIRONMENTAL MANAGEMENT SYSTEM**

Over the last few decades, environmental issues have been treated as peripheral concerns to business and framed as added costs driven primarily by regulation or customer requirement. Today, many companies are regarding environmental performance as a competitive strategy. Indeed, a form of “sustainable enterprises” is emerging where environmental and social performance is embedded proactively into core business processes, systems, products, and strategy of the firm. The Scalable Enterprise Environmental Management System (SEEMS) is a new e-Business strategy proposed at MERC to leverage the Internet, WWW, e-Supply Chain Management and other advanced technologies, such as knowledge management and intelligent agents, to allow organizations to manage environmental performance across the virtual sustainable enterprise in a collaborative, effective and efficient way. In this chapter, the underlining rationale and motivation for this new direction are first introduced, then the research challenges are discussed including enterprise application integration, intelligent agent-based structures and knowledge management in achieving the SEEMS strategy. The methodologies for knowledge representation and extraction in SEEMS using ontology and eXtensible Markup Language (XML) are then presented. Afterwards the design and implementation of SEEMS are described in terms of system architecture and main functional modules.

## 6.1 Rationale and Motivation

The industrial world is in the process of profound change being driven by two major technological and societal developments. One is the Internet, which has the potential to drastically change the way corporations conduct business from designing and manufacturing products to managing supply networks and customer relationships. The other, just as powerful, is the recognition that the earth's ecosystem is being threatened by excessive greenhouse gas emissions resulting in global warming and the potential for climate change. Growing a strong industrial economy while maintaining a clean and healthy environment is a daunting challenge; however, with companies rapidly embracing e-Business strategies, a unique window of opportunity exists to develop new technologies and decision support tools that can alter current industry practices along a pathway towards sustainability, enhancing resource productivity, improving cost efficiencies and reducing lifecycle environmental impacts.

A dedicated research and development initiative focused specifically on these new internet-enabled technologies, decision support tools and business strategies must be undertaken in order to develop a rich scientific base and drive innovation before the window of opportunity closes. The primary goal of this initiative is to develop a scalable enterprise environmental management system (SEEMS) to integrate sustainability seamlessly into everyday corporate business practices and strategic decision-making. SEEMS is envisioned as a configurable web-enabled portal integrating *horizontally* across the enterprise to link product realization and production activities crossing corporate boundaries along the entire extended value chain, and *vertically* extracting information and data transparently from enterprise resource planning (ERP), product data management (PDM), and legacy database systems within the organization.

Distinguishing features of SEEMS are robustness, reliability, flexibility, and the ability of the system to dynamically adapt to changing conditions.

The major underlining rationale and motivation for this new program is based on the following emerging trends and technological drivers:

1. In today's global economy, leading edge companies are beginning to form agile collaborative partnerships which cross organizational and geographic boundaries. This *cooperate to compete, virtual enterprise* concept is being referred to in the manufacturing sector as "Design Anywhere, Manufacture Anywhere (DAMA)". For example, the Matsushita Corporation promotes this new collaborative product development strategy as *TechnoStory*, a corporate-wide initiative to create partnerships with their customers as well as their suppliers to bring new products into the marketplace faster and cheaper. These collaborative technologies are Internet enabled and still under development with significant challenges to the complexity of cultural issues and implementation. As described in a recent DAMA engineering conference, several American companies from various product sectors, including electronics, automotive, aerospace, and textiles, have embraced these concepts and have DAMA implementations underway [MRT, 2001]. However, while the current set of DAMA technologies and decision support tools are extremely powerful, they do not consider design for environment, environmental reporting and management, demanufacturing and asset recovery systems, or other issues associated with product stewardship and sustainability. Industry has struggled for years to integrate product stewardship and environmental lifecycle performance throughout all aspects of the product development process. Now, this goal will be even more

challenging unless DAMA technologies and tools are developed with environmental sustainability as a core element and fully functional consideration.

2. The Engineering Directorate of the National Science Foundation (NSF) announced a research initiative on Scalable Enterprise Systems to foster the development of a science base for enterprise-wide business automation. NSF recognizes that “the promise of ERP is more than enterprise-wide interoperability and consistency. Its objectives should also include standardization of its principal functional modules to minimize customization and enhance reliability. Currently, ERP implementations require a high degree of customization. Full implementation often takes years with many efforts never completed. What is needed is a theoretical foundation similar to the one provided to database systems by the relational model. Development of this science base has the potential of giving rise to a new research field.” While recognizing the importance of environmental management as a critical enterprise system function, none of NSF’s projects concern scalable systems for sustainability or product demanufacturing.

3. At a recent meeting in Bonn, Germany, environmental ministers and government officials from around the world forged an historical agreement to reduce greenhouse gas emissions that threaten global warming and the potential for climate change. One element of this agreement is the potential for trading greenhouse gas credits on the open market; consequently, GHG reductions may have a bottom line economic impact on governments and corporations. It remains to be seen if credit will be allocated to end-of-life product recovery and material recycling as an acceptable method for reducing GHG. If so, then there could be a tremendous economic stimulus to material recycling programs and a boost to design-for-environment initiatives and the overall demanufacturing industry.

The US was the only major industrialized nation at the Bonn meeting to oppose the greenhouse gas reductions, as outlined in the Kyoto Protocol, saying that it would adversely affect the American economy and its ability to stimulate economic recovery across the world. Clearly, many political and industrial leaders perceive economic growth and environmental sustainability as competing, not complementary, priorities. Without the new technologies and decision support tools envisioned in this R&D program, the two goals of economic security and environmental sustainability will continue to be incompatible and unreachable.

The primary research thrusts that have been undertaken in this dissertation are the following:

- *Modeling* of enterprise-level processes including process specifications, decision support, and various levels of abstraction.
- *System architecture* issues including both horizontal and vertical integration platforms or frameworks. These issues also include standardization of application programs, data extraction and allocation principles.
- *Supply chain network design* issues in the broader context of enterprise systems. These include structures for the integration, coordination, and management of the complex variety of activities associated with product design, outsourcing or strategic alliances with demanufacturers and recyclers, and decentralized mechanisms to enhance performance of the overall enterprise system.

Further research work being investigated includes *Collaborative decision making* in scalable enterprise systems including the sharing of collaborative knowledge and

protection of core knowledge, and the incorporation of risk and uncertainty using fuzzy decision strategy.

The following development work has been conducted building upon the research thrusts and leveraging existing work on web-enabled technologies, decision support tools and environmental sustainability.

- *Formulation of the requirements document* to formalize the structure and framework for SEEMS development and detailed implementation plans.
- *Integration of existing modules* to leverage work already underway by MERC, CTC and partner organizations including MLCA, WebVDM, Sustainable Target Metric, and DFE design, analysis and engineering support tools.
- *Development of wrappers and adapters* to interface with standard ERP and PDM and workflow systems; i.e., SAP and Windchill.
- *Creation of intelligent agents* to support functional activities associated with decision support, reporting, notification, emissions credit bidding, engineering analysis and data extraction and allocation.
- *Implementation of the SEEMS structure and framework* to enable the web portal to be configurable and scalable with a focus on robustness, reliability, flexibility, and the ability of the system to dynamically adapt to changing conditions.



## 6.2 Research Challenges

The SEEMS strategy is about enterprise application integration, environmental knowledge extraction, performance evaluation, change notification, environmental reporting, and deployment of other environmental management tools across the breadth of the virtual enterprise in a global web-based environment. It is about the sense of involvement and collaboration that each partner in the extended virtual enterprise has a responsibility for the environmental impact of products or services throughout the entire lifecycle. SEEMS is designed to be able to embed environmental management and involve partners into every product lifecycle stage and beyond that to end-of-life stages and next generations.

In practice, the environmental information resides in many dispersed sources, and is coupled with product design, manufacturing, and business data. The challenge of SEEMS is getting all of the pieces of scattered environmental data to fit together in a way that is easy to understand, use and administer, and is configurable and scalable throughout a global virtual enterprise.

New e-Business initiatives such as Design Anywhere Manufacturing Anywhere (DAMA) strategy and Collaborative Product Commerce (CPC) solution have been highlighting many possible technologies to deploy the SEEMS. There are still many problems that need additional exploration both in industry and academia before such a solution can be achieved.

One of the issues is enterprise application integration over the web-based environment. The enterprise applications, such as CAD/CAM/CAE, Design for Environment (DFE), Enterprise Resource Planning (ERP) etc., are being used by different partners through the multi-lifecycle production system. A comprehensive model

is needed to clarify the levels of integration. Second issue is agent-based design as opposed to traditional passive execution design. The components in SEEMS would be able to autonomously interact with other parts of the system to exhibit fault tolerance and gain in operational efficiency if they were designed to operate as agents. These characteristics will be critical in the distributed e-Business system. The most important issue that needs to be addressed is the need of unified and Internet-oriented knowledge consolidating mechanism. The lack of this mechanism leads to ad-hoc implementation models and non-standard system. Recently research areas of ontology-based knowledge management and XML technology are emerging to drive consensus relative to the information share and exchange, and interoperating over the Internet.

### **6.2.1 Enterprise Application Integration Model**

SEEMS implies a concept of integration where application tools, processes, and pieces of information across the multi-lifecycle production systems are to be interoperated over the Internet platform, so that environmental information can be extracted, understood and exchanged from dispersed data repositories residing in different enterprise tools. It involves many technical issues such as information model, operational model, interface method, Internet-based communication method, etc. Figure 6.1 gives an overall picture of virtual enterprise integration across the product lifecycle and the integrated e-supply chain. The integrated supply chain partners constitute a virtual enterprise.

In this diagram, *CAD/CAM/CAE* applications address authoring, modeling and analysis of products and generate production information, typically in the model file. *Design for Environment* (DFE) Tools evaluate and examine the product design and

feedback environmental performance to the designers. *Product Data Management* (PDM) systems manage engineering documentation in the form of design file and metadata. *Computer Aided Process Planning* (CAPP) tools support the authoring of assembly and installation instructions. *Sales Configurators* facilitate the make-to-order process by defining customer specific options. *Manufacturing Execution System* (MES) manage shop floor activities. *Enterprise Resource Planning* (ERP) systems provides data capture,

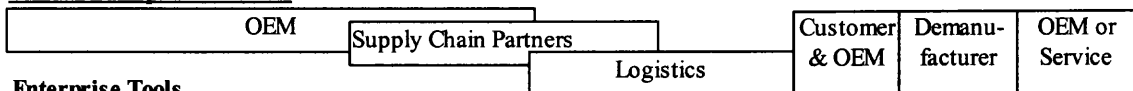
#### Product Lifecycle Stages

Material extraction & synthesis	Component outsourcing	Product Manufacturing	Distribution	Usage	Demanufacturing	Recovery & Reuse
---------------------------------	-----------------------	-----------------------	--------------	-------	-----------------	------------------

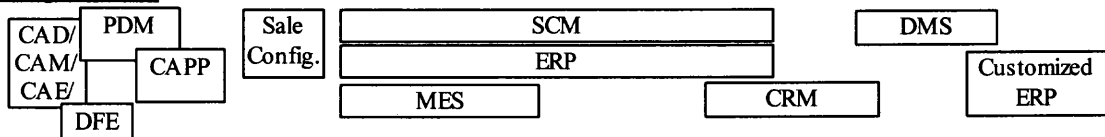
#### Multi-lifecycle Production Workflow Stages

Design	Manufacturing Engineering	Order fulfill	Procurement & Production	Distribution	Customer Delivery	Use & Service	Demanufacturing	Recovery & Reuse
--------	---------------------------	---------------	--------------------------	--------------	-------------------	---------------	-----------------	------------------

#### Virtual Enterprise Network



#### Enterprise Tools



#### Three Levels of Integration

<i>Data/Information Model</i> needed to process data from repositories, systems and platforms
<i>Integrated Business Process Model</i> needed to provide optimized workflow
<i>Distributed Computing Model</i> needed to interconnect software systems across the Internet



**Figure 6.1** Virtual Enterprise Integration Model

reporting, and integrates distinct functions such as inventory management, production planning, human resources and finance at a transaction level typically within company boundaries. *Supply Chain Management* (SCM) systems decision support capability through real-time analytical systems for functions that cross company boundaries. *Customer Relationship Management* (CRM) systems target acquisition and retention of

customers. Many of these systems are evolving beyond the enterprise to address supply chain collaboration.

Figure 6.1 shows that there are three levels of integration across the product lifecycle, or the virtual enterprise. They are distributed computing level, process level and data level. The three levels are related with each other but have different integration goals and approaches.

Distributed computing level is the lowest level in which the issue is accessing data and decision support tools from distributed sources over the Internet. The distributed computing solution for the complex scenario in SEEMS is no easy development work. Often, the software systems that need to be interconnected were not originally designed for communication within a distributed environment, thus providing no inherent interface for communicating with the outside world. Even if such interface exists, low-level network programming for interconnection of distributed sites can be a challenge that application programming experts may not be prepared to address. Therefore, availability of tools and standards that can ease distributed communication is an important aspect in this level of integration.

There have been significant developments over last ten years in the creation of middleware solutions that provide standardization for communication with distributed software components, as well as, layers of abstractions that provide more effective ways of programming in distributed environment. The Common Object Request Broker Architecture (CORBA) of the Object Management Group (OMG) emerged in the 1990's is an important standard for access to distributed software components [OMG, 1998]. The CORBA standard has matured significantly since the early 1990's, providing advanced

features such as event notification and transaction processing. In parallel with the maturity of the CORBA standard, several different solutions for distributed object computing have also emerged based on the use of JAVA technology [JAVA, 2000]. The JAVA's Enterprise JavaBean [EJB, 2000] specification provides a sophisticated software component model which can provide a cleaner separation between business logic and low-level distributed computing issues. In the SEEMS design, JAVA EJBs are applied to act as agents to perform various functions.

Process level integration is also important in that product lifecycles typically involve many different groups and goes through many processes. The output from one process must often serve as the input to the next process, creating a workflow of activities between collaborative groups. Integrating and analyzing business processes in the environment of virtual enterprise requires systematic approaches and decision-making technologies. High-level business process models need to be abstracted and well defined. System analysis and simulation tools are also required to facilitate the process definition and optimization. The hyper-network framework of Integrated E-Supply Chain (IESC) and associated decision methodology and simulation tool presented in chapter 5 are good examples of this kind of process integration tool.

The idea of data level integration is to enable disparate and heterogeneous systems to interoperate by exchanging structured data that every application can understand. Approaches that have been pursued to enable application interoperability include three types [Burkett, 1998]. One type is to build point-to-point translators that convert data bound to one application into the data format of a target system; second type is to build shared database that is used by multiple applications; and the third type is to

constitute database federations in which each repository makes its data visible and accessible via Application Program Interface (API) to other applications in the federation. These approaches are problematic due to low efficiency, semantic clashes, or huge and complex database schema. To address these challenges, various groups within industry, academia, and government have been developing sharable and reusable models known as ontology [Ciocoiu, et al, 2001]. All ontologies consist of a vocabulary along with some specification of the meaning of the terminology within the vocabulary. In doing so, ontology support interoperability by providing a common vocabulary with a shared machine-interpretable semantics. Under this approach, integration and interoperability are achieved by writing translators between the terminology used in each application and the common ontology.

### **6.2.2 Agent-based Design**

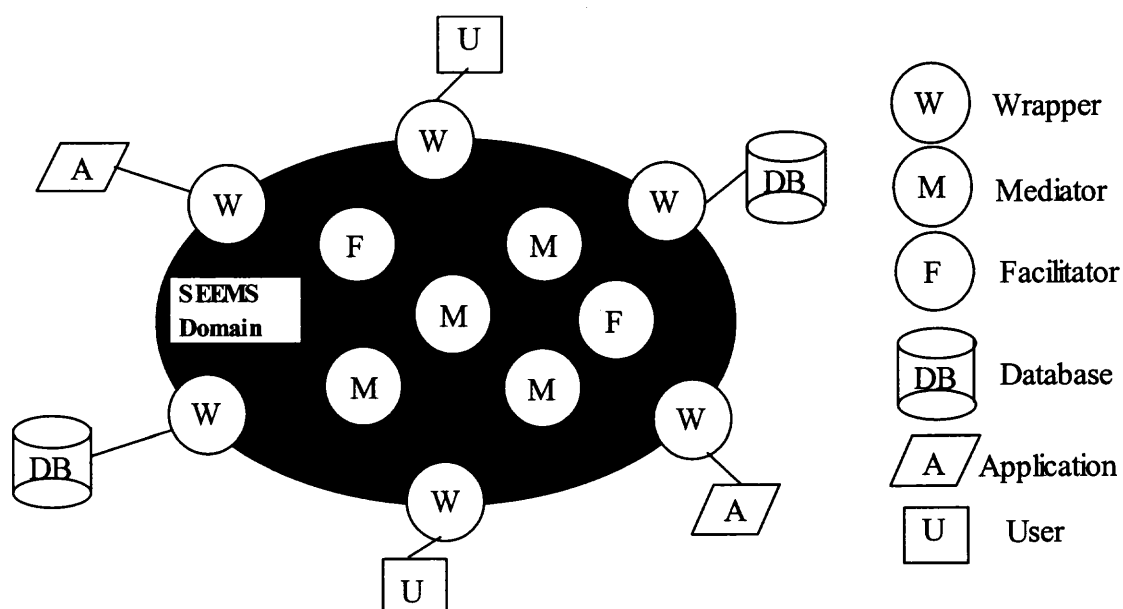
The SEEMS is a web-based environmental management system which connects to various enterprise applications such as CAD/CAM, ERP or SCM tools to extract environment-related data, perform assessment and evaluation, send notification, generate environmental report, etc. The passive execution model of traditional systems is no longer appropriate in e-Business environment of SEEMS. Instead intelligent or autonomous agent-based design is a good alternate for distributed and efficient execution.

Research on the intelligent agents has mushroomed in the past few years. There are two areas of research on agents [Isbister and Layton, 2001]. One is on the use of AI techniques to create software components that performs information filtering, processing, parsing and other autonomous tasks for users. The other is on the agent as an interface

metaphor that aids users. An agent can be described as an entity that captures behavioral characteristics of the problem for a specific process or activity. An intelligent agent is an autonomous entity that can navigate heterogeneous computing environment and can, either alone or by working with other agents, achieve some goal [Fischer et al., 1996].

Much of the foundational research has already been established, yet to date these technologies have had little impact on the e-Business applications. In the SEEMS domain, agents can provide such functions as automation, notification, guidance, as well as knowledge processing, reporting, and learning in a highly open and dynamic architecture. A typical agent-based e-Business can be sketched as shown Figure 6.2.

Some commonly used agents such as wrapper, mediator, and facilitator are shown in Figure 6.2. Wrappers are agents that act as proxies for external knowledge sources, typically databases in legacy systems, to provide a bridge between the legacy system and the e-Business application. Wrappers also connect users to the system by transforming a user's request into the internal knowledge representation language. Mediators are the



**Figure 6.2** Agent-based Design of SEEMS

internal knowledge-processing agents that can add value in some way to the knowledge obtained from other agents. Typical mediator tasks include filtering, sorting, and fusing knowledge obtained from scattered sources. Facilitators are the “matchmaker” agents that allow other agents to register their identity, location, and function.

The agent-based approach is promising due to its flexibility, plug-and-play property, and powerful knowledge processing capability, and easy adaptation to an Internet communication model. In the SEEMS environment, intelligent agents can be designed to extract knowledge, generate information as well as to perform certain functions. Inter-enterprise information agents provide the trusted mediator to exchange information between the separate companies that make up a virtual enterprise.

It is commonly agreed that agent-based systems to support the next generation of Internet commerce must adopt a common information model if they are to interact without misunderstanding. In the next section, an Internet-oriented information model — ontology-based XML technology will be discussed as a potential solution to this problem.

### **6.2.3 Ontology-based XML Method for Knowledge Representation and Integration**

The lack of interoperability among various enterprise applications in an e-Business environment is one of the major problems facing today’s enterprise. For the proposed SEEMS design, the challenge is even bigger because of the heterogeneity of the enterprise environment-related information residing in dispersed sources.

Many technologies have been developed to resolve information heterogeneity. The most recent effort is the research of ontology. An ontology is an explicit specification of a conceptualization [Gruber, 1993]. It is a formal structure that expresses



concepts needed in a certain domain in a way that is effective for facilitating translation of those concepts, and is free from the problems of imprecision and ambiguity associated with natural language [Ciocoiu, et al, 2001]. An ontology can provide a deep categorization of knowledge so that it can be reasoned with at various levels of abstraction. In essence, it provides the means to associate a semantic with a set of terms that demote categories of entities of interests.

Ontology includes a vocabulary for referring to the subject area, and a set of logical statements expressing the constraints existing in the domain and restricting the interpretation of the vocabulary. To represent an ontology, a presentation language is needed. Knowledge Interchange Format (KIF) based Ontololingua [Genesereth and Fikes, 1992] and Loom [Loom, 2001] are examples of representation language based on first-order logic. However, for applications on the web it is important to have a language with standardized syntax and inherently Internet-enabled. Over the last couple of years, Extensible Markup Language (XML) has emerged to be a standard language for data sharing and interchange on the web. Therefore, it is desirable to exchange ontologies using XML syntax.

XML is not a programming language, and even not a markup language itself, but rather a language for developing markup languages. HTML is one markup language that can be defined in XML. Other such languages for specific application domains can also be developed. Any XML compliant system should be able to read and parse a document, no matter what the specific markup language is. So XML is a powerful, elegant technique for thinking about, exchanging, and presenting data in a platform-independent manner.

XML consists of three main components. The XML file itself defines the structured content and the syntax for the document structure. Tags are used to set off markup entities from the actual content of the document. And a Document Type Definition (DTD) or XML Schema defines what tags can appear in a document, how those tags can be nested, and what attribute each tag can have. DTD and XML Schema are also called XML vocabulary. XML vocabulary is a structured ontology that specifies the possible content of an XML document. It is a model of data, and usually should be small in scope and specific in application if the meaning of the terms to be clear and unambiguous to the user of the vocabulary. XML are standalone in use, but should be a part of a comprehensive structure specified via a mapping.

A DTD or Schema defines the structure, content, semantics and rules associated with XML documents. The processor can retrieve DTDs or Schemas and use the rules to generate a well-formed XML document instance or parse the validity of a document instance. DTDs use a syntax namely Extended Backus Naur Form which is difficult to read and use. The Schema is a replacement for DTDs to use XML syntax to describe the language they define, and support for datatypes and inheritance. XML Schema was approved as a World Wide Web Consortium (W3C) Recommendation in May 2001. In SEEMS design, the XML Schemas are expressed to share knowledge vocabularies and allow machines to carry out rules made by people.

Ontologies support interoperability by providing semantics for terminology in a computer-interpretable format, and play a critical role in knowledge modeling and integration. Meanwhile, XML is designed to be a platform-independent and web-friendly structuring syntax for the representation and exchange of data on the Internet, and allows

the specification of a specialized document structure. Ontology-based XML is a powerful interoperable technologies to lead the Web to its full potential as a forum for information, commerce, communication, and collective understanding. Due to the intentional generality of XML and the specific requirement of enterprise environmental management, significant work must be done to specify how ontology-based XML can be used in the SEEMS domain. In section 6.3, the usage of ontology-based XML in enterprise environmental knowledge representation and integration will be shown.

### **6.3 Knowledge Management in SEEMS**

The Internet is rapidly accepted as a new and promising business vehicle. Companies who deploy Web-based strategies are in a better position to compete, collaborate and take advantage of emerging technologies. SEEMS is a web-based enterprise application that leverages knowledge integration and XML technologies to achieve Internet-based collaborative environmental management at the product level as well as the enterprise level.

#### **6.3.1 Knowledge Modeling of the Lucent Sustainability Target Metric**

The Lucent Sustainability Target Metric introduced in chapter 4 is a universal metric which possesses numerous necessary attributes to be used in SEEMS as an environmental performance evaluation metric. As discussed in chapter 4, the Target Metric can be applied to the enterprise facility, product or service level. Resource Productivity (RP), used as a cumulative measure of environmental impact, offers an alternative to the supply

line LCA. Eco-efficiency (EE) extends RP, based on the value provided by the business, provides an absolute indicator for sustainability.

In order to model this metric, ontologies are used to abstract the knowledge contents and hierarchy. Two ontologies need to be structured. One is the Target Metric Evaluation ontology, and another the Target Metric Carrying Capacity ontology. The evaluation ontology categorizes the assessment level, environment aspects, and economical values that are necessary for performance evaluation. The carrying capacity ontology depicts the environmental impacts and their carrying capacities. Figures 6.3 and 6.4 are the ontologies for The Lucent Sustainability Target Metric.

The two ontologies are closely related when applying the Target Metric to do the evaluation. The carrying capacity ontology is stored in a central location for being maintained and updated according to the version upgrade. The evaluation ontology resides in distributed locations for being used to do the performance evaluation. The evaluation agents retrieve the carrying capacity values when performing certain functions.

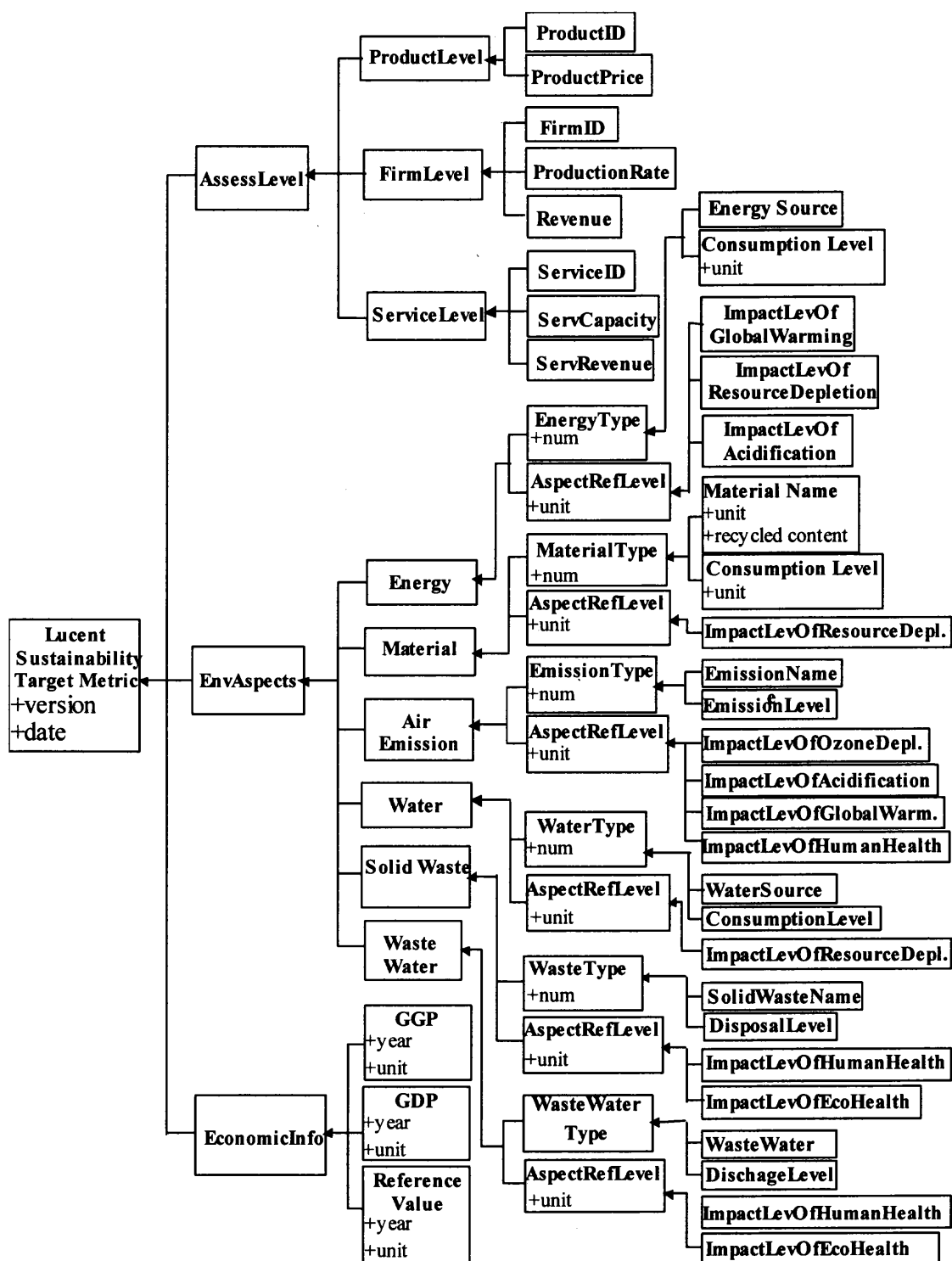


Figure 6.3 Target Metric Evaluation Ontology

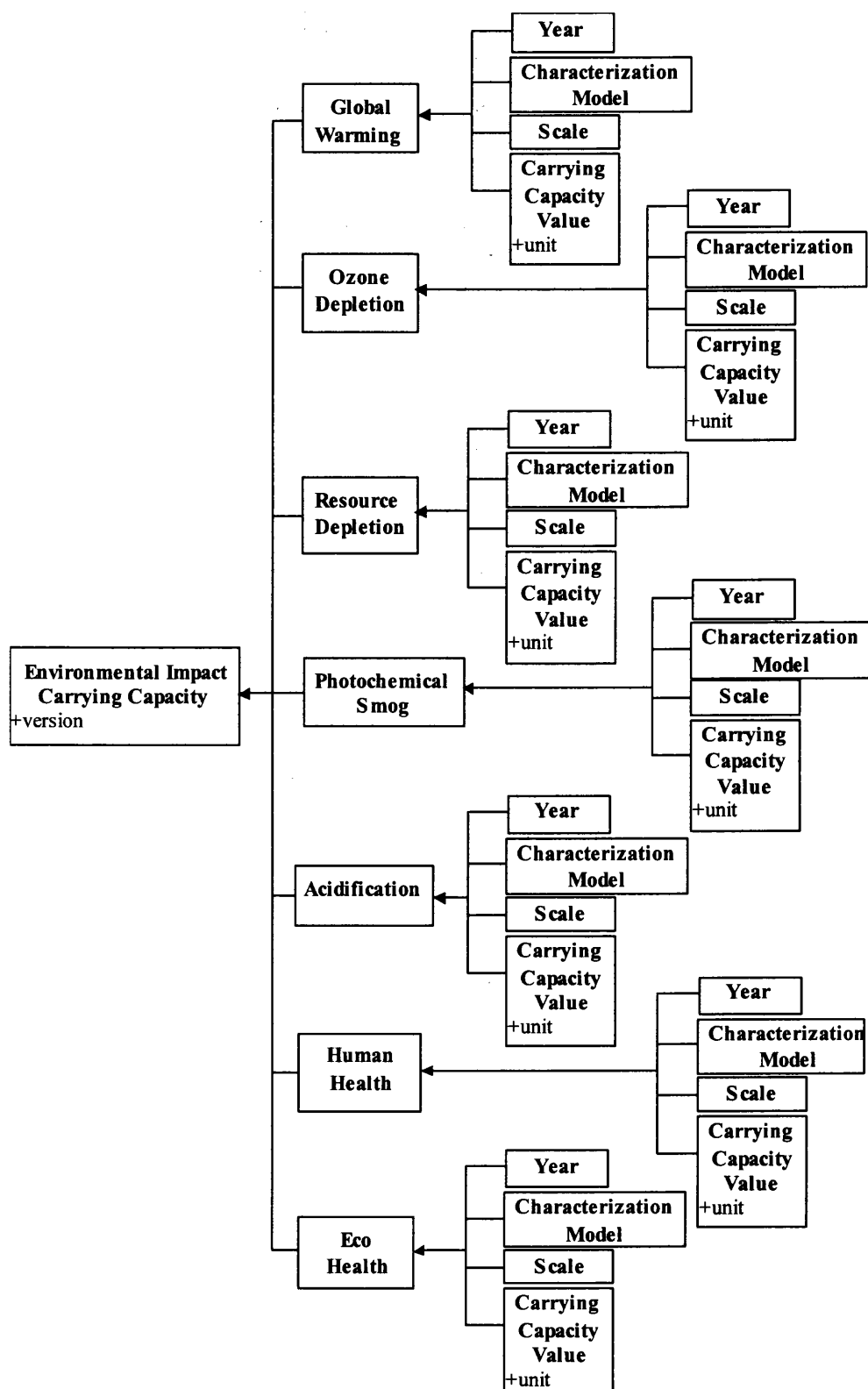


Figure 6.4 Target Metric Carrying Capacity Ontology

Based on these ontologies, the universal format of XML is applied to encode them to Internet-enabled structured documents. Figure 6.5 is a part of XML Schema file for the evaluation ontology. Figure 6.6 is an XML document instance for a product assessment. The Schema is used to define, describe, and catalogue XML vocabularies and rules by which XML document can be generated and parsed.

```
<?xml version="1.0"?>
<Schema version="1.0"
  xmlns="http://www.w3.org/2001/XMLSchema"
  xmlns:dt="urn:datatype">
  <description>This is the XML schema file for Lucent Sustainability
    Target Metric</description>
  <ElementType name="Lucent SustainabilityTargetMetric"
    content="eltOnly" order="seq">
    <attribute type="metricVersion" dt:type="String"
      required="yes"/>
    <element type="AssessLevel"/>
    <element type="EnvAspects"/>
    <element type="EconomicInfo"/>
  </ElementType>
  <ElementType name="AssessLevel" content="eltOnly">
    <element type="ProductLevel"/>
    <element type="FirmLevel"/>
    <element type="ServiceLevel"/>
  </ElementType>
  <ElementType name="ProductLevel" content="eltOnly">
    <element type="ProductID"/>
    <element type="ProductPrice"/>
  </ElementType>
  <ElementType name="ProductID" content="textOnly" dt:type="String">
  </ElementType>
  <ElementType name="Product" content="textOnly" dt:type="double">
    <attribute type="unit" dt:type="String" required="yes"/>
  </ElementType>
  <ElementType name="EnvAspects" content="eltOnly">
    <element type="Energy"/>
    <element type="Material"/>
    <element type="AirEmission"/>
    <element type="Water"/>
    <element type="SolidWaste"/>
    <element type="WasteWater"/>
  </ElementType>
  <ElementType name="Energy" content="eltOnly">
    <element type="EnergyType"/>
    <element type="AspectRefLevel"/>
  </ElementType>
  <ElementType name="AspectRefLevel" content="eltOnly"
    dt:type="double">
    <attribute type="unit" dt:type="String" required="yes"/>
    <element type="ImpactLevOfGlobalWarming"/>
    <element type="ImpactLevOfResourceDepletion"/>
  </ElementType>
</Schema>
```

```

        <element type="ImpactLevOfAcidification"/>
    </ElementType>
    <ElementType name=" EnergyType" content="eltOnly">
        <element type="EnergySource"/>
        <element type="ConsumptionLevel"/>
    </ElementType>
.
.
.
</Schema>

```

**Figure 6.5 XML Schema for the Target Metric (*A Part of*)**

```

<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<!--This is an XML file for the Target Metric evaluation of a product-->
<productMetric xmlns="x-chema:TargetMetric.xml"
    metricVersion="1.1">
    <!--This XML document is generated based on the schema
    file TargetMetric.xml-->
    <AssessLevel>
    <ProductLevel>
        <ProductID>pid89034</productID>
        <ProductPrice unit="USD">120</ProductPrice>
    </ProductLevel>
    </AssessLevel>
    <EnvAspects>
        <Energy>
            <EnergyType num="1">
                <EnergySource>Electricity</EnergySource>
                <ConsumptionLevel unit="KWh">213</ConsumptionLevel>
            </EnergyType>
            <AspectRefLevel unit="MJ/yr">
                <ImpactLevOfGlobalWarming
                unit="MJ/yr">1560</ImpactLevOfGlobalWarming>
                <ImpactLevOfResourceDepletion
                unit="MJ/yr">2130</ImpactResourceDepletion>
                <ImpactLevOfAcidification
                unit="MJ/yr">1280</ImpactLevOfAcidification>
            </AspectRefLevel>
        </Energy>
        <Material>
            <MaterialType num="1">
                <MaterialName recycledContent=0>Aluminum</EnergySource>
                <ConsumptionLevel unit="Kg">0.56</ConsumptionLevel>
            </MaterialType >
            <AspectRefLevel unit="Kg/yr">
                <ImpactLevOfResourceDepletion
                unit="Kg/yr">32</ImpactResourceDepletion>
            </AspectRefLevel>
        </Material>
        <AirEmission>
        </AirEmission>
        <Water>
        </Water>
        <SolidWaste>
        </SolidWaste>
    </EnvAspects>

```



```

        <WasteWater>
        </WasteWater>
    <EconomicInfo>
        <GGP year="1999" unit="BillionUSD">23.5</GGP>
        <GDP year="2000" unit="BillionUSD">5.5</GDP>
        <Vr year="2000" unit="MillionUSD">20</GGP>
    </EconomicInfo>
</productMetric>

```

**Figure 6.6** An XML File for a Product Assessment

The XML generator and parser are designed and prototyped using Java and Enterprise Javabeans (EJB). EJB is a widely-adopted server-side component architecture for Java 2 Platform, Enterprise Edition (J2EE). It enables rapid development of mission-critical applications that are versatile, reusable and portable across middleware. EJB components are server-side components written entirely in the Java programming language. EJB components contain business logic only. System-level services such as transactions, security, threading are automatically managed for the EJB component by the EJB server.

EJB architecture is inherently transactional, distributed, portable, multi-tiered, scalable and secure. In the SEEMS environment, EJB components are fully portable across any EJB server and any operation system. EJB supports rapid application development that comes from the productivity benefits of writing components in the Java programming language. EJB has broad industry adoption: industry-wide collaboration on the specification already yielded a superior architecture and ensured adoption. The application has high portability: business logic can run everywhere with platform-independence and middleware independence. More attractively, it is portable across multiple servers and databases.

### **6.3.2 Knowledge Extraction from Enterprise Business Applications**

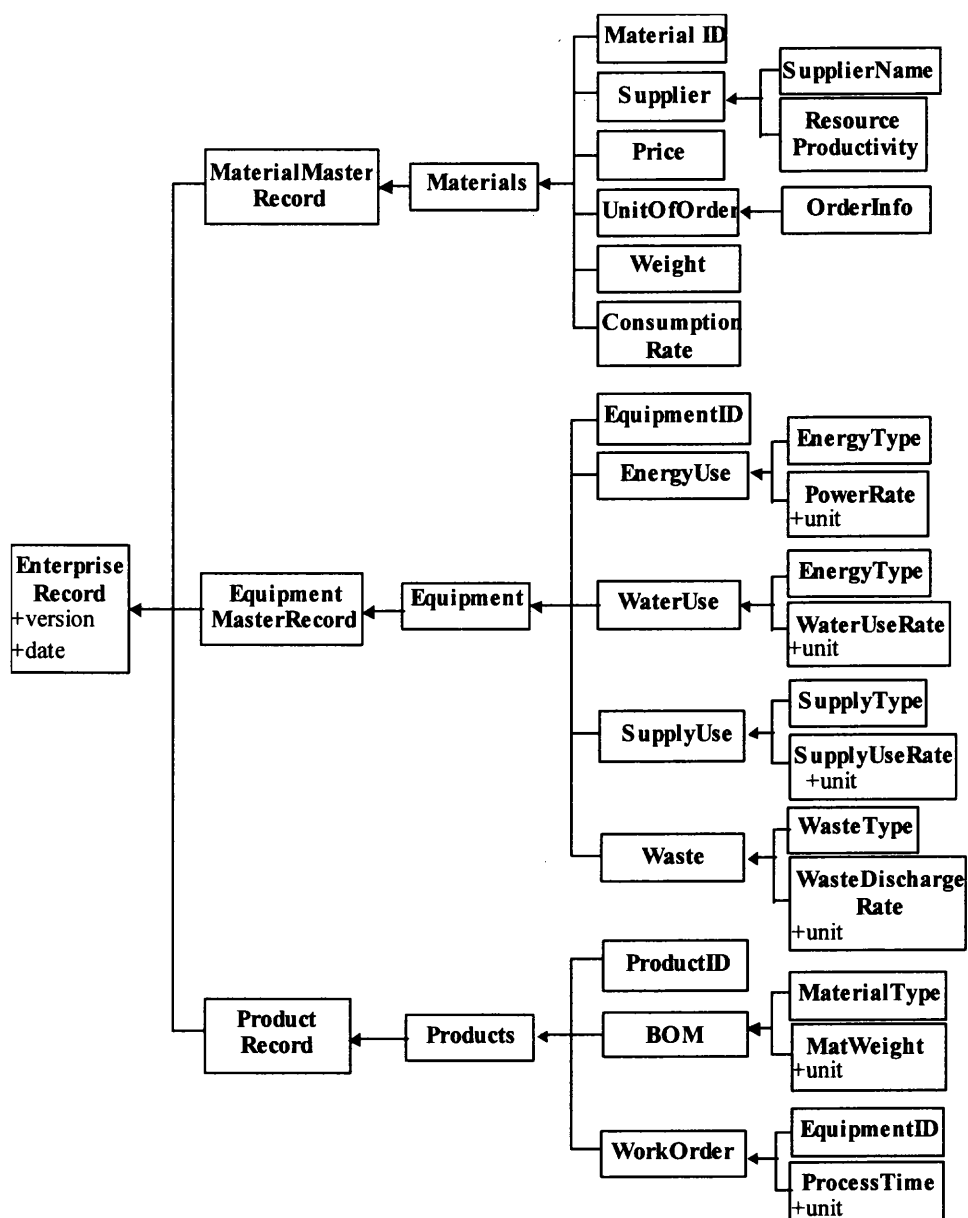
Many companies use Enterprise Business Applications such as Enterprise Resource Planning (ERP) systems to plan, organize and control their activities. ERP is an industry term for the broad set of activities supported by multi-module application software that help a manufacturer or other business manage the important parts of its business. ERP ties in many business areas including Sales and Distribution, Materials Management, Production Planning, Plant Maintenance, Human Resources, Accounting, Controlling, and Workflow.

Typically, an ERP system uses or is integrated with a relational database system. The company-wide continuous databases represent all of a company's functions. Much of the information needed for environmental management is included in these databases within the ERP system. SEEMS knowledge management deals with information extracting from different databases, allocating to a certain assessing level, and wrapping to a unified format.

Leading ERP systems are provided by SAP, Baan, PeopleSoft and Oracle Corporation. The SAP R/3 is a typical ERP system which provides an integrated suite of software application modules that serve to automate and standardize key business processes. It provides real-time database updates for integrated applications. SAP R/3 can support organizations with multiple companies in different locations around the world. The product environmental lifecycle data can be registered and compiled using the SAP R/3 system [Januschkowetz and Hendrickson 2001]. The data required for environmental lifecycle assessment are shown in Table 6.1.

**Table 6.1** Typical Lifecycle Inventory Data [Curran, 1996]

Input	Output
Material/Substance	Products
Electricity	Recycled Material Output
Natural Gas	Solid Waste
Fuel Oil	Air Emission
Compressed Air	Waterborne Emission
Water	Discharged Water

**Figure 6.7** ERP Environmental Management Ontology

SEEMS design enables a certain agent called *adaptor* which is served as information extraction module adapted to a specific ERP system. Using SAP R/3 system as an example, relevant product and process data reside in various main components of the system such as Material Master Record and Equipment Master Record. An ERP Environment Management ontology is constructed based on these data sources. Environmental related data can be extracted from the database in these components, and then encoded to a unified XML structure. Figure 6.7 is the ontology structure.

The terminology used in the ontology structure will differ depending on different specific ERP system connected and accessed by the SEEMS, but the knowledge contents and hierarchy will remain the same. If enterprise level environmental assessment is being performed, data are sufficient for the Target Metric Evaluation in terms of the aspects of energy, material, water, solid waste, and wastewater consumed or discharged in a certain period of time. But if the assessment level is at the product or service level, necessary allocations must be made to product or service for each environmental aspect according to product BOM, equipment usage, manufacturing time, and production rate.

## **6.4 SEEMS Design and Implementation**

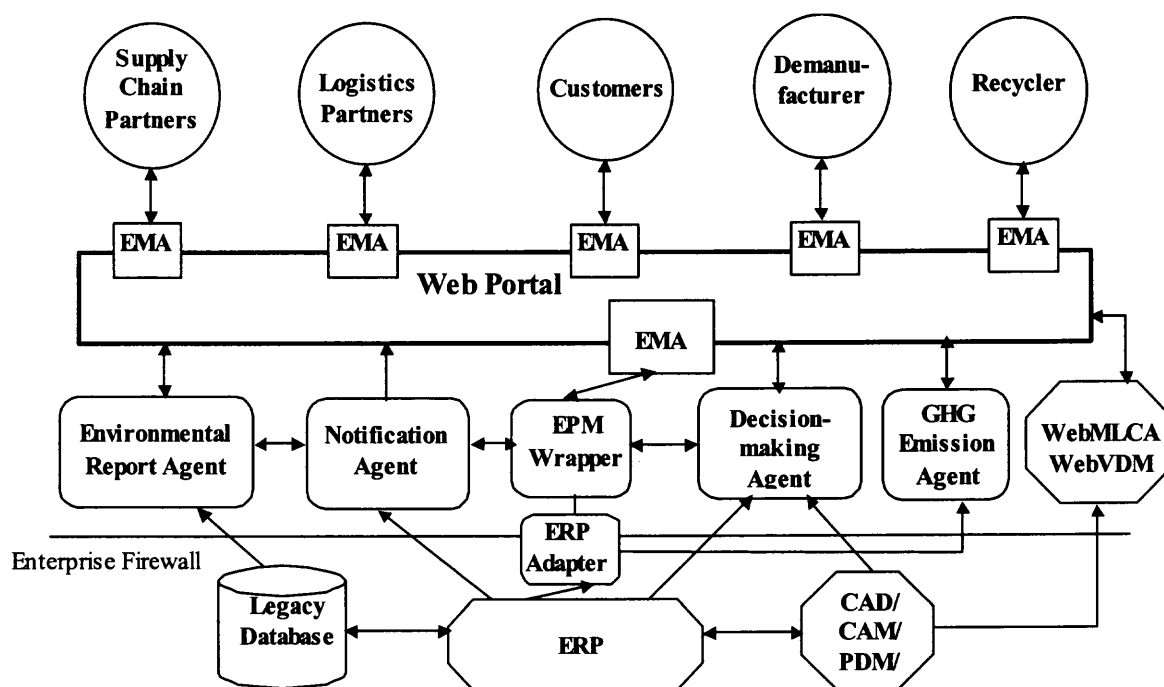
### **6.4.1 SEEMS Architecture**

Within the context of web-based solutions, the term scalability often refers to the ability of an application to continue to function well as its context changes in size or volume. Additionally, scale can be applied to its ability to move to a new context such as a new operating system. An enterprise web portal can provide the scalability since any size of

user group can access and conduct certain tasks with security and permissibility. The SEEMS is thus based on an enterprise web portal.

The idea of SEEMS is to use a web portal as a single “pool” of shared environmental data about an enterprise, product and process from which companies involved in a virtual supply chain can easily access in a consistent and transparent way. This pool may contain the material structure of a product, descriptions of every modification to that product, customer input or suggestions, and any other information vital to the environmental performance of the product. It provides organizations with the opportunity to share information at any given stage of the manufacturing chain, allowing all parties to be involved from the start of development, and achieve collaborative sustainable development. Figure 6.8 gives the architecture design of SEEMS.

In Figure 6.8, partners along the supply chain can connect them to a web portal,



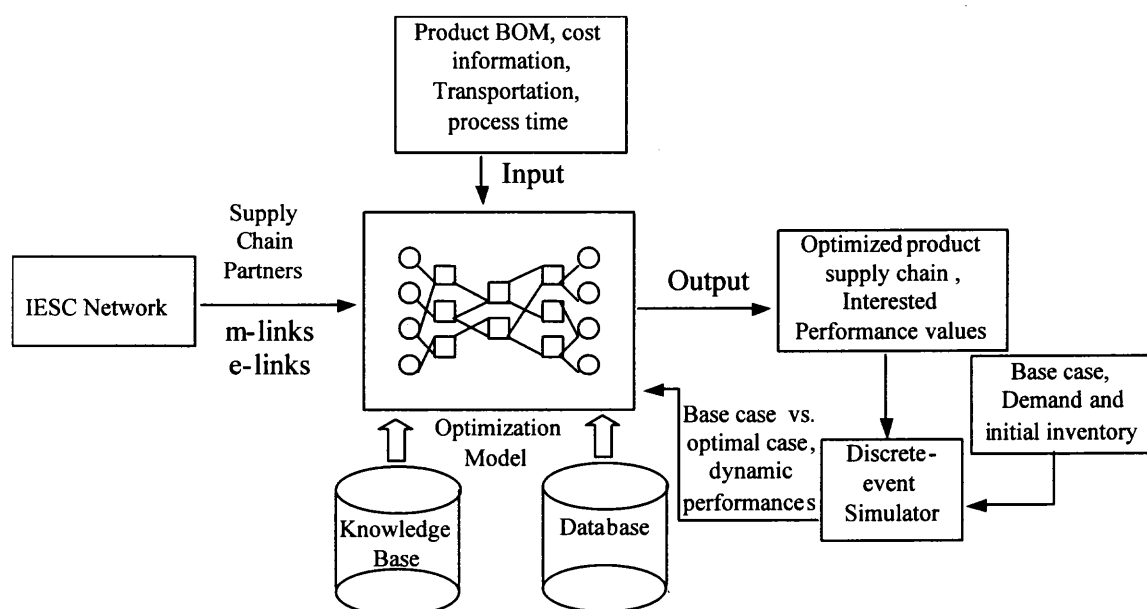
**Figure 6.8 SEEMS Architecture Design**

accessing, sharing and exchanging environmental data along the product lifecycle as well as supply chain. The EMA stands for Environmental Metric Adapter that can extract necessary data from each partner's ERP system, and wrap them into a standard format. Several agents work behind the web portal. Decision-making agent gets information from partners and support decision analysis such as supply chain partner selection and configuration. The IESC model presented in chapter 5 will be used as a central model and algorithm for this agent. EPM wrapper is an agent extracting enterprise environmental information from ERP and legacy database and encode it into a unified format. The ERP adapter is a bridge between specific ERP system and the SEEMS. The notification agent watches for design or process changes and notify the environmental performance change to environmental managers, designers or other partners. Environmental report agent receives request and automatically generate reports such as Toxics Release Inventory (TRI) report to the public. The GHG credits agent evaluates the GHG emission reduction credits of an entity for future GHG constraints and can connect to a global GHG trading hub.

#### **6.4.2 Integration of IESC Model**

The IESC Method described in chapter 5 is used as a supply chain decision module in the SEEMS system. The module is illustrated in Figure 6.9. The supply chain stages and partners with possible m-links and e-links are first input into the IESC model to build the supply chain network. At the same time, initial conditions such as product bill of materials, unit cost of components, process time in each stage, etc. are also input into the model. The selection of best combination of partners and links is performed in

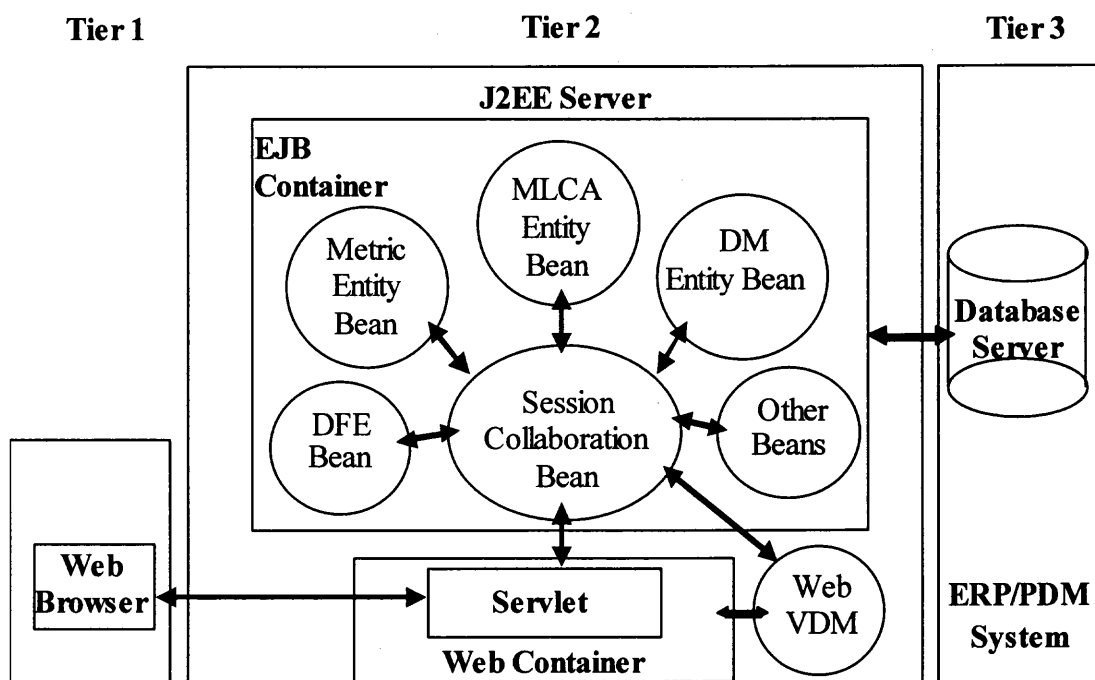
optimization model that uses fuzzy multi-objective optimization algorithm. The objectives can be cost and cycle time minimization, as well as best environmental performance in terms of energy and emissions. The optimization model is supported by a knowledge base providing facts and rules in computation procedure and a database containing environmental effects of materials and transportation information in order to evaluate the environmental implication of the product supply chain. The output of the IESC model is an optimized product supply chain configuration with corresponding performance measures. It is noted that network optimization only provides a single “snapshot” of the supply chain. In order to understand and validate the result, a discrete-event simulation approach based on the IESC network is needed. The simulation model takes optimized network and a pre-determined base case as input model and conducts experiments for understanding the dynamic inventory distribution, throughput and result robustness of the system. The simulation is a tool to validate the optimization model because the result of it will show whether the optimal case is better than the base case in terms of dynamic properties. If it is not, the optimization model should be revised.



**Figure 6.9** A Supply Chain Decision-Making Module in SEEMS

### 6.4.3 Implementation Model of SEEMS

The implementation model of SEEMS is a three tier client-server model. Figure 6.10 describes the implementation structure. Tier 1 is the client using any web browser on any platform. The client is connected to the servlet in the server side. Tier 2 is a Java J2EE



**Figure 6.10** SEEMS Implementation Model

server which using Enterprise Javabeans technology to implement the agent-based design. Java beans are reusable, portable and flexible software components which can act as metric evaluation agent, multi-lifecycle assessment (MLCA) agent, decision making (DM) agent, and other functional agents. The third tier is the database system residing in ERP systems.



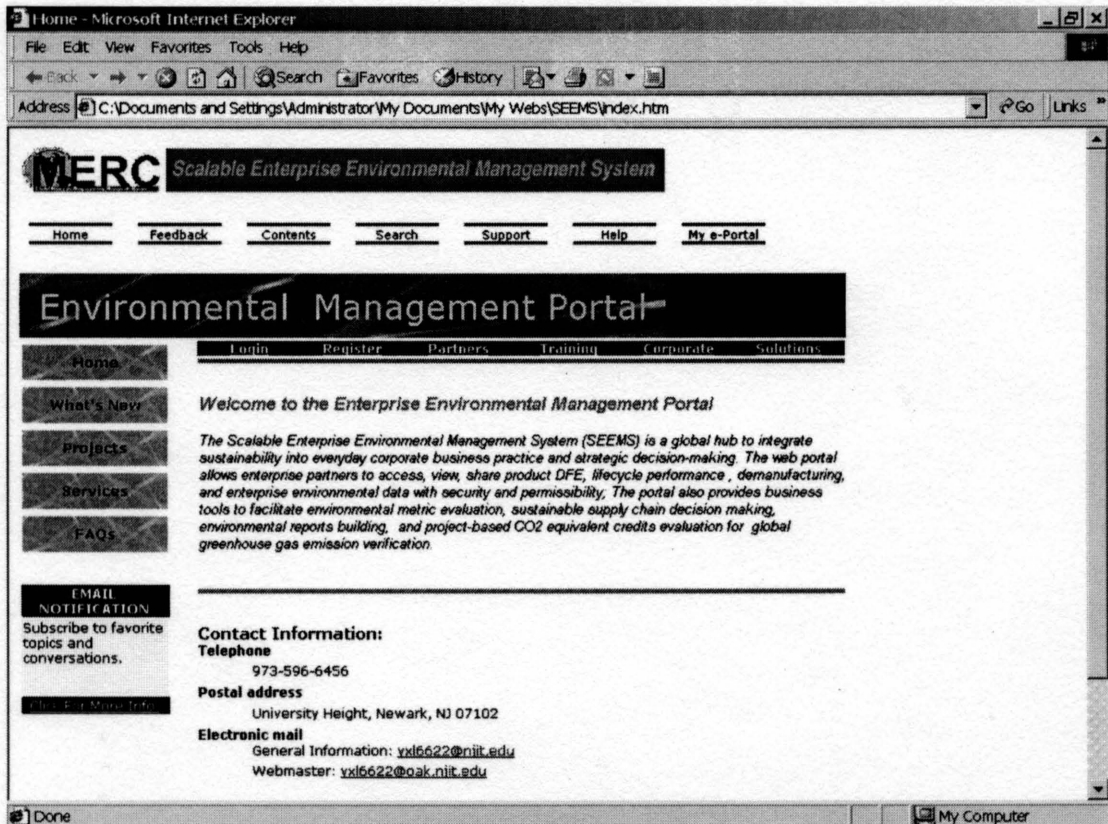


Figure 6.11 SEEMS Web Portal (1)

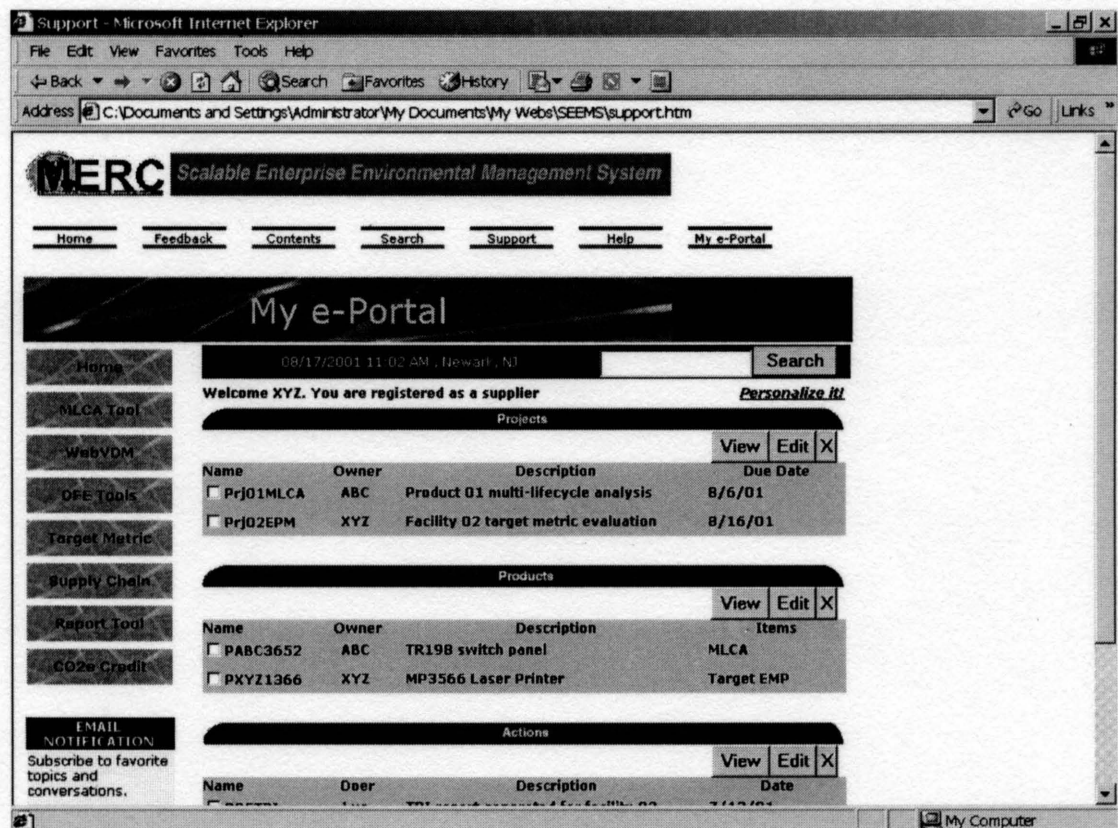


Figure 6.12 SEEMS Web Portal (2)

The web portal markup layout is designed as shown in Figure 6.11 and 6.12. The SEEMS web portal is using the enterprise portal style. Partners can register with the SEEMS group, and login into the system. Figure 6.12 shows a customizable portal for a partner. The partner can have a working screen to view and edit projects, product, and can use business tools provided by SEEMS such as MLCA tool, supply chain decision making tool, Lucent Sustainability Target Metric tool, etc. to perform certain assessment or analysis work to a selected project or product. Some critical actions, such as design change, material change, report generate, etc., to a project done by the user or other partners are highlighted and shown on the working screen.

### **6.5 Summary**

The area of e-Business leverages existing technologies into an area that makes our research more usable and hopefully more able to have greater impact on the every day person's life. SEEMS focuses on Internet-based application integration, knowledge modeling and fusion within an agent-based portal architecture to achieve efficient and effective enterprise environmental management.

This chapter represents the first-step work to use e-Business strategy to conduct environmental management throughout multi-lifecycle production network. As explored in these dissertation, suppliers, manufacturers, logistic carriers, customers, demanufacturers, and recyclers are all responsible for the environmental impacts of products and services. SEEMS is aimed at delivering an e-Business environment for partners involved in the multi-lifecycle production network to collaboratively understand,

manage and improve the overall environmental performance of products and the entire enterprise.

The research challenges in SEEMS are first discussed in this chapter. The application integration issue, knowledge interoperability issue, and e-Commerce oriented system execution issue are all key issues need to be carefully explored. Ontology-based XML technology is applied to solve the knowledge interoperation problem. Agent-based design is adopted to develop the high efficiency of e-Commerce systems. The architecture design of SEEMS is presented, in which a web portal is connected with backend legacy systems such as ERP via several active agents. The implementation model is constructed based on three-tier client server structure. The entire concept of SEEMS is to bring up Internet speed and collaborative tools for environmental management of sustainable enterprises and can open up vast perspectives for many research areas.

## **CHAPTER 7**

### **CONCLUSIONS AND FUTURE WORK**

This chapter summarizes the major contributions and results of the dissertation. The future research issues and tasks of this study are also discussed.

#### **7.1 Major Contributions**

This dissertation presents the methodologies, frameworks, approaches and architectures of e-Business integrated multi-lifecycle production systems. The research work leads to the following major contributions:

1. Identification and analysis of direct and indirect impacts of e-Business to production system including supply chain planning, partner selection, and cost reduction as well as environmental performance based on updated literature survey and phenomena observation.
2. Understanding, implementation and application of the Lucent Sustainability Target Metric in the overall framework of the research.
3. A hyper-network modeling method and fuzzy multi-objective analysis are presented on the integrated e-business enabled production system. The associated simulation method is also provided. A comprehensive case study reveals that the model and approaches can analyze complex e-supply chain networks, understand the trade-offs of the system parameters and obtain the dynamic properties of the system.
4. A knowledge-based solution is provided for web-based enterprise environmental management systems.

5. System model, architecture, and implementation method are presented for a Scalable Enterprise Environmental Management system. The system is aimed to leverage e-Business technologies to achieve sustainable enterprise management.

## **7.2 Future Work**

The future research issues and tasks are:

1. An environmental management workflow model needs to be developed to model the collaborative nature of virtual enterprise sustainable management involved with many partners in the virtual enterprise network.
2. A methodology of knowledge modeling, fusing, and management for the sustainable e-production systems needs to be further refined and explored, in order to deal with the variety of enterprise data models. And ontology transform model is needed when a group of knowledge ontologies are built and are supposed to be interchanged.
3. Organizational design issues that would provide substantive insight and mechanisms for conceptualizing and analyzing the enterprise and the development of “laws of behavior” for scalable enterprises.
4. Collaborative decision making in scalable enterprise systems including the sharing of collaborative knowledge and protection of core knowledge, and the incorporation of risk and uncertainty.

## APPENDIX A

### DATA SHEET FOR NETWORK LINKS IN 5.3.2

This is the data sheet for the example in section 5.3.2.

Lm	TD	TM	Tcost	Pcost	Ocost	Mcost	Σcost	Ttime	Ptime	Otime	ΣTime	Ten.	Men.	Pen.	Σen.	TCO2
1	950	t	0.99	0	0.8	40	41.8	15.8	3	0.5	19.3	11.4	348	0	359	0.87
2	800	t	0.83	0	0.9	45	46.7	13.3	3	0.5	16.8	9.6	322	0	332	0.74
3	600	t	2.5	0	6.2	310	319	10	2	0.5	12.5	28.8	1450	0	1479	2.21
4	500	t	2.47	0	6	300	308	8.3	4	0.5	12.8	28.5	1748	0	1776	2.19
5	700	t	3.5	0	4.6	230	238	11.7	4	0.5	16.2	39.9	1500	0	1540	3.1
6	400	t	1.66	0	4.8	240	246	6.67	3	0.5	10.2	19.2	1390	0	1409	1.47
7	900	a	2.87	0	1	50	53.9	1.8	3	0.5	5.3	75.6	293	0	369	30.2
8	1000	t	9.88	430	8.6	0	448	16.7	2	0.5	19.2	114	0	3504	3618	8.74
9	1100	a	28.1	344	6.9	0	379	2.2	1.5	0.5	4.2	739	0	2803	3542	296
10	850	t	7.07	344	6.9	0	358	14.2	1.5	0.5	16.2	81.6	0	2803	2885	6.26
11	950	a	21.2	330	6.6	0	358	1.9	1.5	0.5	3.9	559	0	2700	3259	223
12	100	t	0.988	0	19.9	0	20.89	1.7	0	120	121.7	11.4	0	2	13.4	0.874
13	150	t	1.25	0	24	0	25.2	2.5	0	120	123	14.4	0	2	16.4	1.1
14	350	t	2.92	0	20	0	22.9	5.8	0	60	65.8	33.6	0	1.5	35.1	2.58
15	80	t	0.67	0	20	0	20.7	1.33	0	60	61.3	7.68	0	1.5	9.18	0.59
16	10	c	4	0	60	0	64	0.3	0	120	120.3	86.4	0	4	90.4	0.56
17	20	t	0.15	0	58	0	58.1	0.33	0	100	100	1.68	0	3	4.68	0.13
18	50	t	0.42	0	0	0	0.42	0.83	0	0	0.83	4.8	0	0	4.8	0.37
19	50	t	0.42	0	0	0	0.42	0.83	0	0	0.83	4.8	0	0	4.8	0.37
20	50	t	0.42	0	0	0	0.42	0.83	0	0	0.83	4.8	0	0	4.8	0.37
21	50	t	0.42	0	0	0	0.42	0.83	0	0	0.83	4.8	0	0	4.8	0.37
22	200	t	0.83	1	0	-20	-18	3.33	1	0.5	4.83	9.6	-21	0	-11	0.74
23	300	t	1.25	1	0	-30	-28	5	1	0.5	6.5	14.4	-21	0	-6.6	1.1

Note: Data is based on one product base. The notation used in the table is as follows:

1. TD: Transportation distance with unit mile;
2. TM: Transportation mode; t: truck, a: air, c: car.
3. T- : Transportation,
4. P- : Process,
5. O- : Operation,
6. M- : Material.
7. en. = energy
8. The unit of cost is US\$
9. The unit of time is hour
10. The unit of energy is MJ
11. Σ: total
12. TCO2: transportation CO2 emission with unit kilogram carbon equivalent (kgCE).

#### Cost, energy, and CO2 emission for transportation in the case study

Transportation Mode	Cost <sup>*1</sup> (US\$/ton-mile)	Energy Intensity <sup>*2</sup> (MJ/ton-mile)	CO2 Emission <sup>*3</sup> (KgCE/ton-mile)
Truck	0.26	3	0.23
Air	0.80	21	8.4
Car	0.25	5.4	0.035

kgCE = kilogram carbon equivalent.

\*1. "Transportation Statistics Annual Report 1999", Bureau of Transportation Status, US Department of Transportation.

\*2. Rejeski, D. "Electronic Impact," *The Environmental Forum*, July/August 1999, pp. 32-38

\*3. "Inventory of US Greenhouse Gas Emission and Sinks 1990-1997", EIA, DOE.

## APPENDIX B

### MATERIAL AND ENERGY INVENTORY DATA FOR CASE STUDY

This appendix shows the data of material inventory and energy consumption for each part and component of a personal computer system used in the case study (section 5.5). The disassembly experiment was conducted in MERC at NJIT.

Part Name	Material	Weight (kg)	Material Energy Intensity (MJ/kg)	Production Energy Intensity (MJ/kg)	Energy (MJ)
Monitor	Plastic	4.10	120		
	Leaded Glass	6.38	15		
	Copper	0.18	150		
	Steel	1.98	23		
	PCB	0.01	120		
	Total	12.65		52.8	1329
Keyboard	Plastic	0.83	120		
	Steel	0.34	23		
	PCB	0.01	120		
	Total	1.179		129	260
Chassis with power supply	Aluminum	5.80	300		
	Plastic	2.74	120		
	Other Metals (Steel)	2.72	23		
	Total	11.27		82.8	3066
Floppy Drive	Plastic	0.01	120		
	PCB	0.05	120		
	Steel	0.31	23		
	Total	0.37		116.1	58
CD ROM	Plastic	0.02	120		
	PCB	0.05	120		
	Steel	0.96	23		
	Total	1.03		116.1	149
Hard Disk Drive	Steel	0.42	23		
	PCB	0.04	120		
	Total	0.46		116.1	68
				(MJ/mm <sup>2</sup> )	
Mother Board	PCB (24 x 30.5 cm <sup>2</sup> )	0.23	120	0.0018	159.0
LAN card	PCB	0.14	120	0.0018	21.7
Soundcard	PCB	0.14	120	0.0018	21.7
CPU (processor)	PCB (5 x 5 cm <sup>2</sup> )	0.02	120	0.0018	6.9
Memory	PCB (3.2 x 13.3 cm <sup>2</sup> )	0.02	120	0.0018	9.5
<b>TOTAL</b>		27.48			5148

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