AN INTEGRATED APPROACH TO ENVIRONMENTALLY CONSCIOUS DESIGN AND MANUFACTURING

by

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(ABSTRACT)

The problem addressed in this research was to develop an approach for the simultaneous green design of products and associated manufacturing processes including demanufacturing concerns. We propose a generic approach called *Integrated Environmentally Conscious Design and Manufacturing* (IECDM) which can be applied to address problems in the ECDM domain.

IECDM incorporates environmental considerations into the engineering design process, thereby increasing a product's total life-cycle value (including its end-of-life value) as experienced by the customer, manufacturer, and society, while simultaneously reducing impacts on the environment caused by that product and its manufacturing processes. IECDM is a novel integration of Quality Function Deployment (QFD), Life-Cycle Assessment (LCA), Multiple Criteria Decision-Making (MCDM), and Cost-Benefit Assessment (CBA). The focus is on process, based on modification of the traditional QFD methodology to incorporate environmental issues and green product-design decisions through the life-cycle design activities of synthesis, analysis, and evaluation.

This dissertation presents a QFD-based IECDM approach, a mathematical CBA model, and an IDDS (Integrated Design Decision-Support) framework with a design-flow-chart application for incorporating environmental criteria into product and process eco-design. The IECDM problem is defined as: given the customer and environmental requirements, develop an integrated approach for green product design that results in maximization of the product's total life-cycle value (TLCV). Initially, through investigation in the field of ECDM, we specified a clear ECDM domain within Industrial Ecology. Then, we proposed various state-of-the-art techniques that were used to implement ECDM in the literature. After we defined the IECDM problem, we developed an integrated approach that led to a generic QFD-IECDM methodology for dealing with problems in the ECDM domain. Finally, for implementing the proposed methodology, we developed a tentative IDDS framework to encourage long-term development followed by an example.

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GLOSSARY OF ACRONYMS

ABC	Activity-Based Costing
AHP	Analytical Hierarchy Process
CBA	Cost-Benefit Analysis (Assessment)
CE	Concurrent Engineering (or Simultaneous Engineering)
DEF	Design Evaluation Function
DFR	Design For Recyclability (Remanufacture, Reuse, & Materials Recovery)
DFD	Design For Disassembly
DFD	Design Function Deployment
DFE	Design For Environmentability; Design For the Environment
DFM	Design For Manufacturability
DFR	Design For Recyclability
DFS	Design For Serviceability
DFT	Design For Testing
DFX	Design For 'X' approaches and methodologies
ECM	Environmentally Conscious Manufacturing
ECDM	Environmentally Conscious Design and Manufacturing
FDM	Function Dependence Matrix
FMEA	Failure Modes and Effects Analysis
HoQ	House of Quality
IECDM	Integrated ECDM
IDDS	Integrated Design Decision-making Support
ITP	Integrated Test Planning
KB-IECDM	Knowledge-Based Support IECDM
LCA	Life-Cycle Analysis/Assessment
LCCA	Life-Cycle Cost Assessment
LCD	Life-Cycle Design
LCD&E	Life-Cycle Design and Engineering
MADM	Multiple Attributes Decision-Making
MCDM	Multiple Criteria Decision-Making
MODM	Multiple Objectives Decision-Making
MROs	Materials Recovery Options

NTM	Nontraditional Manufacturing (or Machining) Processes
PRC	Product Realization Cycle
PROs	Product Recycling Options
QFD	Quality Function Deployment
QFD-IECDM	Quality Function Deployment-based IECDM
RE-IECDM	Reverse-Engineering focus IECDM
SPC	Statistical Process Control
TLCV	Total Life-Cycle Value
TQM	Total Quality Management
VE	Value Engineering

CHAPTER 1

INTRODUCTION

1.1. GREEN PRODUCT DESIGN AND REALIZATION
- 1.1.1. Background
- 1.1.2. Factors Promoting Implementation of ECDM Strategies
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1.5. DISSERTATION ORGANIZATION

An evolutionary design paradigm, which starts with consideration of the environmental impacts caused by products and product-related processes during the product and process design stages, is known as *Environmentally Conscious Design and Manufacturing* (ECDM). ECDM has been increasingly characterized in the last ten years within the domain of Industrial Ecology. The ECDM paradigm is recognized by many major manufacturers for its potential capability and advantage for the development of truly 'green' products[1].

In this chapter, the discussion of ECDM includes: (1) background of ecodesign evolution; (2) general questions regarding ECDM concepts and techniques; (3) specific problems raised by these

[1] See Miller and Szekely [1995] for a better understanding of a framework for identifying who and what is behind the concept of 'green', the dynamics in which this concept is applied, and the strategic importance of this topic.

questions in research; and (4) an IECDM approach that addresses the problem and illustrates how this problem is investigated. Finally, a brief summary of the remaining chapters is presented.

1.1. GREEN PRODUCT DESIGN AND REALIZATION

As ECDM has evolved, the success of a manufacturing company has come to depend on its ability to design, manufacture, and sell greener products and/or services, as well as on its ability to take back and demanufacture its products at their end-of-life. In addition to the functionality for which the product is intended, product development should give due consideration to such issues as added end-of-life value, quality, performance, and environmental compatibility[2]. The challenge faced in ECDM evolution is to address these issues in the development of the ecoproduct and in the ecomanufacturing processes so that its functional, economic, and environmental requirements are met. Several design models have been developed to address functional and economic issues, but few of them address environmental requirements[3].

1.1.1. Background

In a global market economic situation, industries find that they need to design and manufacture better and greener products to stay competitive. Socolow and his co-authors [1994], in their work Industrial Ecology and Global Change reported that industry is increasingly recognizing the need for new approaches to product development, in order to:

- include environmental criteria in product and process design;
- improve cooperation between firms and government regulators in developing more precisely targeted, cost-effective environmental policies; and
- anticipate future environmental constraints, liabilities, and environmental improvement opportunities.

Motivated by the fact that interactive impacts exist between the product supply chain and the environmental chain in the industrial ecosystem, this research postulates a unified method for these

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[2] The term 'environment' generally covers both the external environment of an industry (pollution) and the internal environment (working conditions, health). Some papers are only concerned with the external environment but nearly all considerations have the same value for the internal environment, and both are the responsibility of the practicing engineer/researcher [Remmerswaal, 1990]. In our proposed cost-benefit assessment model, both external and internal environmental costs are considered.

[3] Since the term 'ecological' and 'environmentally friendly' or 'environmentally conscious' are used interchangeably, without legal protection; and this has been found in various reported papers. For this reason, we may assign the term 'eco-' to efforts of design activities and manufacturing operations instead of the term 'environmentally-conscious,' for convenience. For example, we use the terms eco-system, eco-factory, eco-design, eco-manufacturing, and so on.

interactive impacts in green design and manufacturing, as well as for recycling. Before we explain the proposed integrative research strategy, the factors that affect current product development strategies and ECDM issues are introduced, as well as the product realization cycle.

To facilitate activities in the functionality-based design model, design methods have been developed by designers and researchers[4]. In addition, the well-known Quality Function Deployment (QFD) methodology has been employed as a new synthesis tool for exploiting quality as a strategic means to gain superiority, using QFD-related methods, such as Life-Cycle Design (LCD) and Concurrent Engineering (CE). Most recently, environmental issues have been increasingly considered in the conventional product development cycle. These considerations have led to the need for evaluation of environmental impacts, such as Life-Cycle Assessment (LCA). Also, the concepts and techniques of Integrated Life-Cycle Management (ILCM) have been employed, that focus explicitly on the real decisions that firms make and on the specific economic and environmental performance matrix that are used to evaluate business-related choices. The Life-Cycle Cost Assessment (LCCA) is such a costing tool, which is used in ILCM to help the design team make decisions when environmental costs are involved in the green product development cycle.

Customers have become more demanding in terms of functionality and environmental friendliness and sophistication[5]. The customer wants to fully exploit the new facilities provided by new and emerging technologies, to improve the performance and functionality of the product and its processes, and to reduce costs and environmental impacts. All these have led to the realization that a system is necessary for an integrated design that address these issues. The *Integrated ECDM* (IECDM) developed in this research is such an integrated approach for the use in green design problems.

1.1.2. Factors Promoting Implementation of ECDM Strategies

In this section, factors leading to and promoting ECDM evolution are examined. The value of the recoverable materials from a majority of products at the time of their disposal is usually small in relation to their initial production cost. Therefore, it is difficult to persuade and motivate the manufacturer and first buyer to make changes to the product that would improve the eventual ease of recovery of these materials [Henstock, 1988], especially if these changes cost money, or have even a small actual or imagined effect on the initial performance, functionality, or desirability of the product. This situation is changing, however.

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[4] Design methods are essentially tools and techniques used in the design process.

[5] Customers include consumers who purchase and use the products and services, and the government that imposes the environmental regulations that firms must obey.

Today, most leading companies have taken initiatives to improve the environmental performance of their products and processes that, in turn, reduce environment impact. What are the changes in the 'environmental consciousness' that favor movement by firms away from 'end-of-pipe' solutions towards environment-oriented product design and production? Wook Lee and Green [1994] provide the following model of the links between commercial objectives and environmental policy issues that provide the impetus for firms to innovate a green product design paradigm and its production (Figure 1.1). The following major factors are often recognized by manufacturers.

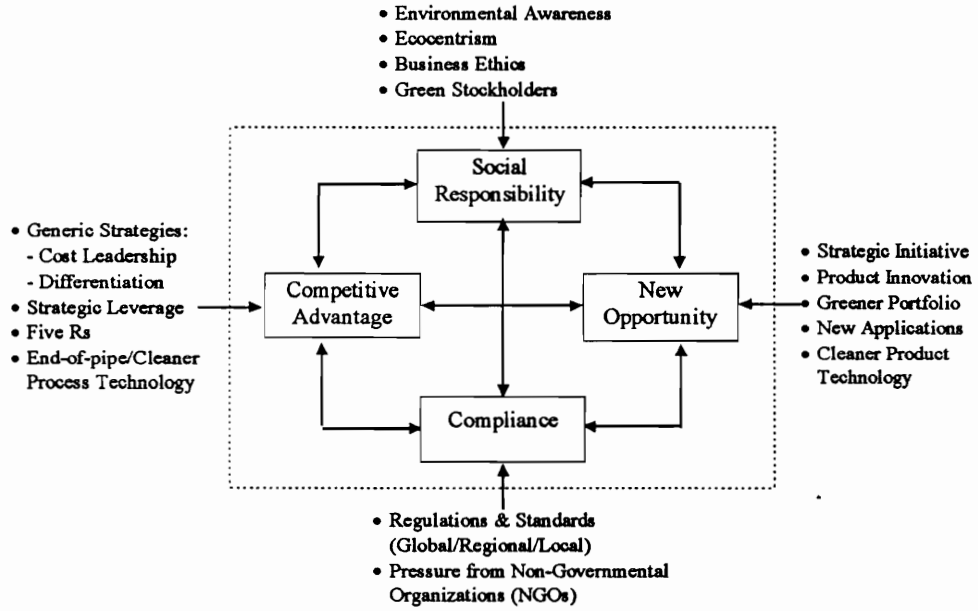


Figure 1.1. Factors promoting ECDM strategy in a firm (Source: Wook Lee and Green, 1994)

Competitive Differentiation. Traditionally, marketplace decisions have been based on a product's performance, quality, and price. In the world-class competition of today, some non-price factors are being included in the company's competitive strategy. All signs indicate that environmental impacts, one of the non-price factors, have become the most important factor in the commercial world during the 1990s.

A designer has always had the opportunity during designing to consider environmental issues based on a product's disposal. Such concerns are reflected in the market, where a substantial number of products are made to be recycled, are biodegradable, and are free from toxic substances. However, the existence of environmental effects or constraints imposed upon the manufacturing process has seldom been an issue for designers while planning product and process designs, because the waste and pollution generated from manufacturing processes are considered by-products of manufacturing and hence are

assumed not to affect the product's quality and productivity. This kind of waste and pollution is usually taken care of by plant management staff. Consequently, the costs incurred become part of the fixed cost of the factory and are intangible to the product realization process. As a result, little effort has been made to design "green" products and "environment-friendly" manufacturing processes.

This situation has changed. Many companies are now approaching the "green" issue by using procedures to ensure that both new and existing systems (products and processes) are toxicological and environmental-friendly.

Customer Consciousness. Humans believe that a healthy natural environment not only enhances their quality of life but also assures them that their quality of life will be sustained. Customers are increasingly concerned about the environmental quality of the products they use and the quality of the environment they live in. Consumer awareness of potential damage inflicted upon the environment by current abuses of technology is beginning to cause pressure for developing green products and clean manufacturing operations. For example, an environmentally conscious factory should implement processes that are not harmful to the natural ecology. Regulatory bodies tend to respond to this change in customer attitudes by developing legislation against those factories that neglect environmental issues. Major companies are beginning, therefore, to systematically review the environmental performance of their supplies (products and services).

Governmental Regulatory Pressures. Upcoming environmental legislation is expected to impose environmentally related restrictions on industrial and consumer product manufacturers. To address environmental problems, regulations inspired by the "polluter pays principle" are emerging. Motivated by environmental laws and customers' environmental consciousness, manufacturers are being forced to seriously consider how to produce greener products and also maintain competition at the same time. When a complete legislative scenario is available, manufacturers will be even more encouraged to move into the recycling industry.

Above all, trends in the product development process are likely to continue. Some additional motivating factors have also contributed to this remarkable trend toward environmental improvement.

Profitability Improvement. An eco-design approach to systems (or *eco-design* systems) can have a significant impact on profitability through savings in manufacturing and other operating costs, by waste elimination-related strategies, and through increased market share[6]. A growing trend toward safer product design and production becomes the company's responsibility in order to provide a safe, healthy working environment for its employees.

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[6] In this work, the term system can represent both product-system and process-system.

Employee Satisfaction. Nowadays, employees and their families are increasingly conscious about their responsibility to the environment. Incorporation of such values into business activities contributes to positive feelings about the workplace [Fiksel, 1994].

International Standards. Coordinated by the International Standards Organization (ISO), many manufacturers are participating in a worldwide effort to establish standards for environmental stewardship over the full product life cycle. Since this concern about the environment seems to parallel recent concerns about quality, there is a good chance that ISO standards will be instituted for environmental issues, very much as ISO 9000 addressed quality issues, in order to bolster consideration of environmental concerns during product and process design. In fact, the ISO Technical Committee 207 (TC207) has developed a set of environmental quality management standards. These include the Environmental Management System (ISO 14001 certification), Environmental Auditing (ISO 14010s), Environmental Labeling (ISO 14020s), Environmental Performance Evaluation (ISO 14030s), and Life Cycle Analysis (ISO 14040s). The ISO 14000 series of standards may be grouped into two categories: "product evaluation" and "organization evaluation" standards that are related to the subject of environmentally conscious design and manufacturing. More detailed discussion is found in Cascio *et al.* [1996].

In summary, the combination of green legislation, market forces, and the increasing demands to lower cost and meet demand have led to an awareness of the environmental impact of industrial activities [Shemg *et al.*, 1995]. All of the above factors force the industry to pay more attention to designing new products/processes that are environmentally sound systems, and to design products that are easily recyclable, including redesigning older products to make them more environmentally-friendly. This view has lead to several design and business philosophies which engineers and managers have begun experimenting with: Design for the Environment (DFE), ECDM, Life-Cycle Assessment (LCA), Life-Cycle Cost Assessment (LCCA), Industrial Ecology, and Sustainable Development. Furthermore, these trends affect the product realization system (including product design, development, production, and demanufacturing); the trends are moving the product realization system from being performance- and quality-driven to being marketing- and environment-driven.

1.1.3. The Ecoproduct Realization (Development) Cycle

Ecoproduct realization can be defined as an approach to product design production system, and industrial processes that allows progress toward the goals of Industrial Ecology (such as waste reduction in material and energy inputs, maximization of energy efficiency, and minimization of overall environmental impact, not just within a product plant but at all stages of design, production, distribution,

consumption, recycling and disposal). Therefore, when we are solving problems of an ecoproduct realization system, we are often dealing with two problems: (1) a greener production system (facilities) with or without demanufacturing capacity, and (2) a corresponding product design and development system, which is our focus in the research. This research work is concerned with building a design decision-support and analytical model to generate and exploit the information for ecodesign decisions in the ecoproduct realization system, especially environment-related information for use in ecodesign procedure.

We develop an integrated approach to deal with an efficient and effective ecoproduct realization system. For most firms, the creation and distribution of products and services are their primary functions. The design procedure is critical to these endeavors. The design phase is where the dominant characteristics (or attributes) of a product and processes are identified and determined, and thus, the part of the product life cycle where the potential environmental improvements can be introduced.

We may also envision the product realization system as a cycle running in conjunction with the product life cycle. In the context of environmental issues, the *product development cycle* is the process by which ecoproducts and manufacturing processes are designed with demanufacturing policies as feedback information for design of product and processes. In practice, numerous configurations of the product realization cycle exist. Figure 1.2 provides a generic ecoproduct realization cycle that we will deal with in the research. This cycle contains needs analysis, requirements specification, design product solution, design manufacturing solution ,and design demanufacturing solution. System aspect shows that the product (eco)design is not only a downstream effort but also a feedback-stream consideration. In short, the ecoproduct design should consider the manufacturing and demanufacturing issues simultaneously at the early design stage. For our purpose of investigating interrelationships of actual product design and manufacturing/demanufacturing processes design, the integrated approach contains both the Life-Cycle Design efforts and the Concurrent Engineering philosophy, leading to our unique IECDM approach.

In this research, product realization system focuses on design procedure which is understood as the "design function," involving designers, production engineers, environmental engineers, marketing/sales/logistics people, customers etc. The new "ecodesign function" may be carried out by a "design team" which has responsibility for the "ecoproduct" throughout its life-cycle. The ecodesign function must look at the product in its life-cycle phases: needs analysis, requirements identification, development/design, production, distribution, usage or consumption and recycling/disposal. In each of these phases the "design team" must look at the environmental consequences (impacts) of the different alternative solutions. The product's total life-cycle value (TLCV) is determined by the selection of design concept, product-related attributes, materials, processes, recycling options, and so forth. The new

situation is that environmental factors are an obvious and visible part of the design criteria in a product realization system (or product development cycle).

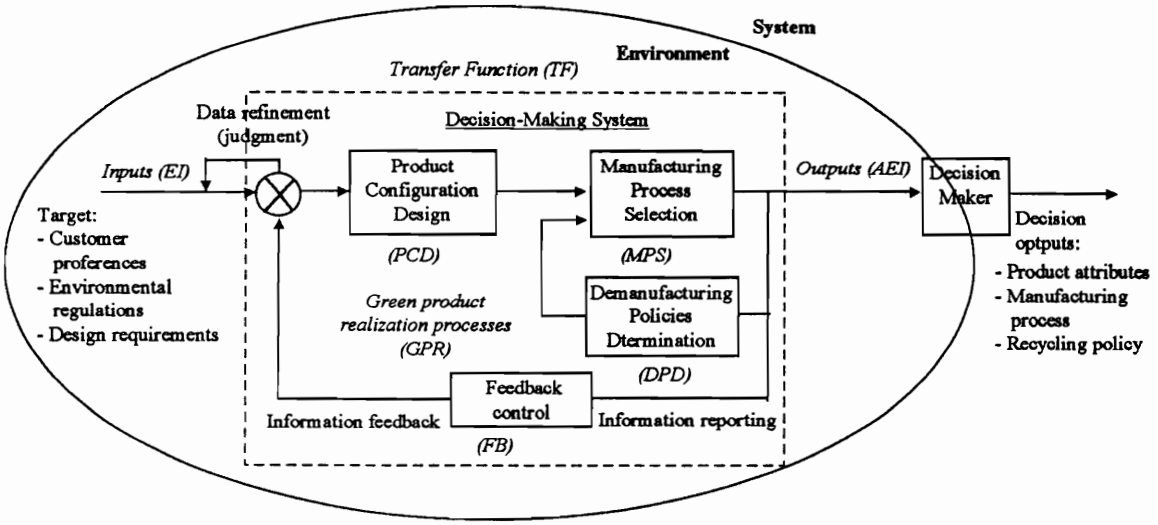


Figure 1.2. System aspect of interactive impacts between system and environment

In our research, we identified the following three ways firms manage their ecoproduct realization functions:

- Designing ecoproducts and processes that address specific environmental concerns through the integration of environmental attributes together with other product-related attributes in design decision-making,
- Incorporating environmental considerations directly into the product design procedure which could be developed as the integration of individual methodologies that have interrelationships among them, and
- Providing continuous feedback to the ecoproduct design team through the integration of function of product-related attributes identification, manufacturing processes selection, and demanufacturing policies determination.

To perform these ecoproduct realization functions, an integrative strategy for research is required.

1.1.4. An Integrative Strategy for Ecoproduct Realization

Green industrial development is not a goal that can be achieved and then forgotten. It is a way that manufacturers can continuously contribute to the environmental improvement of their products and

production operations. Achieving real environmental improvement requires a systematically integrated methodological approach that can help decision makers select the 'best' alternative and also continuously improve its environmental compatibility through design selection and design changes.

Many engineering problems (including green engineering), especially in design and material selection, have several possible feasible solutions which create the need for making decisions or choosing between alternatives. In many cases a decision has to be made in the face of poorly defined problems or inadequate data and information. In such cases design decision-making techniques can be employed to help design selection and change. This is why we use a decision-support methodological approach within an IECDM system. To this point, the IECDM is viewed as a design decision-support system which requires a methodological approach to help the design team select the best candidate alternative. As a long-term research needs, an integrative design decision-making support (IDDS), which integrates Quality Function Deployment (QFD), Life-Cycle Assessment (LCA), Multiple Criteria Decision-Making (MCDM), and Cost-Benefit Assessment (CBA) analysis techniques, is introduced as an integrated process for green system design and to determine the 'best' candidate alternative and environmental improvements. A conceptual IECDM model is illustrated in Figure 1.3.

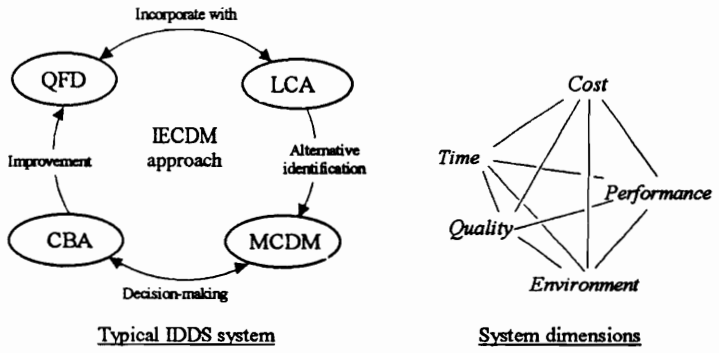


Figure 1.3. A typical integrated life-cycle ECDM model

For long-term research needs in environmental-oriented product realization, we propose an Integrated Design Decision-Support (IDDS) system as shown in Figure 1.4. The purpose of the IDDS system is to increase the applicability of environment-oriented product design and development, and to perform design selection and design changes procedures in the product realization system. In the IDDS system the focus is on integrating four well-structured methodologies: QFD, LCA, MCDM, and CBA, for ecodesign and analysis.

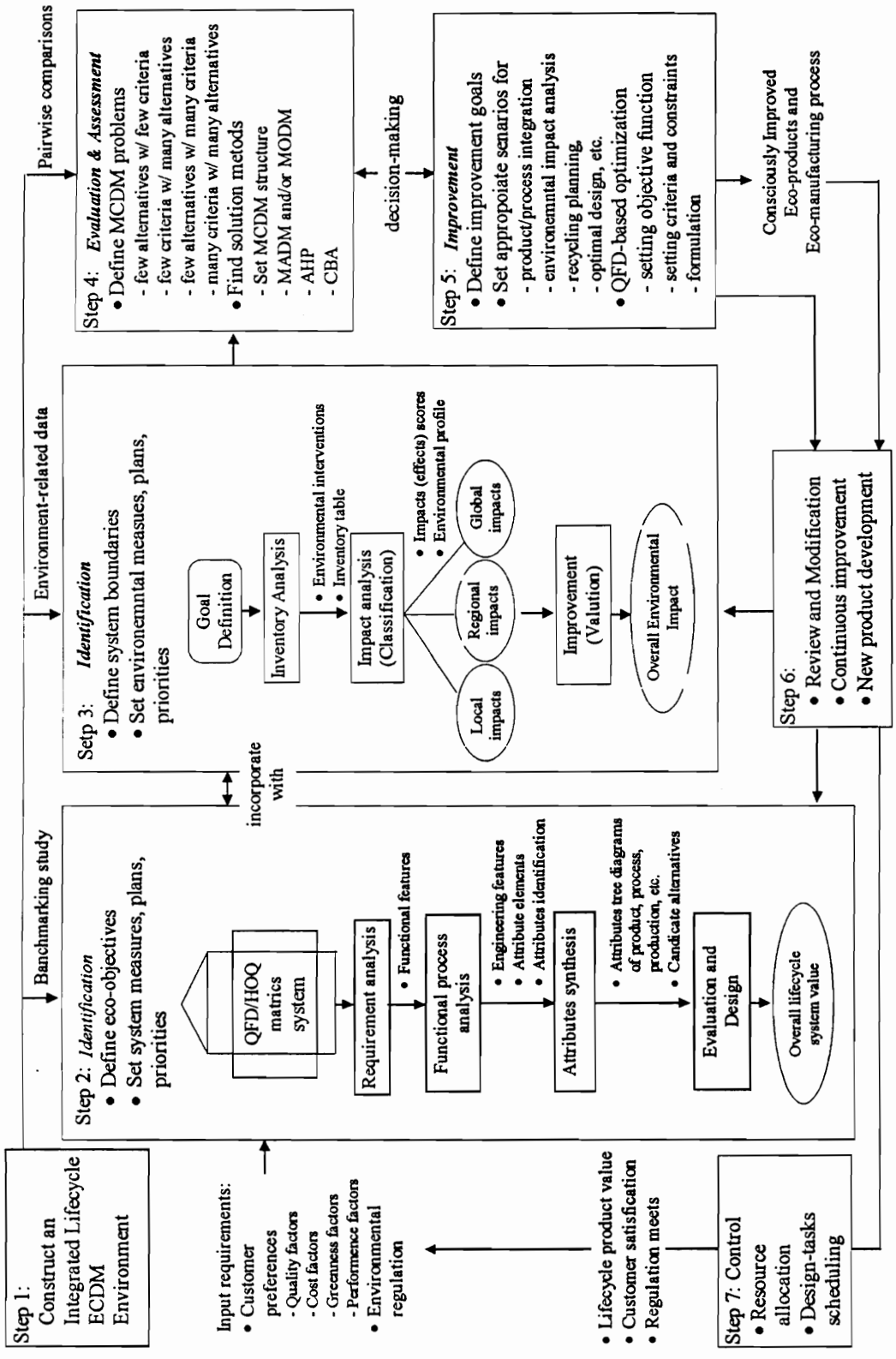


Figure 1.4. Scheme of the proposed temporary Integrated Design Decision-Support (IDDS) system

The IDDS system consists of a structured model which describes the interrelationships among methodologies and the relevant design decision-making responsibilities for ecoproduct realization. From the integrative approach viewpoint, IDDS with IECDM approach combines the contributing techniques of QFD, LCA, MCDM, and CBA. From a regulatory perspective, the IECDM implementation (management) can be defined as a collection of continuous design improvement activities for reducing environmental impacts or for increasing the product's TLCV. These proactivities of IECDM approach are performed through an IDDS model, in a totally integrated effort towards improving environmental performance at every system (and/or organization) level.

In this stage, short-term research focuses on the development of QFD-based methodology, applications of MCDM, and solution of mathematical CBA model for some components within the IDDS. QFD-based IECDM process provides us with a useful technique to generate product-related attributes and to identify product alternatives based on the perceptions of the final recipient of the design team. Next, the CBA formulation is employed for design evaluation by obtaining TLCV of each product alternative. Then the product with the largest total life-cycle value is selected. QFD-based IECDM approach provides the template for linking the related methodologies for green product design and development.

1.2. QUESTIONS IN IMPLEMENTING ECDM STRATEGIES

In a natural ecosystem, interactive impacts exist between the supply chain and the ecological chain. For reducing or avoiding these impacts, companies are required to implement their own ECDM in Industrial Ecology. Questions arising from implementation of ECDM strategies are the motivation for developing a generic IECDM methodology for solving problems in the ECDM domain.

1.2.1. Interactive Impacts Between the Supply Chain and the Ecological Chain

A key challenge facing the manufacturing industry is the maintenance of its role as a global technological leader while avoiding negative environmental impacts. The facts discussed above have caused corporate environmental goals to radically change. Manufacturing enterprises from all industries are going "green" in the industrial ecosystem. According to Bloemhof-Ruwaard and his coworkers [1995], there are interactive impacts between the product supply chain (including recycling supply chain for dealing with returned products) and the environmental chain, as illustrated in Figure 1.5, which illustrates the domain of Industrial Ecology.

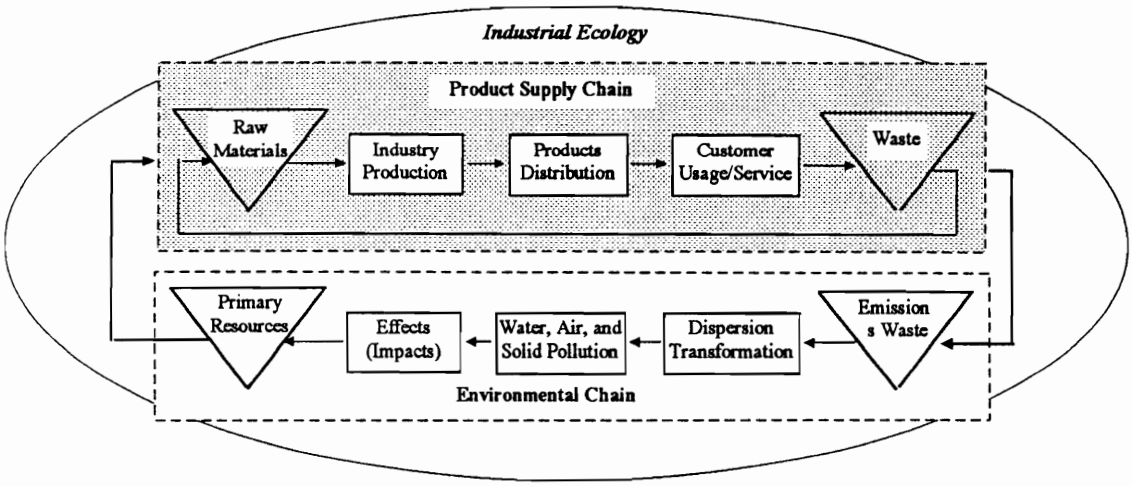


Figure 1.5: Framework of the interactive supply chain and the environmental chain

Environmental issues play an important role in routine product design and development. Decisions about product design, production planning and process selection, logistics, location, allocation and inventory control, and even recycling policies will change due to customer preferences and the governmental environmental regulations. The waste and emissions that are caused by the supply chain result in serious impacts on the local and global environment, such as global warming and acid rain. The relationship between the supply and environmental chains is the domain of Industrial Ecology, in which manufacturing enterprises adopt their own environmental strategies and practices. Consequently, there is a need to implement new design and manufacturing strategies in order to deal frequently with environmental impacts caused by the supply chain. The evolutionary ECDM paradigm is such an ecologically-conscious strategy.

Firms have essentially begun to incorporate ECDM efforts (see Figure 1.6) into their product design and manufacturing processes and into their corporate strategies in order to address environmental concerns. A green product may be defined as one that, at the ultimate end of its useful life, passes through disassembly and other reclamation processes to reutilize non-hazardous and renewable materials [Brady, 1992]. ECDM strategies deliberately attempt to reduce the ecological impacts of industrial activity without sacrificing quality, cost, reliability, performance, or energy utilization efficiency [Darnall, *et al.*, 1994]. The ECDM paradigm-related concepts will increasingly be an acceptable and useful approach in the green product design and development cycle.

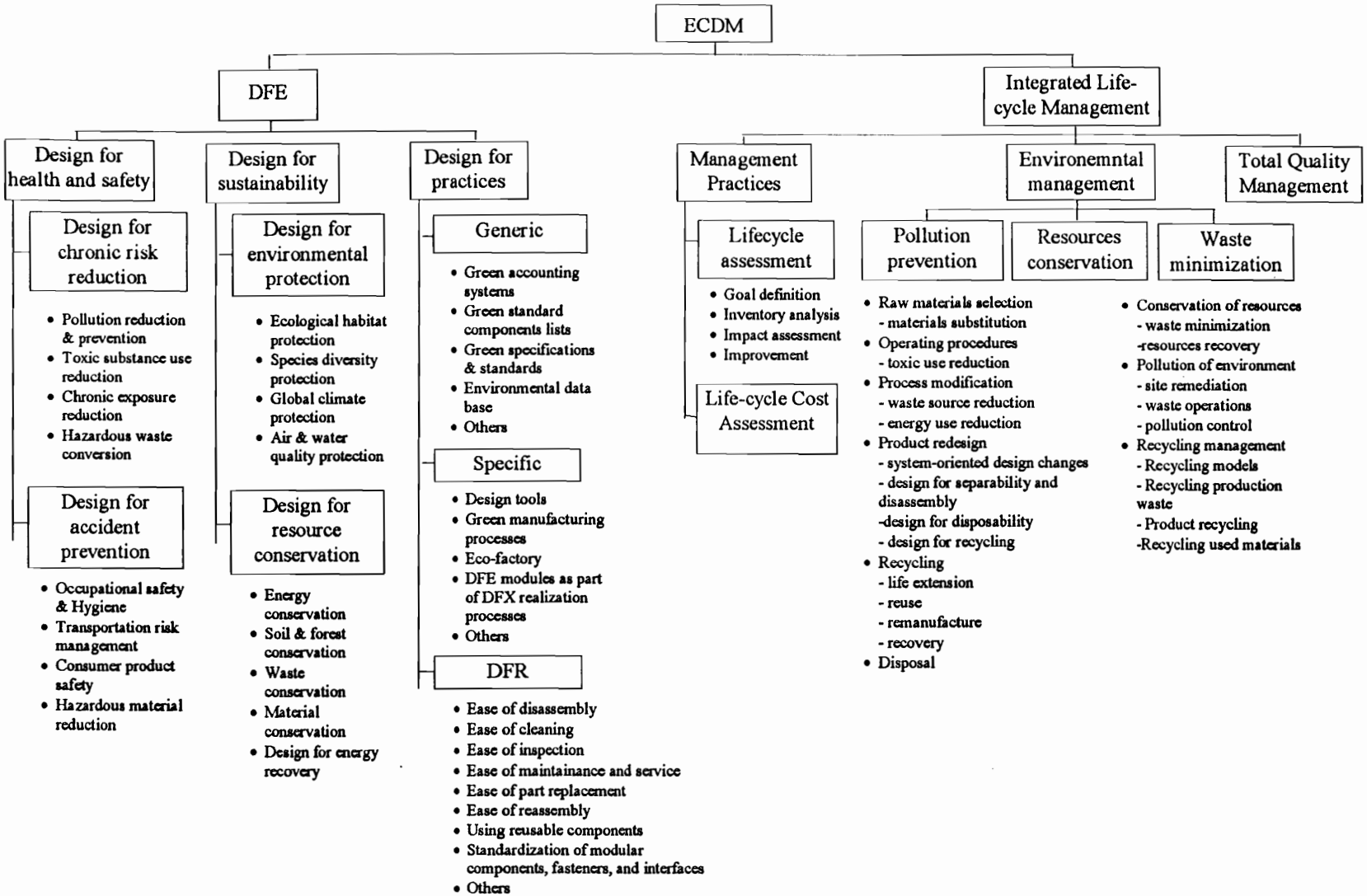


Figure 1.6. General ECDM-related strategies model

Efforts leading to environmental friendliness result in complicated problems, however. The general ECDM paradigm requires new design and specified analysis methods and methodology in order to shift from reactive end-of-pipe treatment to integrated, multi-disciplinary, proactive design activities. While the explicit consideration of environmental objectives and constraints in product development cycle can lead to a green technology solution, the question as to what is green depends on how environmental problems and system boundaries are defined in practice.

As problem definitions and system boundaries as well as strategies change, solutions also change. Weinberg [1993] categorized three paradigms that highlight the different roles that green technology can play with respect to the environment: *Environmental Protection* (e.g., environmental safety, waste prevention, recycling or waste treatment), *Resources Management* (e.g., resource conservation, waste reduction, recycling and recovery), and *Eco-Development* (e.g., green product and technology, eco-balance, and recycling in a closed materials loop). Even though these roles often overlapped in dealing with real-word environmental problems, the focus of this dissertation is on the Eco-Development paradigm. We will discuss the basic components in the domain of ECDM briefly in the following section.

1.2.2. Components of General ECDM Domain

Based on the literature review (refer to Chapter 2 for details), ECDM involves the systematic planning, development, and implementation of manufacturing processes and technology that minimize or reduce environmental impacts caused by a product and its processes, and that can design products that are recyclable, or that can be remanufactured or reduced. ECDM is emerging as a systematic approach, addressing the entire system of environmental impacts across the entire product life cycle. In practice, ECDM has been used in reference to a variety of practices and concepts, and has been described both narrowly and broadly. In order to provide a foundation for understanding ECDM-related problems, it is important to establish a complete description of ECDM, to fully capture all environmental improvement opportunities. Then define our own research and approach on general ECDM problems concisely.

Depending on the characteristics of various industries and the system boundaries being defined, different product design and manufacturing strategies can be adopted in implementing ECDM concepts. Figure 1.6 shows a hierarchical breakdown of efforts and various disciplines for achieving ECDM, which are reflected in the practices of many manufacturing companies. This classification scheme itself also points out potential questions that firms may face, and other potential research areas in ECDM practices.

The ECDM framework can be defined by two major categories: design for environment (DFE) and life-cycle environmental management (LCEM), as shown in Figure 1.6. The first category, DFE, incorporates the idea of impact prevention into the initial product design process (i.e., analysis, synthesis,

and evolution). DFE is the practical application of ECDM concepts. DFE contains design for health and safety, design for substainability, and design for practice. The second category, LCEM, incorporates environmental management (waste minimization, resources conservation, and pollution prevention), the philosophies of total quality management (TQM), and the tools of life-cycle assessment (LCA) and life-cycle cost assessment (LCCA). We introduce efforts in the ECDM domain briefly as follows.

Environmental Conscious Design and Manufacturing (ECDM). The ultimate aim of ECDM is to reduce negative environmental impact by improving the environmental friendliness of product, processes, and activities. A significant difference between ECDM and waste management or pollution prevention is that the ECDM approach is a proactive action that reduces environmental impact in the early product design stages. Product designers and manufacturing engineers as well as the managers of companies have great responsibility in planning and implementing environmentally-safe and environmentally-friendly manufacturing operations. Much can be gained by careful analysis of products, their design, the materials used, and the manufacturing processes and practices employed in producing these products. ECDM can be generally divided into two efforts: Design for Environment (DFE) and Life-Cycle Environmental Management (LCEM). The ECDM approach is a proactive activity that aims at preventing negative environmental impacts. Certain guidelines can be followed in this regard, as outlined below [Kalpakjian, 1995].

- Waste reduction--reducing materials waste at the sources by refinements in product design and by reducing the amount of materials used.
- Materials selection and process modification--conducting research and development in environmentally safe and friendly products and manufacturing technologies.
- Product redesign--reducing the use of hazardous materials in products and process.
- Operating procedure--ensuring proper handling and disposal of all waste.
- Recycle-- making improvements in recycling, waste treatment, and reuse of materials.

Integrated Life-Cycle Environmental Management (ILCEM). Life-cycle management should include the environmental issues [Quakernaat and Weenk, 1993], especially the integrated Life-Cycle Environmental Management (ILCEM). LCEM or eco-management is a precondition for greener product development and product production. It is a comprehensive and flexible life-cycle framework for making planning, design, and operating decisions, that explicitly considers costs assessment and environmental impact assessment, and other fundamental business matrix together with environmental, health, and safety factors. Unlike other general business management programs, ILCEM is a green marketing-oriented management concept which focuses on a firm's green production-related decisions. A

number of potential functional applications of ILCEM include management practices (LCA and LCCA), environmental management (resources conservation, waste minimization, and pollution prevention), and total quality management (TQM). We discuss each component briefly as follows.

Life-Cycle Environment Management: Environmental management is a set of techniques and disciplines that moves firms away from concentrating on the clean-up of pollution, towards greener production and the prevention of waste and pollution. As the focus of attention switches from the process to the whole plant, firm, supply chain, recycling chain, and product life-cycle, the information intensity of environmental-related activity by the company rises substantially.

The primary goals of environmental waste management often include such targets as prevention of pollution, minimization of wastes, and reduction of energy consumption. Historically, health and safety have been the major concerns in waste management. Although these still apply, and waste must be managed in a way that minimizes the risk to human health, the perspective of waste management should be widened today to include other effects of waste on the environment. Environmental concerns about the management and disposal of waste can be divided into the following two major areas: conservation of resources and pollution of the environment [White, P. *et al.*, 1995].

Concerns over conservation of resources have led to

- waste minimization (or waste reduction)--to generally reduce the amount of waste generated.
- resource recovery--to slow down the exhaustion of non-renewable resources (such as materials and energy), and to help to lower the use of renewable resources to the rate of replenishment.

Potential or actual pollution is the basis for current environmental concern over waste management. What is needed is an overall strategy to manage waste with reduced environmental impact, of site redemption, waste operation, and pollution control at an affordable cost. The main idea is to prevent waste and reduce environmental impacts. Thus, implementation of ECDM strategies is required for ecoproduct development.

Life-Cycle (Environmental) Assessment (LCA): The key auditing tool for environmentally-conscious production (or greener production) and effective eco-management is the Life-Cycle Environmental Analysis, also known as the Life-Cycle Assessment (LCA). The LCA is a set of techniques for assessing and evaluating the environmental pollution (impacts) associated with a product, process, or activity throughout a product's life cycle. LCA identifies and quantifies resources (energy and materials) used and wastes released to the environment in order to assess the impacts of the use of resources and of their release on the environment and to identify and evaluate opportunities to improve the environment [SETAC, 1993]. Therefore, LCA becomes the main integrating tool in eco-management, as

its focus on products and overall life-cycle is so inclusive: it embraces the impacts of suppliers, processes within the firm, distribution, use, disposal and options for reuse and recycling [Christie *et al.*, 1995]. It consists of four steps: goal definition, inventory analysis, impact assessment (classification), and improvement analysis (evaluation). In design practice, LCA is a support tool in the ECDM process. Furthermore, the result from LCA, namely the environmental impacts profile, is one of the important factors used for the evaluation of design alternatives.

The primary goal of Life-Cycle Assessment/Management is to save money by making purchasing, operating, and maintenance decisions, based on the full life-cycle cost of a material, product, process, or service, which explicitly includes the costs of environmental, health, and safety-related issues. In many cases, the alternative with the lowest life-cost also provides an opportunity for pollution prevention and source reduction. However, in most cases, a firm is required to make a trade-off between costs and other goals. In these cases, ILCEM provides the information decision-makers require to make informed decisions that impact cost-benefit analysis.

Environmental Total Quality Management (TQM): TQM is important in reconciling the top-down and bottom-up approaches and in integrating environmental awareness at all levels of business activity. Although corporations have applied strategic principles for years, dramatically rising costs for environmental compliance have caused companies to consider whether strategic planning approaches can also be applied to more efficiently manage environmental responsibilities [Blake, 1994]. The major component to the management strategy of ECDM is the so-called Environmental TQM. Environmental TQM helps to achieve the objective of waste minimization by analyzing current operational procedures and identifying the need for change. TQM can form an essential component of ECDM, which offers common ground for improved environmental management.

Design for the Environment (DFE). Design for Environment is the systematic process by which firms design products and processes in an environmentally conscious way based on industrial ecology principles across the entire product life-cycle [Lenox and Ehrenfeld, 1995]. As mentioned, the ECDM paradigm has become a common practice in industry, thereby indicating the importance now being given to environmental problems. A major emphasis, and the most important in the ECDM approach, is on Design for Environment (DFE) or green design, with "green" meaning environmental friendliness. DFE embraces waste minimization goals through reuse/recycle, remanufacture, and disassembly strategies in design practices. DFE integrates environmental considerations and constraints into existing product and process design practices. Three major areas are discussed in DFE: design for health and safety, design for sustainability, and DFE practices. This DFE approach anticipates the

possible negative environmental impacts of materials, products, and processes so that they can be considered at the earliest stages of design and production. The main objectives of preventing pollution at the source and recycling rather than disposal led to the concepts of Design For Reusability, Remanufacturability, and Recyclability (DFRs), as well as Design For Disassembly (DFD).

The terms reuse and recycle are generally considered to be the returning of components or materials back up the supply chain to the original manufacturer or producer. Design for reusability and recyclability integrates in product design phases the characteristics that allow for the reprocessing of materials into forms that are different from their original manufactured form. Design for disassembly (DFD) is the process of designing products so they can be easily broken down into like materials for recycling, reuse, or remanufacturing [Richard, 1991]. DFD's intent is to design products for maximum recyclability and efficient disassembly, offering an easier remanufacturing process.

1.2.3. Barriers to ECDM Implementation

The above discussion provides a brief, but comprehensive understanding of potential questions and problems in the field of ECDM. In order to adapt an ECDM strategy, a firm must identify the boundaries of the problems for implementing its own ECDM strategies. Nevertheless, firms are recognizing the need to migrate towards DFE and environmentally friendly management. For the ECDM approach to be fully utilized, however, a whole range of tools and methodologies are required to facilitate an adequate assessment of the consequences of different ECDM-related strategies. These tools include technological advances, better analytical models, and an acceptance of ECDM at all levels of the organization throughout the product life cycle. There are numerous reasons why selection and implementation of ECDM strategies may be inhibited, both at the level of the firm and at the level of national and international policy-making. These relate to internal influences, technology problems, and the lack of external incentives, as shown in the Table 1.1 [Christie *et al.*, 1995]

At the firm's level, according to Sarkis [1995], there are two barriers to the ECDM implementation: the scarcity of technology to implement ECDM process and design changes (such as DFE-related techniques and LCA tools), and the scarcity of analytical modeling tools (such as environmental cost-accounting models). Furthermore, ECDM is not adequately addressed in most decision making, thereby impeding implementation of ECDM in the overall manufacturing industry [Wilhelm *et al.*, 1993]. This inadequacy is due to a lack of knowledge about influencing qualitative (intangible) attributes and the lack of analytical tools to manipulate those attributes. All of these handicaps make ECDM implementation a difficult problem. Implemented correctly, however, ECDM will help a company create environmentally sound processes and products that are globally competitive.

Table 1.1. Factors inhibiting cleaner production (or ECDM strategy) innovations

Internal factors in firms	Technology problems	Lack of external incentives
Lack of support from senior management	Cost of cleaner production solutions compared to end-of-pipe solution	Low demand for greener products
Lack of skills	Lack of proven cleaner technologies	Poor return on investment (e.g., in recycling system)
Lack of finance for investment	Ease of fitting end-of-pipe technologies	Regulators not promoting cleaner production
Lack of information in-house	Complexity of new techniques (e.g., LCA and LCCA)	Lack of support services
Short-termism	Lack of standards	Lack of pressure from stockholders
Low awareness of environment	Investment cycle and sunk costs	Low energy and material prices

(Source: Christie et al., 1995)

In our research we believe that both the technology and the modeling tools for an ECDM approach should address involving environmental design requirements in product and process design and redesign. In addition, whole ECDM-related attributes should be simultaneously integrated into the decision-making system. To overcome the above-named barriers to ECDM implementation is our primary motivation in this research. Once we define our own ECDM problem in the next section, we will present an Integrated Life-Cycle ECDM (IECDM) approach to help companies develop environmentally conscious products and processes through a well-structured design decision-making process.

1.3. PROBLEM SETTING IN RESEARCH

As discussed in the previous section, having been forced to be responsible for the environmental impacts of its product development process and its products at their end-of-life, industry intends to employ the ECDM approach, and to manufacture products that have minimum environmental impacts and disposal costs. Thus, the resulting environmental and resource consequences need to be assessed and evaluated at the development stage to minimize the total negative impacts or to maximize environmental compatibility, in order to increase total product value. In addition, it is necessary to improve existing production, distribution, and disposal practices to remedy the existing pollution and waste problems. Given the increased emphasis on pollution prevention and waste elimination as part of ECDM practices, some questions that may be asked are:

- What product and process design features within a facility contribute to the environmental releases?

- What are different ways to effectively and efficiently reduce the environmental releases to an acceptable level while at the same time eliminating a potentially risky investment?
- How can the true cost of manufacturing a product be determined when the costs are associated with the pollution control equipment necessary to reduce the environmental releases (for example, emissions) from the facility?

To answer these questions, a firm needs to implement ECDM strategy for ecoproducts development. However, some barriers to complete the ECDM implementation currently exist. To overcome these difficulties, an evolutionary design process must be constructed to incorporate environmental requirements into product and process design. Also, a new methodology must be developed that can be used for evaluating the life-cycle environmental impacts of the product system and for assessing its life cycle costs. The product system must be made functionally, environmentally, and economically viable. This section will describe the motivation to develop an integrated life-cycle ECDM (IECDM) system, the general environment-related questions raised from industrial and academic perspectives, and then will present the associated research problem statement.

1.3.1. Motivation for IECDM Development

Researchers and practitioners have, over the years, successfully worked towards developing a variety of methods and approaches to be used in the product realization system (i.e., product design and development process). However, when they are studied in the field of ECDM, none seem to provide the complete answer, or rather just provide simple answers for every complex question[7]. The efficiency of the proposed method depends on the scope and the particular situation in which decisions are made. The barriers discussed in the previous section also inhibit the implementation of ECDM strategies. This research attempts to remedy the deficiency by developing an integrative approach with a more complete solution in the context of environmental-oriented product design and development.

Despite concurrent efforts to integrate design and manufacturing, the industry has paid little attention to issues such as product use, disposal and demanufacturing for product reuse, refurbishing, recycling, recovery, and remanufacture. The major concern has been to get the product to the market and then let the customer and society, generally, take care of the quality of the environment. In the past, the environmental impacts of a system were not considered in the design decisions (neither by design evaluation methods nor through design optimization techniques) because industry never directly

[7] Simple answers may not be totally wrong, but they are more often only part of the answer to complex questions posed by the environment-related issues in a product realization system. The proposed QFD-based IECDM system encourages asking more questions, and therefore answers more complex questions, and obtains more complete answers.

experienced its effects. But now the situation has changed. Customer preferences and environmental regulations dictate consideration of environment-related issues during the product development process, thereby making industry more responsible for the environmental compatibility of their product systems. Incorporating environmental impact considerations into the design process makes the design problem more complex, however. An appropriate integrated methodological approach to treat such a design evolution situation is needed. Here, the integrative approaches are viewed from different aspects.

Integrated approach to incorporate environmental considerations. Integrated approaches are required for implementation of the ECDM strategy by a firm. In order to help a firm effectively manage these additional environmental responsibilities, we have developed an IECDM in this research.

Our IECDM approach is based on concepts from Operations Research and design decision-making, which will lead to two important results: an optimization-based Cost-Benefit Assessment (CBA) model and an Integrated Design Decision-Support (IDDS). Briefly, this method takes Concurrent Engineering (CE) and Life-Cycle Design (LCD) one step further, so that all environment-related considerations are taken into account throughout the life cycle of a product, from design, materials processing, manufacturing, and customer use, to demanufacturing and disposal of used products. The IECDM engineering process, which now considers environmental design requirements in 'green' product development, has the goal to consciously improve the environmental compatibility of a product and its manufacturing processes.

Integrated approach to design, manufacture, use, disassembly, and recycling. Assessing the 'best' practicable ECDM options in a product realization system does not simply involve consideration of polluting processes in the production system. Rather than seeing design, manufacture, use, demanufacture, and disposal as discrete phases with little to do with one another, these processes must be considered in an integrated way[8].

Product design greatly affects downstream activities through product development. According to Fabrycky [1987], decisions made initially, during the design of a product system, will determine about 80% of the total system costs[9]. Any optimization with regard to cost, after the product design has been completed, will affect only 20% of the total expenditure. This common idea is still true in the IECDM

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[8] In this research, we use 'demanufacturing' instead of the term 'disassembly.' Demanufacturing includes the considerations of planning, policies, and process related to recycling/reproduction as a whole. Disassembly, viewed as a recycling technique as part of the demanufacturing scheme, is employed to reuse, refurbish, remanufacture, and recycle.

[9] A system is defined as a product or process (or both) that performs a specific function to satisfy the needs of the customer. The terms 'system' and 'product' will be used interchangeably since process itself can also be viewed as a type of 'system' in a sense.

approach. In a particular IECDM context, product design becomes crucial, as it is at this stage that decisions on materials and components can be taken that can minimize later waste and consumption, reducing environmental impacts, and maximizing the potential reuse and recycling of parts or whole products; it is also at this early stage in production that design factors can influence the production process for the new product, and demanufacturing processes of returned products for environmental purposes.

Manufacturing processes, on the other hand, by their very nature, generate the most potentially environmentally harmful waste and emissions (pollution). Therefore, manufacturing engineers, product designers, and the managers of companies have great responsibility in planning and implementing environmentally sound product and manufacturing operations in order to reduce the harmful environmental impacts and to improve environmental compatibility. By properly using techniques on ecodesign-related issues, significant advances in the IECDM methodology can be made, while still achieving the industrial goal of maximizing the total value of the product system.

Integrated approach for methodologies with interrelationships. Much can be gained by a careful design and analysis of products, their materials, and the manufacturing processes and practices employed during their production. These involve proper modeling techniques for analysis, synthesis, and design (evaluation or/and optimization) of system products/processes using a system-wide concurrent engineering perspective.

In addition to the life-cycle system engineering approach, this study describes the methodological approaches that result in a general qualitative and quantitative process. It provides a way for an environmentally sound industrial development that integrates life-cycle assessment (LCA) into the IECDM engineering process, so as to incorporate the environment-related information. Also, a decision-oriented approach can be developed that simultaneously combines life-cycle assessment (LCA) information into product design and process selection.

Ideally, the IECDM approach must be tailed for different industries and product areas such as automobiles, electronics, and durable goods, in order to address the different environmental effects and constraints imposed on product design and manufacturing processes. In addition, a set of units is needed for comparing the life-cycle environmental impacts of alternative products and processes, for the measurement of environmental performance of the IECDM methodology, and for evaluating the environmental life-cycle impact during product development. Accordingly, a set of measurement matrices needs to be created for an "environmental burden index" that will indicate the degree of environmental-friendliness or the environmental impacts of alternative product system designs. Armed with knowledge about environmental constraints, ecodesign processes, and green index information, our IECDM

methodology can incorporate an environmental-impact perspective while designing a product and its related manufacturing processes.

1.3.2. Problem Description from both Industry and Academic Aspects

The IECDM methodology is developed from both an industry-feasible focus and an academic-research focus. Questions influencing IECDM methodology development are discussed. Then the whole picture of the ecodesign problems that an IECDM approach has to face is introduced.

Questions Influencing Development of the IECDM Methodology. Two basic research problems influence the development of our IECDM methodology as a result of the interactive impacts between the supply chain and the environmental chain. They are:

1. The industry research problem

   How do environmental issues (considerations of customer preferences and environmental regulations) affect design of product and its manufacturing process as well as recycling policies, that in turn affect total product value?

2. The academic research problem

   How does the design of product and its manufacturing process affect the product's environmental compatibility? *What approach can be used to achieve minimization of environmental impact caused by product development*?

The industry research question deals with building a new design decision-support or methodology to help manufacturing companies develop green products that meet customers' needs and environmental regulations. The academic research question deals with the theoretical issues involved in developing such a decision-support system or methodology to be used in industry. In addition, with a broad design context, both the industrial and the academic questions lead to the following basic design questions: "How can we creatively solve environmental problems at all design activity levels?" "How do we estimate environmental impacts of products before they are made, in the early design stage?" "How do we incorporate environmental considerations and criteria into the product development process?" "How do we resolve conflicts among various design criteria across design activity levels?" "How do we maintain consistency between design decision levels?" "How can we evaluate and determine the best alternative solutions?"

Putting the above questions in perspective, the broad complex question addressed in developing IECDM methodology becomes:

Is there any unifying model that can design ecoproducts by simultaneously considering various design attributes and requirements pertaining to economy, quality, performance, time, and environment ?

If so, the next question that arises is:

How can we determine if our methodology is able to improve and optimize the environmental compatibility of a production system (including product and process) as a whole?

In order to answer these environment-related questions, an integrated approach is needed, to develop our IECDM methodology. In our IECDM methodology, both of these practical questions are explored through optimization-based and decision-oriented approaches.

Getting the Whole Picture of the IECDM System Problem. We define our own problem in the ECDM domain for use in IECDM development. Thus, the purpose of the IECDM is to maximize total product value at its end-of-life. Figure 1.7 shows the ECDM-related problems that we dealt with in this research. Total product value is generally the goal of a company. System design evaluation and/or design optimization are essential procedures in ecoproduct development in order to maximize the product's total value. In the context of IECDM, the product's total life-cycle value (TLCV) is created from the production activities and the demanufacturing schemes. Both production and demanufacturing efforts are significantly affected by the product design and the production system in which they are realized, either of which may contribute to increase or reduce the value of a product. In most cases, both results are possible.

From a product design perspective, total product value is basically contributed by performance functionality/quality, environmental compatibility, and economic viability. From a manufacturing process perspective, the coordination of disassembly, remanufacturing, and recycling operations with each other, and with other company's manufacturing facilities, are complex tasks. There appears to be a need for analytical models that will allow designers and engineers to gain insight into the product-design and manufacturing-process issues that are related to the environment. In addition, the Life-Cycle Assessment (LCA) is developed and employed as a tool to evaluate the environmental burden of manufacturing processes of products. The results of LCA are an important factor in the evaluation of the environmental impacts of a product and its manufacturing process. Life-Cycle Cost Assessment (LCCA) is used for an economic assessment of the environmental issues. The life-cycle approach is one of the significant features of the IECDM framework. Another feature involves product/materials-oriented and system-oriented approaches. These approaches lead to the integration of DFE, LCA, and LCCA into our IECDM approach.

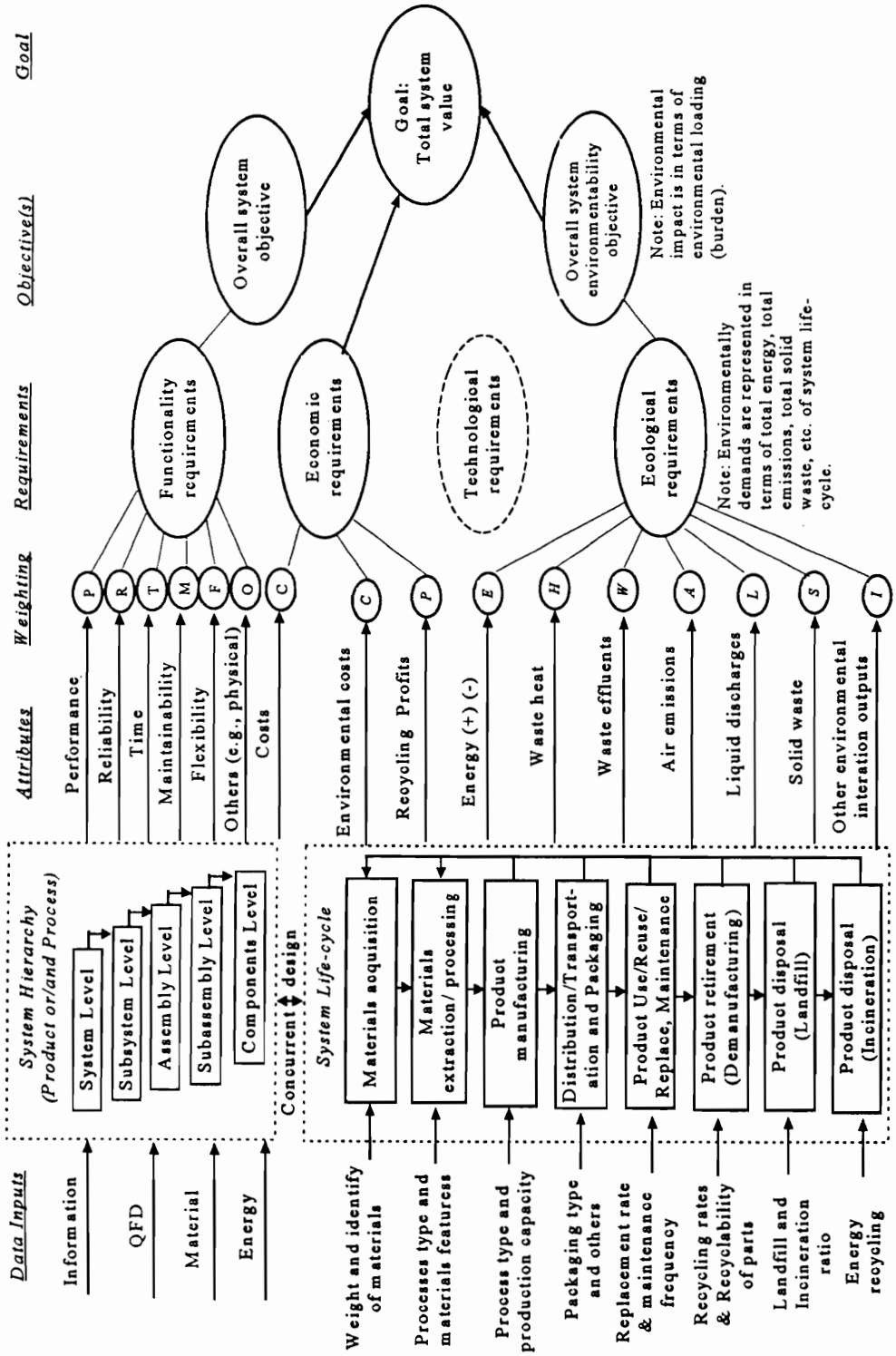


Figure 1.7: A general conceptual model of system design evaluation and optimization.

To the best of our knowledge there appears to be no work currently under way that simultaneously examines the environment-related considerations of product ecodesign and manufacturing/production processes with demanufacturing/recycling capacity using integrated models and methodologies. Figure 1.7 illustrates a general model for achieving the goal of product's total life-cycle value (TLCV) concerning environment issues. However, the model does not cover the general green technologies of product design and recycling technology of manufacturing/industrial systems, whereas our integrated approach covers recycling and demanufacturing options in the IECDM system, since recycling and demanufacturing activities may provide a potential value added to a product. This model illustrates that (eco)design decisions are affected by environmental issues together with other factors such as performance, cost, time, quality, and so forth.

Considering this model, a unified IECDM methodology has been developed as a guideline for dealing with specific ecodesign problems in the domain of ECDM within industrial ecology. In addition, continuously improving the total product-value and system-environmental compatibility is the top goal of the IECDM system. To deal with this complex design problem, we have developed a twofold effort in IECDM methodology: the QFD-based IECDM methodology, an optimization-based cost-benefit assessment (CBA) model, and an integrated design decision-making support system. We will discuss them sequentially.

1.3.3. Problem Statement and Focus of the Research

To reduce the barriers of general ECDM implementation, there is a need to develop a new methodological approach that will be applicable to implement ECDM strategy into the corporation and to systematically make environmentally-conscious decisions in the product realization system. We present the IECDM as such a methodological approach that will aim at incorporating environmental considerations into engineering design process, to increase a product's total life-cycle value including its end-of-life value, while reducing the environmental impacts caused by product and processes.

As a long-term research need, the final goal is to develop an IECDM system that integrates several different design paradigms and various approaches for an environmentally sound system in industrial ecology. This IECDM system in practice has three parts: a QFD-based IECDM methodology, an optimization-based Cost-Benefit Assessment (CBA) model, and an integrated design decision-support (IDDS) system. The first two parts are our focus in the research. The IECDM is an integrated system for product design-related methodologies, which will be applicable to the product realization system.

The development of this IECDM system first requires a plan to describe the individual methods and methodologies that constitute the IECDM system. The next requirement in the development process

are individual methodologies which consider their interrelationships with the IECDM system and with other methodologies in making design decisions. A well-structured framework is needed to construct individual methodologies into the IECDM system.

Considering the template of the QFD House of quality, these interrelated methodologies are implemented in the IECDM system, which is the QFD-based IECDM. The first part of the IECDM system deals with the development of a IECDM methodology based on a well-structured QFD framework. Within the QFD-structured framework, an acceptable and flexible IECDM methodology for a system designer who has comprehensive knowledge of the environmental issues is developed, which is a widely acceptable tool for integrating customer requirements (including environmental requirements) into product and process design. QFD basically relies on a qualitative, rather than a quantitative, assessment of the relationships between design performance and engineering characteristics. Therefore, the QFD-based IECDM process will focus on matrix methods used for constructing the (eco)Design Evaluation Function (DEF) that relates performance objectives and decision variables. The QFD-based IECDM process, as expected, can be applied in every major industry, including chemicals, electronics, motor vehicles, consumer products, food and beverages, pharmaceuticals, pulp and paper, petroleum, electronic power, and even national defense.

Further, an analytical Cost-Benefit Assessment (CBA) model is formulated in the QFD-based IECDM process. A unified approach is applied to establish an optimization-based CBA model. CBA formulation is developed as an evaluation function that characterizes the interrelationships among activities of design, manufacturing, and demanufacturing for estimating a product's total life-cycle value, in order to investigate the environmental impacts on the product realization system and its behavior. The production system is considered as a manufacturing process with recycling/ demanufacturing capacity. The CBA model is employed for simultaneous consideration of product design, processes/material selection, and recycling policy determination.

Operationally, in the IECDM system, the QFD-based process provides us with a technique to generate product-related attributes and to identify product alternatives based on the perceptions of the final recipient of the design team (including the customer). Next, the CBA formulation is employed for design evaluation by getting total life-cycle value of each product alternative; then the product with largest total life-cycle value is selected with respect to the optimal production and recycling plans.

Finally, from a design-decision point of view, an integrated design decision-making support (IDDS) system is established that integrates QFD, LCA, MCDM and CBA models to help the decision maker select the 'best' candidate alternative through a design selection and design change procedure, i.e., a QFD-based IECDM process. The ultimate purpose is to develop a computer-aided product realization

tool to show how environmental information is incorporated into the green design process. This computer-aided IDDS system is out of the scope of our research.

1.4. THE THESIS OF THIS RESEARCH AND CONTRIBUTIONS

In order to develop an IECDM methodology to deal with the complex design problem shown in Figure 1.7, a unique integrated approach was undertaken. This section describes that approach, the research objectives, and the expected results.

1.4.1. IECDM Methodology Related Study

The design evaluation and optimization procedure of a product and manufacturing process are generally viewed as iterative (involving analysis, synthesis, and evaluation) in a multi-dimensional domain. Owing to the complexity of problems related to environmental impacts analysis and evaluation for green systems design, related work has been conducted in the area of industrial ecological systems, Life-cycle assessment (LCA), Life Cycle Design (LCD), Design for "X" (DFX) paradigm, Design for the Environment (DFE), Life Cycle System Engineering, Concurrent Engineering (CE), Environmentally Conscious Manufacturing (ECM), Life-cycle Costs Assessment (LCCA), matrix methods, and Quality Function Deployment (QFD). In addition, multiple criteria decision-making (MCDM) methods, including multi-attribute decision-making (MADM) and multi-objective decision-making (MODM), are also considered in development of IECDM methodology. A brief description of these related studies follows.

Just as designers realized the need to consider the effect of design decisions on downstream activities, such as Design For "X" (DFX) techniques, which occur very early in the product life cycle, so too have they begun to realize the need to consider the effect of system eco-design decisions on the environmental loading (burdens) which "actually" occur during the manufacturing process stages as well as at the end of the product's life cycle. Concurrent Engineering (CE) is used to help the designer consider multiple design decisions simultaneously. That is, the various engineering activities (tasks) in the product and production development processes are integrated and performed as much as possible in parallel rather than in sequence. Typically, DFX methods focus on a single new area (or single design event) of performance as the appropriate design driver, while CE focuses on design evaluation as a function of performance in several areas (or several events in the design procedure). However, neither approach explicitly includes environmental considerations.

Life-cycle engineering begins to address the environmental impact of a product from cradle to grave. Life-cycle thinking is essential in considering environmental problems. Briefly, Life-Cycle Assessment (LCA) is a concept and methodology for estimating, evaluating, and auditing the environmental performance of a product, process, or activity from raw materials acquisition to ultimate disposition through recycling, incineration, landfill operations, or composting. An improvement assessment in LCA (which includes inventory analysis, impact analysis, and improvement assessment) is a systematic procedure for identifying, evaluating, and selecting among alternative opportunities for improving the energy, resource consumption, and environmental release profile of a product or process.

Environmental quality is continuously improved by using Design for the Environment (DFE) approaches that can help to identify the "best" ecoproduct design from the viewpoint of the environment. From an economic viewpoint, Life-Cycle Cost Assessment (LCCA), which involves environmental economics, is another important issue for cost-effectiveness analysis in the IECDM engineering process. As is well known, most of the traditional LCC (life-cycle costing) systems do not consider the environmental effects on production costs, while LCA itself does not involve the life-cycle cost calculations. The LCCA system plays an essential role in bridging the gap between traditional LCC and LCA. The general ecodesign approach to environmental improvement requires a methodology to evaluate life-cycle environmental impacts and to decrease the time and cost of performing these analysis activities. This approach leads to the fact that both LCA and LCCA are necessarily incorporated into IECDM methodology. In other words, there exists a trade-off between economic, ecological, functional, and technical product alternatives during design evaluation and optimization procedures. In addition, for ease of acceptance by the system designers, the IECDM methodology should be developed for a user who does not necessarily have knowledge of the environmental issues involved. One of the purposes of this research is to provide a system for such users.

Other researchers have explored Design for Disassembly and Demanufacturing (DFDs) methods to facilitate DFE rules and principles. All of these efforts take an important step toward the evaluation of product designs from the environmental point of view, and some of them consider optimization of disassembly operation and recycling plans. They do not help, however, in the incorporation of environmental considerations and other requirements into the entire product life-cycle. Quality Function Deployment (QFD) by its very nature can serve the function of integrating various methods/tools and approaches for environmentally-conscious product development. It also provides a well-structured framework to develop and implement IECDM methodology.

The general QFD approach, one of the structured-design methodologies, assumes that systems should be designed to satisfy customer's desires, and that these "customer attributes" will be the guiding force behind design decisions relating to "engineering attributes", that is, system characteristics and

technology requirements. It provides a structure within which the relationships between engineering design decisions and resulting design performance, including customer environment attributes, can be determined for the more detailed design phases. On the basis of a QFD framework, our IECDM methodology has been developed for green product design evaluation and optimization. However, QFD relies on a qualitative rather than a quantitative assessment of appropriate tradeoffs between attributes. Therefore, other analytical methods are employed in our IECDM methodology, such as the Analytic Hierarchy Process (AHP), hybrid Multi-Attribute Decision-Making (MADM) technique, and mixed multi-objective optimization methods. All related studies are discussed in detail in the literature review.

1.4.2. Uniqueness of the Research

This research derives its uniqueness from a variety of aspects that include:

(1) A focus on the life-cycle engineering and system-oriented approaches as well as on the closing of the product/material loop approach.

(2) Investigation of different design paradigms and approaches for environmentally-conscious system development for industrial ecology.

(3) Development of the IECDM approach as the green engineering guideline for ecodesign evaluation and optimization.

(4) Development of a mathematically-based CBA model that simultaneously determines product-related attributes, manufacturing-processes, and product-recycling options.

(5) Construction of a conceptual integrated-design decision-support (IDDS) system, incorporating QFD, LCA, MCDM and CBA modes for long-term research needs.

The IECDM approach developed in this research offers simple, yet effective and comprehensive, guidelines on how to practice environmental friendliness in the context of ecodesign and ecomanufacturing, as well as demanufacturing efforts, throughout the product life-cycle in industrial ecology.

1.4.3. Research Objectives and Expected Results

The general goal of this research is to stimulate designers to incorporate environmental aspects in the product design and development process through

- utilization of ECDM-related methodologies
- development of a new methodology that can
  - -- integrate various structured methodologies (such as LCA and QFD); and most of all,

-- incorporate environmental and customer requirements into design of product and product-related processes including recycling issues.

The primary objective of this research was, first, to develop a QFD-based IECDM process for application in the ecoproduct realization system, and second, to formulate a CBA problem that coordinates issues of design, manufacturing, and demanufacturing within the IECDM for evaluation of product design alternatives. In achieving these primary objectives, the intermediate objectives were to:

(1) Investigate various approaches and methodologies for development of the IECDM system:
- Investigate various aspects that contribute to environmentally sound industrial development and to the development of IECDM methodology;
- Contribute to the paradigm of environmentally-conscious industrial development, i.e., environmental friendliness; and
- Gain insight into the engineering process of IECDM through methodological approaches.

(2) Identify and define the characteristics of the IECDM system, with specific reference to the role of environmentally-oriented product design and development:
- Define and describe what is meant by "Integrated" and "Life-cycle".
- List and identify the desirable features of the IECDM system.

(3) Identify and define the integration issues to be considered in the development of the IECDM system:
- Review the various current approaches and methods contributing to ECDM.
- Select and integrate the proven methodologies essential to the development of the IECDM system.
- Identify the ecoproduct realization system and its boundaries.

(4) Develop the QFD-based IECDM system that is constituted by individual methodologies.
- Extend the QFD-based methodology to identify attributes and alternatives for a product and its related processes.
- Identify the QFD-based IECDM process for a design decision-analysis problem through a well-structured design flow chart.

(5) Formulate the optimization-based Cost-Benefit Assessment model:
- Identify the cost components and their relationships in a product realization system.
- Formulate a mathematical CBA model that relies on the information generated by the QFD matrix and LCA for design-evaluation in the QFD-based IECDM process.

(6) Illustrate the QFD-based IECDM as well as the CBA model through a hypothetical example, which will demonstrate the applicability of the IECDM methodology in solving problems in the ECDM domain.

In addition:

- An industrial ecological concept is introduced, and various approaches for environmental-conscious product development (especially the life cycle assessment approach) are investigated.
- An IECDM system, which is characterized not only by increasing environmental considerations but also by extended life-cycle framework, is defined in the research for environmentally-oriented product development.
- LCA is introduced as a tool for environmental impacts estimation and evaluation, and then is incorporated in IECDM methodology for ecoproduct design.
- A life-cycle cost assessment (LCCA) concept in the IECDM engineering process is emphasized and implemented for analyzing cost-benefit of the designed product system.
- An integrated ecodesign, decision-making support system based on multi-criteria decision-making is developed that integrates QFD, LCA, MCDM, and CBA models in order to show how environmental considerations are incorporated into eco-products development.
- A number of research topics research related to the IECDM methodology are recommended for further.

In summary, the proposed QFD-based IECDM and associated methodologies ensure that a ecoproduct is designed, integrating environmental requirements together with other product-related attributes in design decision-making. The generic IECDM approach offers simple, yet effective and comprehensive, guidelines on how to practice environmental-oriented product design and development.

1.5. DISSERTATION ORGANIZATION

This dissertation document has been organized into two parts with eight chapters and a supporting appendix. Figure 1.8 shows the research profile in the development of the IECDM methodology.

PART I: Literature Review and Conceptual IECDM Development

Various aspects and investigation of different methodologies and approaches are provided in the literature review. Part I aims at incorporating Quality Function Deployment (QFD) principles and methodology into the Environmentally Conscious Design and Manufacturing (ECDM) process that offers important benefits in Designing For the Environment (DFE) and in bringing new "green" products efficiently to market as well as increasing in customer satisfaction.

Chapter 1 introduces the overall research setting and problem domain. Chapter 2 is a life-cycle literature review to illustrate how literature is related to our research on IECDM methodology. Given the

research emphasis, Chapter 2 introduces the concepts of industrial ecology that define the domain of the research. In the framework of industrial ecology, various approaches for environmentally conscious product development are reviewed. The Life-Cycle Assessment (LCA) that is critical to the evaluation of the environmental burden of a product system is also introduced. In Chapter 3, design synthesis, synthesis, and evaluation based on the proposed IECDM approach are described, incorporating life-cycle framework, concurrent engineering, and environmental issues for environment-friendly product development in the industrial ecosystem. To successfully implement the IECDM engineering process, a conceptual QFD-IECDM methodology is developed as a tool for new green products development in Chapter 4. Both qualitative and quantitative methods are investigated and applied in the QFD-based ECDM methodology that combines the life-cycle assessment for dealing with multi-attribute decision making (or system design evaluation) problems during environmentally-conscious product development. A design evaluation and optimization procedure is defined. In Chapter 4, we also describe the formulation of a QFD-based optimization problem approach that is used in the defined design evaluation and optimization procedure.

Part II: Modeling Approach to the IECDM Problem

Part II aims at the application problem in IECDM methodology both qualitatively and quantitatively. Considering the framework of IECDM methodology, a quantification model is applied for the design of a product and its manufacturing process. Chapter 5 illustrates a unified approach for simultaneous consideration of product design and process selection as well as demanufacturing policies under the constraints of environmental issues. On the basis of a unified approach model, we develop an optimization-based Cost-Benefit assessment (CBA) with the objective of maximizing a company's profit. In Chapter 6 a formal example is proposed in order to demonstrate how environmental data are incorporated into design decisions analysis in the QFD-based IECDM. A tentative integrated design decision-support (IDDS) is specified, followed by a design-flow-chart for ecoproduct design and development. Finally, in Chapter 7 we re-evaluate our efforts and objectives; this is followed by our recommendations on some topics for future research related to IECDM methodology.

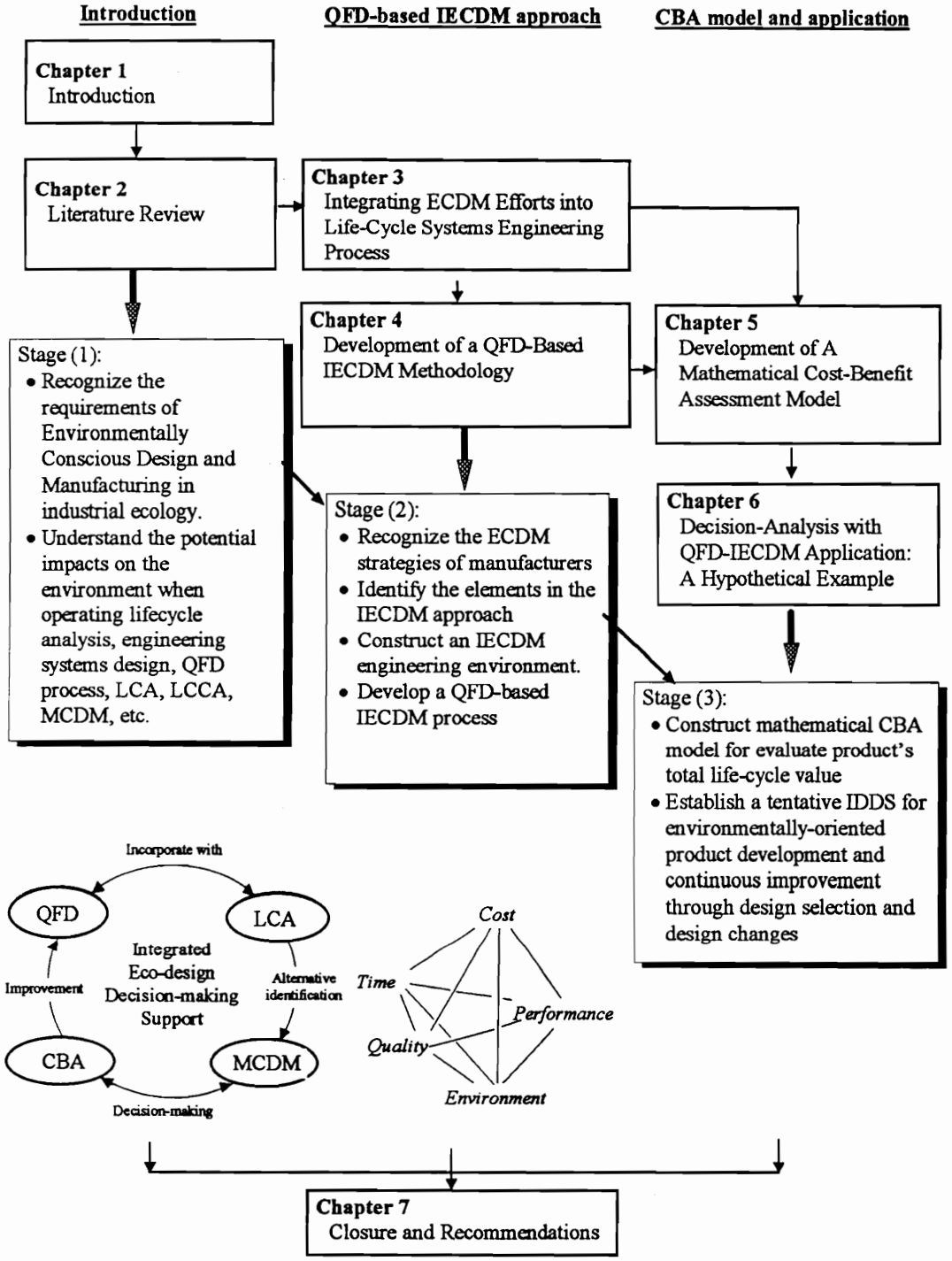


Figure 1.8. Research profile in development of IECDM methodology

CHAPTER 2

LITERATURE REVIEW

2.1. THE SCOPE AND PURPOSE OF THE LITERATURE REVIEW
2.2. INTRODUCTION TO INDUSTRIAL ECOLOGY
2.2.1. Definition of Industrial Ecology
2.2.2. Life-Cycle Based System Approach to Implement Industrial Ecology
2.2.3. Evolution of Environmentally Conscious Design and Manufacturing
2.3. STATE-OF-THE-ART TECHNIQUES APPLIED TO IMPLEMENT ECDM
2.3.1. Life-Cycle Assessment
2.3.2. Engineering Design Theory/Methodology and Process
2.3.3. Design For "X" and Concurrent Engineering
2.3.4. Design For the Environment
2.3.5. Quantitative Measurement
2.3.6. Life-Cycle Cost Assessment
2.3.7. Quality Function Deployment
2.3.8. Multiple Criteria Decision Making
2.3.9. Ecomanufacturing and Ecofactory
2.3.10. Non-Traditional Manufacturing
2.3.11. Integration Approach Issues
2.4. SUMMARY OF LITERATURE REVIEW
2.4.1. On Industrial Ecology Approaches
2.4.2. Observation and Applications form Literature Review
2.4.3. Learning From Literature Review: Integrative Aspects

The goal of this research is to develop an IECDM methodology and to prove the proposed hypothesis: "*There exists a systematic approach to 'green' product development that can be employed to improve efforts of Environmentally Conscious Design and Manufacturing (ECDM) in the industrial ecosystem.*" This hypothesis is the motivation to investigate and develop an integrated approach for product design and realization.

As mentioned in Chapter 1, environmental strategies should be applied to deal with problems in Industrial Ecology that contain the interactive supply chain (studies by industrial engineers) and the

environmental chain (studied by environmental scientists). In this chapter, we discuss the environmental issue related to the industrial supply chain and introduce a life-cycle based system approach applied to implement Industrial Ecology. The literature on ECDM is reviewed, and a variety of practical state-of-the-art techniques, methods, and methodologies applied to the field of ECDM are investigated. Finally, an integrative approach is proposed to incorporate different techniques for solving problems in the ECDM domain.

2.1. THE SCOPE AND PURPOSE OF LITERATURE REVIEW

As mentioned, many factors promote environmental strategies in the ecosystem. Figure 2.1 represents potential environmental strategies and techniques for the industry/ecosystem to consider. We will focus on general techniques on the life-cycle ecodesign and engineering for solving problems in the ECDM domain which, in turn, will provide a concrete body of knowledge to support and implement Industrial Ecology. This chapter addresses a comprehensive review of the ECDM-related literature and state-of-the-art techniques applied within the ECDM domain. By revealing the complexity of the ECDM problems, these techniques can serve as a basis for dealing with ECDM problems. In addition, the essential integration of existing techniques for the green product design and development is also addressed.

The purpose of this literature review is twofold: First, it is intended to provide a sound knowledge background in the areas of Industrial Ecology and of ECDM by discussing a variety of investigations on design methods and tools, as well as methodologies. However, it seems that none of them provide complete technical information for implementing ECDM strategies in industrial ecosystems. In order to obtain environmentally-conscious products, all the various approaches must be involved in the ecodesign process. Within various approaches, well-structured methodologies are our focus, including Life-Cycle Assessment (LCA), Quality Function Deployment (QFD), and Multiple Criteria Decision Making (MCDM). Second, the literature review provides comprehensive information from relevant books and articles pertaining to the subject areas of ECDM and DFE on the development of ecoproducts and eco-manufacturing processes, with specific focus on the life cycle of ecodesign disciplines. This literature review explores various methods/tools that can be employed in integrating environmental considerations into product design and development. The purpose is to provide a compendium of articles and books to be used in facilitating the development of IECDM methodology.

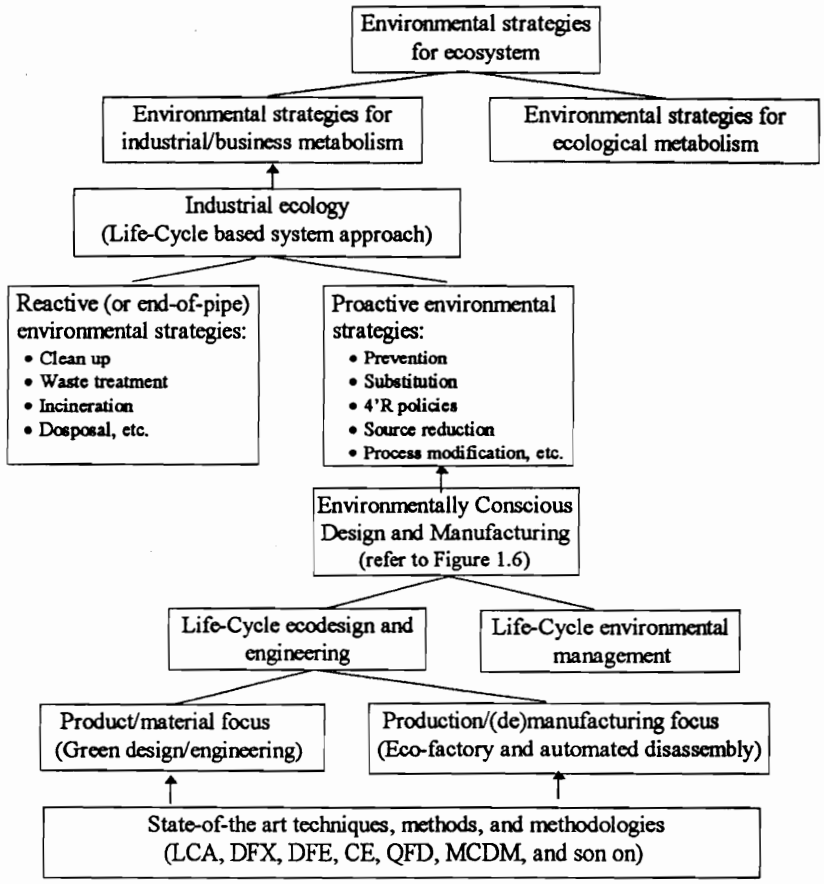


Figure 2.1. Guidelines for environmental strategies

2.2. INTRODUCTION TO INDUSTRIAL ECOLOGY

Fundamental to industrial ecology is that environmental impacts across the entire life cycle of products, from cradle to grave, be considered in decision making. It is in this way that industrial ecology is a *holistic* framework [Lenox and Ehrenfeld, 1995]. The field of industrial ecology (IE) studies how economic (supply chain) and ecological (environmental chain) systems shape and influence each other [Jelinski *et al.* 1992; Frosch, 1994; Graedel and Allenby, 1995]. Attempts to foster environmental friendliness (sustainability) by the ECDM approach are still in an embryonic state. Most current design methods do not explicitly address environmental issues. However, environmental friendliness requires integrating environmental considerations into a product development process that must also meet many other demands, including shortened development cycles and high quality at least cost [Keoleian and Menerey, 1994]. The purpose of IE is to provide such a function to achieve sustainability in the industrial

ecosystem. In this section, industrial ecology is briefly introduced through the perspectives of system-oriented, life-cycle, and closing-the-loop approaches.

2.2.1. Definition of Industrial Ecology

One of the popular definitions asserted by Graedel and Allenby [1995] was a biological analogy[1]:

"*Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. As applied to industrial operations, it requires a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete or waste product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital.*"

In addition to Graedel and Allenby's definition, some other central definitions are given below:

"*Industrial ecology is the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources.*" [White, 1994]

"*...industrial ecology involves designing industrial infrastructures as if they were a series of interlocking man-made ecosystems interfacing with the natural global ecosystem. Industrial ecology takes the pattern of the natural environment as a model for solving environmental problems, creating a new paradigm for the industrial system in the process.*" [Tibbs, 1992].

Industrial Ecology (IE), and the ECDM approach, are new paradigms that shift from "end-of-pipe" pollution control methods and waste management techniques towards strategies for more comprehensive prevention and planning of environmentally sound industrial and ecological system development. Conceptually, industrial ecology is constructed by the supply chain and the environmental chain (refer to section 1.2.1). Industrial ecology addresses issues that will impact future production, use, and disposal technologies throughout the chains. From the product development viewpoint, industrial ecology is a new ensemble concept for industrial design of a product and its manufacturing processes, and for implementation of sustainable manufacturing strategies. The industrial ecology concept is needed to guide industrial activities over the next several decades if we are to move in the direction of achieving

[1] Biological ecology is defined as the scientific study of the interactions that determine the distribution and abundance of organisms. This concept resembles in many interesting and useful ways the interactions of industry and society. Because of its relationship to industry, the field is called industrial ecology.

sustainable development practices [Graedel *et al.*, 1993]. Industrial ecology seeks to optimize the total materials cycle from raw and virgin material to finished material, to component, to product, to waste product, and to ultimate disposal [Jelinski *et al.*, 1992]. Currently, IE is still a broad umbrella of concepts rather than a unified theoretical construction. As such, it is described and presented in different ways by different authors. A critical review on Industrial Ecology is proposed by O'Rourke *et al.* [1995]. Many definitions of IE have been adopted in their review paper. As the definitions show, IE has come to represent a broad set of concepts, tools, analogies, and visions for carrying out organized changes in industrial ecosystems.

2.2.2. A Comprehensive Life-Cycle Based System Approach to Implement Industrial Ecology

Different definitions of industrial ecology converge on one notion: it is a broad framework for design and decision-making. It provides a systems context for understanding the implications of environmental management across many levels of design [Lowe, 1996]. The idea of Industrial Ecology seems straightforward, but there is no rigid formula or decision hierarchy for implementing it. One reason is that what is a successful 'win-win' policy depends strongly upon context. In general, Industrial Ecology policy will only become clear with respect to a specific view of the relationship (or balance) between the economy and the environment, which strongly conditions one's view of the 'environmental problems' it should address. One taxonomy of this relationship can be explored by three perspectives which are also our approaches in this field; thus, the life-cycle based system approach.

To successfully model and plan ecologically sound industrial development, a unified theoretical approach is required. Our approach is an integrated life-cycle based system approach that incorporates several state-of-the-art problem solving techniques, which will be termed IECDM.

Industrial Ecology (IE) as a System. Industrial ecology offers a theoretical foundation to support the transformation to a sustainable industrial system, operating in a balanced fashion in ecosystems between supply and environment chains. According to Lowe [1996], industrial ecology generally implies several distinct principles:

(1) All industrial operations (private and public manufacturing, services, and infrastructure) are natural systems that must function as such within the constraints of their local ecosystems and the biosphere.

(2) The dynamics and principles of ecosystems offer a powerful source of guidance in the design and management of industrial systems.

(3) Achieving high energy and materials efficiencies in production, use, recycling, and service will generate competitive advantage and economic benefits.

(4) The ultimate source of economic value is the long-term viability of the plant and its ecosystems; without that, present business success is meaningless.

These principles suggest the system framework needed in both private (e.g., product manufacturing and service) and public sectors (e.g., government) to transform the industrial system at the level needed.

The system of industrial ecology is often called the *industrial ecosystem*. The same system-oriented concept is used in our IECDM methodology. In this methodology, a system-oriented design approach is used that aims at decreasing the life-cycle costs (including environmental costs) or increasing the life-cycle efficiency of the product in terms of resource usage or waste generation, and finally maximizing total product value at its end-of-life.

The complexity of ecoproduct design is a function of the conflict between various classes of design criteria including environmental criteria, self-interest of the IECDM participants, and other factors affecting eco-product system development and implementation. Consequently, ecodesign activities to reduce aggregate environmental impacts and risks of engineering products and processes must be coordinated using a system-oriented approach.

Furthermore, regarding industrial ecosystems, according to Graedel and Allenby [1995], there are three types of system modes in traditional biological ecology: the linear mode (Type I), the semi-cyclic mode (Type II), and the complete cyclic mode (Type III), which have been ensemble to operate modes of industrial systems. Industrial ecology, in its implementation, is intended to accomplish the evolution of manufacturing from Type I to Type II and, ultimately, to Type III, by understanding the interplay of processes and flows and by optimizing the ensemble of considerations that are involved.

The industrial ecology domain is bounded by the problem of environmental effects. According to Graedel [1994], the domain of IE is conveniently pictured with four central nodes in the life-cycle: the materials extractor or grower, the materials processor or manufacturer, the consumer, and the waste processor. The Graedel and Allenby' modes lead to a more general comprehensive IE model shown in Figure 2.2. Accordingly, it is increasingly realized that the IECDM approach, as a rethinking process of product design and manufacturing, is the way to achieve the goal of industrial ecology.

It should also be realized that the system viewpoint is that of the manufacturer and marketer operating in a consumer product market (i.e., an overall market structure). As shown in Figure 2.2, from the standard point of the industrial ecosystem or overall market system, the industrial ecosystem has several principal elements, namely, material extractors, manufacturers (materials processors and product manufacturers), competitors, retailers, consumers, demanufacturers (e.g., product/equipment salvagers, and material reclaims), waste reprocessors, and the general environment.

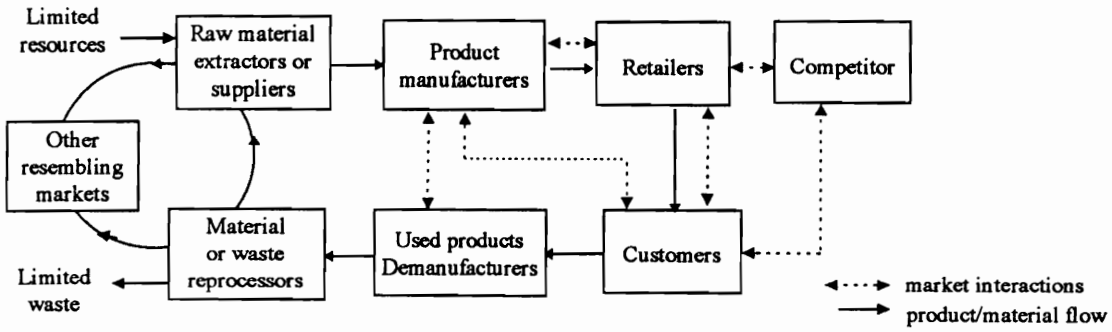


Figure 2.2. The model of the industrial ecosystem

Operationally, the materials supplier provides materials extracted from limited natural resources to the manufacturer. The manufacturer affects the final customer by the product itself, with its function and quality, and by price, advertising, and various promotional devices, etc. The manufacturer affects the retailer by its force and promotional activity, such as a temporary price reduction. The retailer affects the consumer by placement of product, price, special promotions, display, and advertising. Customer sales affect the retailer with respect to stocking and displaying the product, and also affect the manufacturer in product development strategy. Similarly, the retailer presents the manufacturer with a distribution and sales situation to which the manufacturer reacts. Competitive manufacturers enter the system by providing competitive products, which are more likely to hinder than to aid the sales of the product under consideration. In the context of environmental issues, demanufacturing and waste processors are increasingly important in industrial ecosystems. This overall market structure associated with the industrial ecosystem supports the idea that market issues should also be considered in the ECDM paradigm and relevant study. Another way to study the industrial ecosystem is based on product or material focus as follows.

Types of Industrial Ecology Assessment. Industrial ecology is usually pictured in one of two ways, as described in the works of Young and Vanderburg [1992] and Graedel *et al.* [1993] as follows.

Material Life-Cycle Approach (Material-Specific): The product life-cycle includes five stages: raw materials acquisition, material processing, product manufacturing, product utilization, and retirement. The material life-cycle approach selects a particular material or group of materials and analyzes the ways in which they flow through the industrial ecosystem. That is, life cycle assessment (LCA) techniques and models are developed on the basis of material-specific study. In product development, the material-specific analysis is relevant for both the pre-production raw materials extraction scenario and for the post-production disposal/ recycling scenario. A material flow is the back-

bone for the assessment of the environmental impacts from disposal in a landfill or an incineration plant, or from the recycling of some of the materials from the product scrap.

Product Life-Cycle Approach (Product-Specific): The product life-cycle approach selects a particular product and analyzes the ways in which its different component materials flow can be modified or restricted in order to optimize product-environment interaction. Such analysis is particularly appropriate at the initial design stage of a product. In such a case, the environmentally-conscious design of a product is developed on the basis of a product-specific study before the product is actually manufactured. In product development, the product-specific analysis is relevant for both the pre-retirement assembly scenarios and for the post-retirement disassembly/demanufacturing scenario.

To address the concept of industrial ecology, both approaches (product-specific and material-specific) are employed through the IECDM engineering process in our research. The product life cycle generally includes the product development, production, usage, and disposal of a product, whereas the materials life cycle focuses on the life cycles of the constituent materials included in the product. Their relationship is illustrated in Figure 2.3. In addition, regarding product design, the design procedure necessary to meet an identified need, it is apparent that the product design process runs conceptually counter-current to the materials flow. Thus, products are conceived and embodied from their use and production to design and development, while materials are chronologically selected, created, used, and disposed of. Numerous paths for recycling products/materials exist for different products, components, and materials. Only a few of these potential paths are shown in the figure.

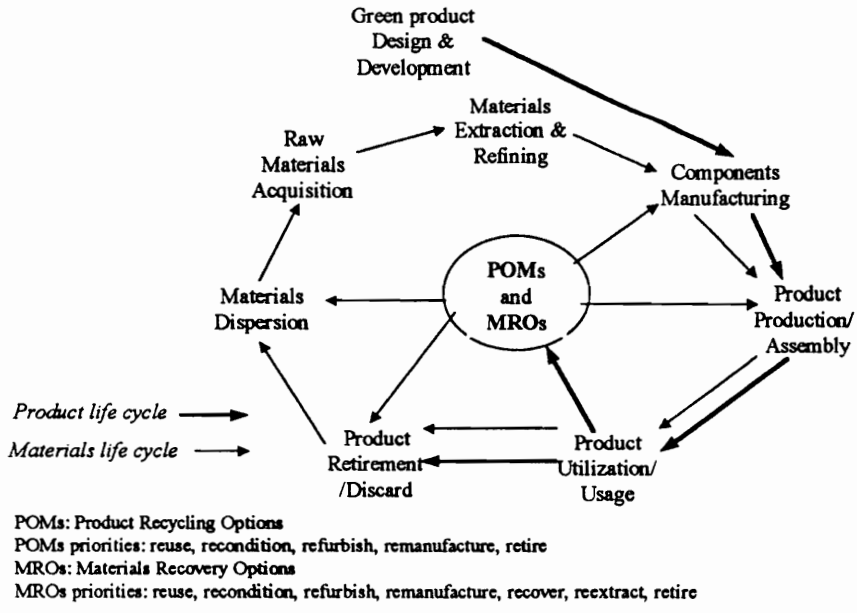


Figure 2.3 Relationship of the product cycle to the materials life-cycle

IE as Life-Cycle Analysis Approach. The attempt to provide guidance to designers for sustainable development (environmentally-sound development) of products includes Life-Cycle Design, Design for the Environment, and ecodesign. Design activities and disciplines are all based on a life-cycle framework that considers the full environmental consequences of a product from raw materials acquisition through manufacturing and use to ultimate disposal of waste. Both the 'closed-loop' and the 'life-cycle' are critical issues in industrial ecology. The life-cycle concept especially will become the backbone of the IECDM methodology in this research. The life-cycle approach is also typically a common structure for various approaches which will be discussed in the next section on 'green' product development. In practice, each company might have to develop a life-cycle concept for environmentally conscious product development. Generally speaking, the idea of the life-cycle analysis approach is to explore the different products' life-cycle phases, including the end-of-life phase (or recycling phase) when dealing with the IECDM related problems.

The concept of "life cycle" is another critical issue in industrial ecology. Olsen and Sutherland [1993] analyzed the "cradle-to-reincarnation" concept as an alternative to existing "cradle-to-grave" thinking. Basically, the goal of industrial ecology (and also of the IECDM approach) is "cradle-to-reincarnation," since if one is practicing industrial ecology correctly or repeatedly there is no grave or no waste. Within the domain of industrial ecology, Life-Cycle Analysis (LCA) is a systematic methodology used for evaluating the environmental effects of a proposed product. In life cycle analysis, all aspects of the product's useful life cycle are considered together in assessing the product.

Life Cycle Approach in Product Design and Development: With regard to future developments, it is important that the cycle between materials and energy consumption, production, product use, and recycling of used products or deposition of waste materials is implemented by applying stringent economical, technical, and ecological assessment factors. The life cycle of the product has to be analyzed [Weule, 1993]. The basis for product development is the holistic life-cycle concept, according to which a product should be seen as having five cycle phases:

- pre-production raw material extraction phase;
- component and product production/construction phase;
- distribution and transport phase;
- use and retirement phase; and
- disposal and demanufacturing phase.

Operationally, there are five stages in a product's useful life cycle. The first stage is the material extraction phase in which raw materials are gathered and shipped to the components' fabricating site. Second, in the fabrication stage, the raw materials are put together to form a set of components and then

shipped to the manufacturing or assembling site. Third, in the manufacturing stage, the components are assembled into a finished good. The fourth stage is the usage phase in which the product is actually used and exhausted by the consumer. Finally, the product must be retired when the consumer no longer wants it.

In each of these stages, there are many complex interactions with the environment. To understand a product's environmental effect, it is necessary to investigate all the effects of the product over its entire life cycle. Therefore, measurement of such environmental effects becomes critical for implementing the industrial ecosystem. Essentially, all the environmental effects can be said to be functions of the product's total design and of its manufacturing process. Nevertheless, it is very complicated to infer environmental effects from product and process design. The development of ecounits provides a unified measurement that can help designers consider the environmental impact of the product and its process simultaneously.

While most process-flow diagrams represent these stages as distinct phases, in reality they will interact and, quite often, overlap each other. Decisions that are made during one stage of the life cycle will frequently have a significant impact on the other stages. Therefore, it becomes necessary to address manufacturing, support or other issues as early in the design process as possible. More precisely, it is well known that over 80% of the costs of a product are committed before a first production run is made. The opportunities for influencing the costs are few once production begins. Therefore, in describing a product life cycle in the context of product development associated with environmental effects, the focal point is the design and production/construction phase. The manufacturer knows this phase best, and a detailed description of production is the starting point of Life-Cycle assessment (LCA). The manufacturer can play a vital role by changing the production process. Designs can increase productive life by improving reliability and durability, can make service and replacement of parts easier, cut packaging volume, and reduce negative environmental impact.

To date, most articles related to green product development provide only qualitative data (conceptual information) rather than a quantitative analysis and synthesis. According to Palmer [1995], industrial contributions to environmental problems can arise from each step of the product's life cycle. First, industrial facilities use natural resources and thereby contribute to the environmental problems that arise from the collection of these resources. Second, industry can create additional adverse environmental impacts while processing these materials into products. Third, industry may contribute to environmental problems in the packaging and distribution of its products. Fourth, depending on the design and function of a product, the use and maintenance and even disposal/recycling of the product may also contribute to a variety of environmental problems. Environmental problems are associated with the entire product/material life-cycle. A general life-cycle model is shown in Figure 2.4, in which customer

preferences and environmental regulations are two major factors that motivate research on environmental efforts, effects, and impacts on each phase of the product life cycle(s). This figure also provides a template for our literature review in next section 2.2.

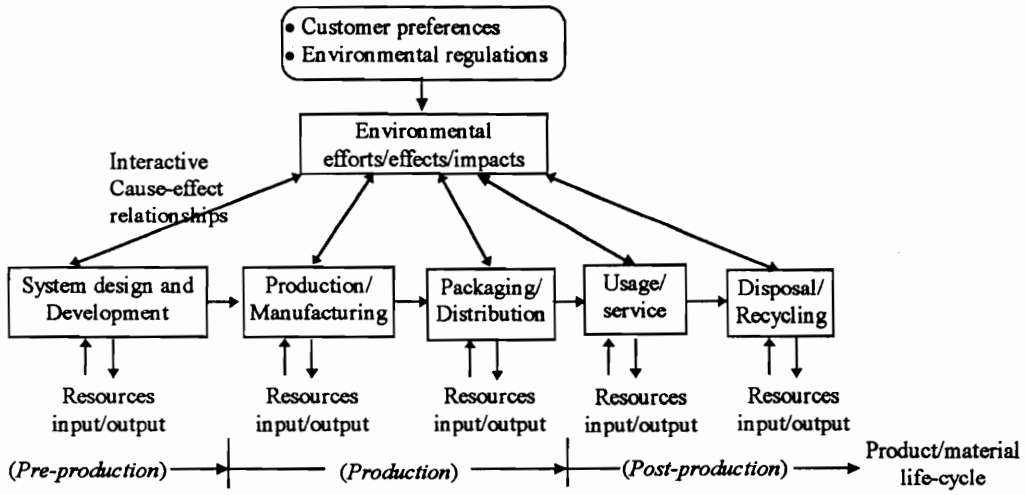


Figure 2.4. A general product life-cycle model as template for the literature review.

Uniqueness of Life-Cycle Approach: The product life-cycle concept for the company must be made "visible" for everyone in the company as a policy directing/guiding all product development activities [Alting, 1993a]. The life-cycle phases in practice might be different for each company. Basically, companies can effectively use a life-cycle approach by implementing the following key steps [see Cohan and Gess, 1993]:

(1) Define the scope of the system (products and processes) boundaries to be addressed in industrial ecology.

(2) Assess or measure the environmental impacts and total costs, for each alternative system design, throughout the product life-cycle.

(3) Make decisions based on the assessed impacts and costs as well as on other criteria.

In the context of environmental issues, several methods have been developed for assessing or measuring the impacts and costs of products, processes, and activities throughout their life-cycle. Some of these methods include life-cycle assessment (LCA), full-cost accounting [Popoff *et al.*, 1993], life-cycle costing [Bailey, 1991], and total cost assessment [EPA, 1992], among others. Generally, the purpose of these life-cycle thinking methods is to measure or assess impacts, in units of emissions, resources, dollars, or other metrics throughout the life-cycle. As pointed out by Cohan and Gess [1993], the major differences between these methods involve how they define life-cycle and stages (cradle to grave, material

or products specific, upstream inputs, down-stream outputs, system boundary to be addressed, etc.), how they measure impacts (cost, volume, weight, and other units and metrics, etc.), the extent to which indirect costs or impacts are included, and who is responsible for the impacts (individual, company, society, environment, etc.).

Life-Cycle Thinking on Environmental Issues. Life cycle concepts and techniques have been used in a variety of fields for a long time. Their application to environmental and energy issues stretches back to the 1960s. At that time the focus was on energy matters (for example, energy consumption related to fossil fuels). In flow charting life cycles, materials-consumption and solid-waste generation as well as resources-conservation issues are routinely included to ensure environmental balance. Over the years different names have been used to describe essentially the same types of efforts. The most common ones are: resource and environmental profile analysis; eco-balance; eco-profile; cradle to grave analysis; life-cycle review (analysis); and Life-Cycle Assessment (LCA) [MacAlasdair, 1993]. Due to developments in the formal methodology for carrying out life-cycle thinking in the environmental area, LCA has been gaining general acceptance. Life-cycle-analysis is the basis for the ecological assessment of products and processes, and has to consider all the materials and energy fluxes as well as the influences of emissions in the gaseous, liquid, or solid state on the environment.

Given changing pressures, it is necessary to address environmental issues from a product as well as a facility (or manufacturing processes) perspective. The area of LCA, both the concept and the methodology, has a role to play in improving our understanding and in reducing the environmental loading (burdens) associated with products, presses, and activities from design and development through ultimate disposition. While the IECDM approach incorporated with LCA methodology may have to be more well-defined before they become widely and universally accepted processes and methodology, the concept of life-cycle thinking is an alternative way of addressing environmental problems in an industry ecosystem. It gives us a new paradigm to build future efforts for pollution prevention and waste elimination, thus resulting in conservation of resources for the future. However, a complete LCA model that contains all the necessary parameters and relevant data does not exist at present. Most of the known models are restricted to energy and material balances.

Another framework of life-cycle thinking related to environmental issues is Life-Cycle Costing (LCC) and Life-Cycle Cost Assessment (LCCA). In traditional system engineering and cost-effectiveness analysis, the LCC technique is used for the procuring system (e.g., a weapon system), design and development, production and/or construction, usage and maintenance, as well as the phase-out of the system at its end-of-life. However, this LCC approach does not address environmental issues and their associated costs. In considering environmental management of products and materials, it is useful to examine the costs and environmental impacts incurred during each stage of the product life cycle,

including manufacturing, use, and disposal. To the extent that monetary costs can be assigned to external impacts, the "true" life cycle costs can be computed [Cohan *et al.*, 1992]. However, decision-making based on life-cycle costs is not yet possible, as many of the tools and techniques are not fully developed. Even more difficult is taking into account the full environmental costs of a product and its related processes. When one examines all general ECDM efforts and activities, it is surprising that a common feature, is that they all focus on a product during the design and development phase, to address issues associated with the product's life cycle from raw materials acquisition through manufacturing, use, and disposal. Thus, life-cycle thinking or considerations can be viewed as the informing theme, with applications to product stewardship, design for the environment, and other environment-related projects, such as eco-labeling [Fava, 1993]. From this standpoint, one may call LCC associated with environment-related costs and issues as LCCA, parallel to LCA.

Industrial Ecology as Closed-the-Loop Approach. The central idea of the 'closed-the-loop' approach is to use products and materials efficiently, that is, to recycle, reuse, refurbish, remanufacture, and recover. By lengthening the product/material life-cycle in a closed-loop system, any harmful impact of the product on the environment will be reduced.

Closed Loop as a Critical Issue in Industrial Ecology: A Spiral Loop System: As in a biological ecosystem, manufacturing processes in an industrial ecosystem make up a "closed-the-loop" network of interdependent processes that use, circulate, and reuse primary and waste materials [Allenby and Fullerton, 1992]. One of the most important concepts of industrial ecology is that, like the biological system, it rejects the concept of waste.

This concept of "closed-the-loop" becomes one of the critical issues in industrial ecology (the other is the "life-cycle" issue). In this approach, *recycling* of products, components, parts, and materials at their highest possible usage, purity, and utility level is of prime importance. Recycling activities include redesign and demanufacturing. Redesign may be defined as the reconfiguration and/or upgrading of a product, with the goal of extending the product life cycle and/or improving the environmental compatibility of products. Demanufacturing is defined as the functional revitalization of a product, with the goal of reusing some parts, remanufacturing other parts and finally reducing the remains to another form [Vadrevu *et al.*, 1994]. This recycling stage (i.e., integration of redesign, disassembly, remanufacturing, recycling, recovery, and reuse), which essentially is the closed-loop structure, can only occur if materials from products that have reached the end of their useful life reenter the industrial stream and become incorporated into new products. During the recycling stage of a product's life-cycle, recycling activities would be the use of raw materials and resources, the amount of waste produced, and the consequent environmental burdens. Conceptually, a recycling system is developed as an extension of

the utilization period of the product life of durable goods. A recycling system that is associated with different recycling options (activities) based on product/material life extension and that creates an economy according to a spiral-loop system is shown in Figure 2.5. Such a recycling (or replenishing) system is employed to minimize matter use, energy flow, and environmental deterioration without restricting economic growth or social and technical progress [Stahel and Jackson, 1993].

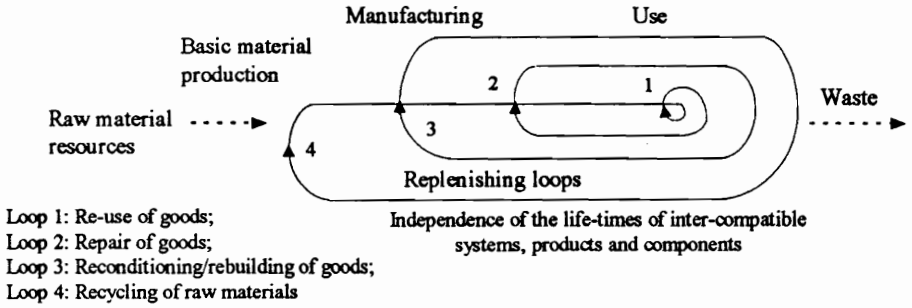


Figure 2.5. A spiral loop system for "4R's" recycling options [from Stahel and Jackson, 1993]

Figure 2.5 illustrates the key elements of this spiral loop system, the "four R's" associated with this system stand for the following:

- *Reuse* of products that are still utilisable but would otherwise be discarded by one party, either by the same party for the same or another purpose, or by another party for a similar purpose. *Reuse* refers to the further use of a waste product in its original form, such as the refilling of a previously discarded container.
- *Repair* of products that are malfunctioning, under-performing, or broken to restore them to full utility.
- *Recondition* (or *Remanufacture*[2]) of products in order to restore them to optimum utility or else update them technologically with new or second-hand components. *Remanufacturing* is the use of a waste, or a waste-derived material, as a raw material for products or fuel that may or may not be similar to the original.
- *Recycle* (or *Recover*) the raw material from durable products as locally available input to the construction of other goods, thereby saving high raw material and transportation costs.

[2] Recondition and remanufacture are different activities in some way. *Reconditioning* restores parts to a functional and/or satisfactory condition by surfacing, painting, etc. *Remanufacturing* restores a product to 'like-new' condition for the same purpose as during its original life-cycle, or reproducing as a 'new' product for secondary purposes, by reusing, reconditioning, reassembling and replacing parts, in which the geometrical form of components/parts is retained.

Recycling of raw materials is the reextraction (or reprocessing) of waste material so that it can be recycled.

In addition, recycling efficiency contained within a general system-oriented efficiency becomes critical in Industrial Ecology. Thus, *design for recycling* (DFR) is one of the most important aspects of industrial ecology. The recycling process must be considered when a process engineer designs a product's manufacturing process. In the context of Design for Environment (DFE), DFE actually contains two major parts: DFR and Design For Disassembly (DFE).

Product/Material Life Extension through Four R's Activities: Generally speaking, from a life-cycle perspective, the 4'Rs in a spiral loop system are part of an environmental economic strategy of durability or optimal resource utilization that has the activity and aims illustrated in Table 2.1, where the aims of different aspects of optimal product/material utilization are shown. In respect to product/material life extension, designing long-life products is likely to require the most economically and environmentally efficient activity among the strategies of optimal product/material utilization (i.e., the 4'Rs strategies). In the practical IECDM approach, extension of the product's utilization life means increasing the total product life-cycle value through the Design for Recyclability (DFR) and Design for Environment (DFE) principles. It is obvious that product-life extension is the motivation of DFR and DFE.

Table 2.1: Product/Material life Extension Activities (options) and Aims

Activity	Aims
1. Long-life products	Design products for long life with a certain quality, using durable materials and replaceable components.
2. Product life extension:	
2.1. Reuse	Extend life of product 'as is' or after cleaning
2.2. Cascading (or away-grading)	Extend product life by lower grade uses (or use among new consumer groups)
2.3. Repair	Extend life to product by preventing and repairing minor decay and damage.
2.4. Reconditioning (Remanufacturing)	Restore product to prime condition by overhaul and component replacement while maintaining optimal utilization.
2.5. Upgrading (or overgrading)	Adapt technology to incorporate latest advances (or meet latest standards); redesign for upgrading product as needed.
3. Component life extension:	Recover and reuse components as well as recycle materials from disposal components

Besides Stahel and Jackson' spiral loop model, Kriwet [1995] distinguished three loops in a product life-cycle, during which recycling activities can take place; they are:

- Recycling of production scrap during manufacturing: utilizing residues (or production scrap) of the manufacturing process, e.g., residues from sheet metal cutting, punching, and injection mounding.

- Recycling during product usage: continued use of a product after an effort at repairing or remanufacturing.
- Recycling after product usage: recycling at the end-of-line stage, the most promising form of recycling for industrial and consumer products.

During these loops, Kriwet further defined different forms of recycling being used, thus:

- *Using* is defined as keeping the shape of the original product for future tasks.
- *Utilization* is defined as making use of the material after dissolving the original shape.
- *Reusing* is defined as keeping the function of the recycled product the same as that of the original product.
- *Using on* is defined as giving the recycled product a different function than that of the original product.

No matter how different the definition of recycling options from various aspects, taking recycling in practice, each company may have its own classification of recycling during its product life-cycle based on different industry categories and product characteristics. However, the critical "closed-the-loop" is always emphasized by companies for their recycling activities. During all these loops, different kinds of recycling are possible, as either shape or function of the original product can be kept or not for future tasks. Based on this idea, Seliger *et al.* [1994] have proposed some examples for the different options shown in Table 2.2.

Table 2.2. Different forms of recycling [Seliger *et al.*, 1994]

Loop	Form of Recycling	Original Product	Recycled Product
Recycling during product usage	Same shape, same function (Reusing)	- Bottle	- Refined bottle
		- TV set	- Repaired TV set
		- Car tire	- Remolded car tire
	Same shape, different function (Using on)	- Milk bottle	- Flower vessel
		- Old tire	- Ship fender
		- Shopping bag	- Waste bag
Recycling after product usage/ Recycling of production scrap	Different shape, same function (Reutilization)	- Glass bottle	- Bottle from recycled glass
		- Aluminum can	- Can from recycled aluminum
		- Sheet metal scrap	- Sheet metal
		- Glass window	- Bottle from recycled glass
		- Aluminum can	- Aluminum window frame
		- Sheet metal scrap	- Wires

Potential Recycling Opportunities in Practical Industry: Based on the 4'Rs concepts mentioned above, a more comprehensive mode is presented in Figure 2.6 which indicates all possible recycling issues in an industrial system. Applying the life-cycle analysis in industrial ecology is the study of the driving factors influencing the flows of selected materials among economic processes. To understand

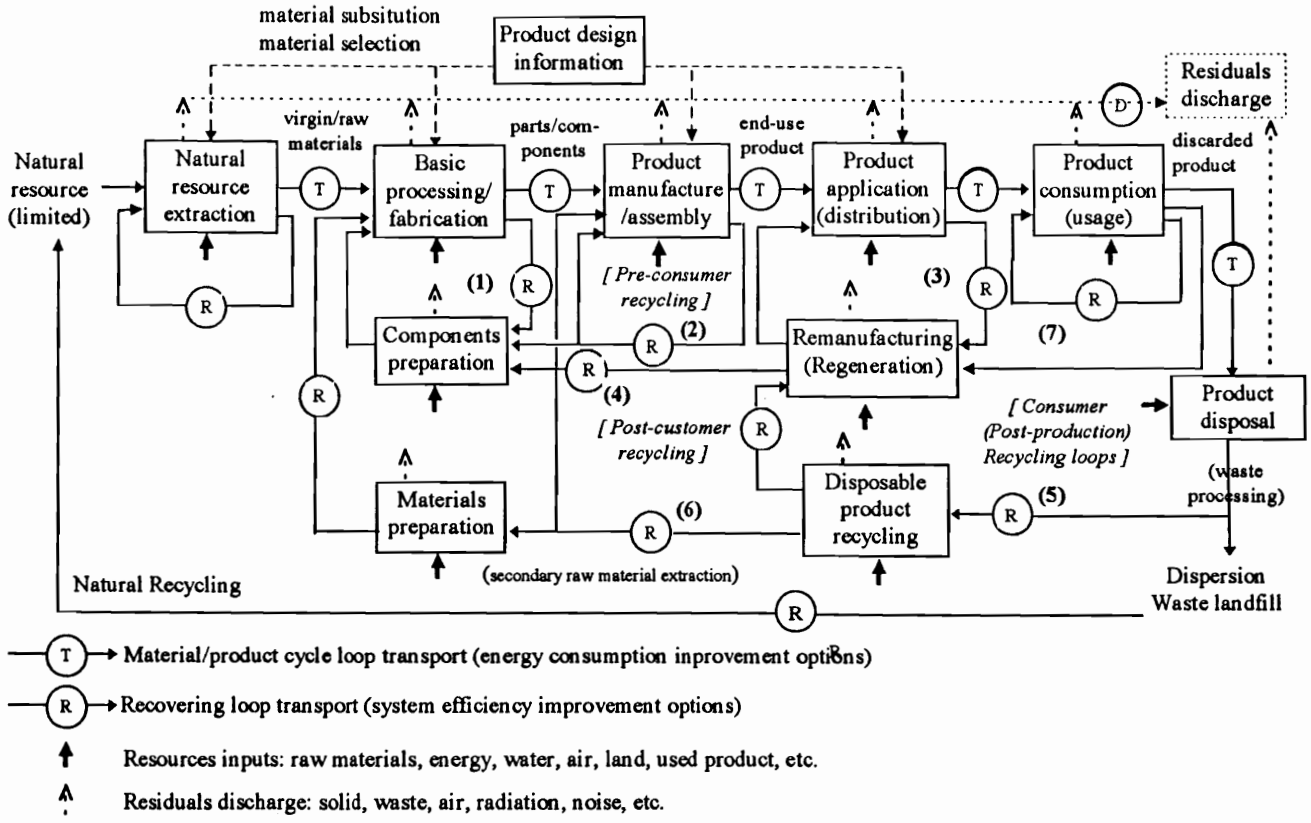


Figure 2.6. The integrated industrial ecology cycle(s): materials life-cycle

better where a material, also a resource, goes once it enters the material flow system or the industrial ecosystem, an integrated industrial ecology cycle(s) for these flows is illustrated in Figure 2.6. In LCA, resources (inputs) and emissions (outputs) are considered in each phase. Emissions impact ecosystem health, human health, social health, resource management, etc.

In Figure 2.6, the model represents the industrial ecosystem, and the environmental economy [Turner *et al.*, 1993], as a materials processing and product transformation system. "Useful" materials are drawn into the industrial ecosystem (economic system) and then undergo a series of changes in their resource states. Eventually (from input to output), the non-product output of the system can be partially recycled, and the residual "useless" materials (wastes) returned to the environment from various points in the industrial (economic) process.

As illustrated in Figure 2.6, the materials that first enter the ecosystem are not destroyed by production and consumption activities; they are, however, dispersed and chemically transformed. In particular, they enter into a state of usefulness and leave in a state of "useless" or "useful" materials. Once the materials balance perspective is adopted, it is easy to see that the way humans manage their ecosystems (economics) impacts on the environment and, in the reverse direction, environmental quality impacts on the efficient working or activities of the ecosystem (economy).

Figure 2.6 is a general "closed-the-loop" model of ecosystems. According to Turner *et al.* [1993], all ecosystems (economic systems) contain a number of recycling flows (recycling opportunities), although the level of recycling effort and activity varies between ecosystems (economics). Recycling flow (1) is known as the 'home scrap' flow because the recycled 'secondary' materials never leave the processing plant. Home-scrap recycling rates are very high. Recycling flow (2), known as 'prompt scrap' flow, also has a high recycling activity rate, but does require the intervention of a secondary material merchant firm (recycling industry) to facilitate the collection of prompt scrap and its redirection back into basic processing. Recycling flow (3), 'retail scrap', is composed of reused and remanufactured materials only when the distribution firm (plant) has such capability itself. Recycling flow (4), 'commercial scrap', is composed of packaging waste and is the staple business of recycling merchant firms (recycling industry). Recycling flows (5) and (6), 'post-consumer scrap', are the potentially recyclable components/parts of the household and small commercial premises waste stream. Finally, recycling flow (7), 'reuse', is a practice that has all but disappeared in modern economics and is now restricted to returnable bottles and a limited number of other examples.

In the context of recycling issues, Turner *et al.* further stated that the policy for implementation of different recycling flow loops is strongly dependent on four product physical factors:

- *mass* (volume of recyclable materials);

- *homogeneity* (the level and consistency in quality terms , known as grade, of the recyclable materials;
- *contamination* (the degree to which different materials and other substances are mixed together); and
- *location* (the number of points at which the materials are first discarded as waste).

Obviously, a manufacturing company would like to implement a recycling policy that is characterized by large mass, high homogeneity, low contamination, and single location, such as recycling flows (1), (2), (3), and (4) which are operated at a high activity rate. In addition, in financial terms, the profitability of recycling flows (1), (2), (3), and (4) will be much higher than recycling flows (5) and (6); indeed the latter will often incur net financial costs. All these recycling activities do not necessarily represent an economically efficient activity. However, it is clear that 100 per cent recycling is not feasible. Therefore, manufacturing companies require some analytical tools or decision-making tools in order to make decisions about their own recycling policies and ECDM strategy.

Hierarchical Priorities for Achieving Recyclability. There is a hierarchical aspect to the basic kinds of product recycling options (PROs) or material recovery options (MROs) and activities, arising from the relative inputs of energy and resources required in order to facilitate them. As discussed above, there are different ways to achieve recyclability. Among them, reuse is the top level of the recycling options; besides re-use, there are a series of scenarios where recyclability can be achieved [Scheidt and Zong, 1994]. For example,

(1) Leasing-oriented products necessitate the re-use of still well-functioning fractions. Some of the apparatus in a rental car after a period of leasing may need to be refurbished by replacing the worn-out outer case with a new one. Then the whole car can be reused. Copiers may require cleaning-up and some functional adjustments before they are sent to customers again for reuse.

(2) Recovered items (e.g., modules and components) can be used. In service centers, critical electronic modules are usually replaced with new ones, but most parts can be replaced by using secondary (used) items of reliable quality.

(3) Recovered items can be used for 'functional upgrading' of the same kind of products. For example, the RAM memory of a PC can be extended by adding an extension board into a bus slot. RAM-chips in discarded PCs can be recovered exactly for this purpose.

(4) Items recycled from higher-level products can be reused in lower-level ones. For example, IC-chips recycled from PCs may be applied in the production of electronic toys.

(5) Differently developed markets make reuse possible too. As illustrated in Figure 2.7, a product can have several lives at first on different levels of market *A* (e.g., regular market). An out-dated

product in market *A* may then live still another life in market *B* (e.g., new market). The used products in markets *A* and *B* may also live in market *C* (e.g., remanufacturing market).

Apart from the scenarios described above, further possibilities of reuse from recycling options are still identifiable.

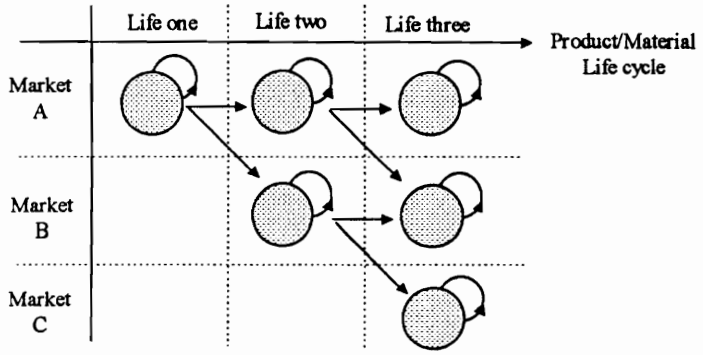


Figure 2.7. Reuse opportunities of different markets

2.2.3. Evolution of Environmentally Conscious Design and Manufacturing

Environmentally Conscious Design and Manufacturing (ECDM) are developed for implementation of objectives of the industrial ecology (for example, green product). It refers to those processes that reduce the harmful environmental impacts caused by manufacturing, for example, minimization of hazardous waste, reduction of energy consumption, improvement of materials utilization efficiency, and enhancement of operational safety [Watkins and Granoff, 1992]. We review the evolution of green design and ECDM history as below.

The basic concepts behind the ECDM approach are not new, but have not attracted enough attention until now. Watkins and Granoff [1992] provide an introduction to the concept of ECDM and address issues such as the need to minimize waste and prevent pollution at its source proactively rather than through "end-of-pipe" treatments. Ashley [1993] and Navin-Chandra [1991a] emphasize the importance of ECDM and "Green Engineering" and point out that it is not only ethically responsible, but also economically sound. A summary study on Green product design has been compiled by the Office of Technology Assessment (OTA) [1992], which focuses on policy and implementation strategies. A book edited by Fiksel [1996b], *Design For Environment: creating eco-efficient products and process*, was published to affirm the legitimacy of DFE as both a management approach and an engineering discipline. Fiksel mentions that effective implementation of DFE requires the development of practical design metrics, guidelines, and verification methods. He also points out that DFE must be deployed within an

integrated system framework in order to provide useful guidance for design decision-making during fast-cycle product development.

Green Evolution and ECDM. In addressing environmental objectives, industry has historically focused on end-of-pipe control (i.e., pollution control via the addition of treatment equipment to waste streams at the end of the production process) rather than on prevention. Consequently, the environmental laws and regulations have enforced the industry to move from end-of-pipe pollution control into "pollution prevention" and "green product design" [Lounsburg, 1994]. Pollution prevention is generally defined as the anticipation and elimination or reduction of industrial waste and emissions through product or process modification. On the other hand, green product design, which is our focus, is a more expanded view of pollution prevention that not only aims at preventing pollution but further pursues product without pollution. Recently, a growing number of companies are finding the "green" products that reduce the environmental burden during use and disposal have additional marketing appeal to consumers.

The key elements of green design are simple to comprehend but challenging to implement, and consequently are the fundamental challenge to engineers and industrial ecologists of the future. With respect to the objectives of green product design, Office of Technology Assessment (OTA) focuses on four objectives of green product design in its report [OTA, 1991] as follows:

(1) *Design For Pollution Prevention.* Examples include reducing the use of toxic materials, increasing energy efficiency (i.e., design for energy efficiency), using less material to perform the same function, or designing products so that they have a longer useful life (i.e., product-life extension).

(2) *Design For Better Materials Management.* Examples include making products and components that can be remanufactured, recycled, composted, or safely incinerated with energy recovery.

(3) *Design for Remanufacturing, Disassembling, and Recycling.* Recycling can reduce virgin (raw) material extraction rates, wastes generated from raw material separation and processing, and energy use associated with manufacturing. It can also divert residual material from municipal waste, relieving pressure on overburdened landfills.

(4) *Design for Composting and Incineration.* Designers can facilitate composting by making products entirely out of biodegradable materials. For example, starch-based polymers (which are inherently biodegradable) and easily composted and films can substitute for plastic in a variety of applications.

Each of these green objectives represents an engineering challenge. Designing products that meet all four elevates the challenge even more. In the context of green design, design trade-offs therefore becomes a major challenge. Trade-offs analysis may be required, not only between traditional design objectives and

environmental objectives, but even among environmental objectives themselves. The perspective of the life-cycle based system approach (section 2.2.2) helps explain the scope of green product design. In the following sections, our literature review will be based on life-cycle system approach that help knowledge and information acquisition in practical green product design and development.

History of ECDM. Traditionally, products have been designed to satisfy only functional requirements and specifications. *System engineering* provides a systematic process of designing a product. The *life-cycle engineering* approach to product development (PD), goes beyond the life cycle of the product itself in Fabrycky [1987]. Consequently, *concurrent engineering* has been applied in simultaneously designing a product and its production processes that not only satisfy functional specification, but are also easy to manufacture, assemble, and maintain. The concurrent engineering is defined by Winner [1988] as:

> "*Concurrent engineering is a systematic approach to the integrated concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset to consider all elements of the product life-cycle, from conception through disposal, including quality, cost, scheduling and user requirements.*"

Moreover, simultaneous or concurrent engineering is the way of expressing the activity of parallel and simultaneous design of the product and its manufacturing process [Clausing, 1989]:

> "*In the ideal form of concurrent engineering, the detailed design of the product is performed concurrently with the development of production capability, field support capability and quality. Quality is developed concurrently with the product design and the development of production and field support capability.*"

In the concurrent engineering paradigm, all issues that are important in the product development are considered simultaneously in the design phase. The typical issues include things such as manufacturability, assembility, maintainability, serviceability, and safety. In a true concurrent engineering approach, requirements address not only product performance but also manufacturing service and other downstream issues including environmental quality [Evanczuk, 1990]. Several works related to the concurrent engineering paradigm can be seen in papers by Kusiak [1993]; Gu and Kusiak [1993]; and Parsaei and Sullivan [1993]. In the context of environmental issues, it is natural to factor life-cycle impacts into concurrent engineering. Thus, the objective of concurrent engineering is the simultaneous consideration of the life-cycle impacts during preliminary system design, along with the immediate considerations of functionality.

Recently, interest has been focused on extending this idea to include environmental considerations or environmental effects. A new area of product design and manufacturing process has

come into being, called *Green Engineering* or *Environmentally Conscious Design and Manufacturing* (ECDM). It becomes important for the designer to be able to consider the environmental effects of a product during the design phase. Within the industrial ecology system, life-cycle based system design and engineering focuses on product design, fabrication/manufacturing, assembly/disassembly, demanufacturing[3], recycling, recovery, and reuse. ECDM is not directly related to the known environmental engineering or pollution prevention engineering. However, ECDM is critical for pollution prevention, waste elimination and reduction of energy consumption. Therefore, an integrative approach which addresses these three elements during the whole product life-cycle is certainly desired. The term ECDM represents in simultaneously engineering with emphasis on its environmental aspects, such as design-for environment (DFE), ecofactory construction, and product-system demanufacturing for recyclization (that is, reuse, recycle, recovery, and remanufacture). In other words, the ecological aspects are the ones that must be planned and considered in advance in order to develop an environmentally friendly system.

For comparing the application of DFE in ECDM engineering to the traditional Environmental Engineering (EE) or Chemical Engineering (ChE), the following statement by Matysiak [1993] can be adapted:

> "... *design-for-environment mentality will encourage a pollution-prevention approach to addressing environmental problems instead of the traditional reliance on end-of-pipe solution.*"

Basically, the notion of green engineering design is based on the idea that products which incorporate environmental concerns will play a role in avoiding environmental problems before they occur, thereby taking a proactive approach to environmental problems rather than a reactive approach, which tries to fix problems only after they occur; see Navin-Chandra [1993]. Green engineering design is aimed at the development of products that are both environmentally compatible and commercially viable. In other words, green engineering is an approach to product and process design that achieves environmental friendliness without compromising a product's quality or its commercial viability. Increased industry awareness of system life-cycle impacts on the environment may bring about a more efficient use of resources and a reduced volume of waste by DFE techniques or ECDM process or Life-Cycle Design (LCD) methodology.

Towards this end, there are several product design concepts which must be implemented. From a product and process design standpoint, DFE is a method by which environmental considerations and

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[3] Demanufacturing is the reduction of a product to its individual parts with the goal of recycling usable parts, remanufacturing certain parts and reducing the remains to another form. The disassembly processes are of particular concern in the design for demanufacturing. Demanufacturing of a product requires controlled disassembly. Disassembly processes are to recover reusable parts for future products. The main demanufacturing costs come from the disassembly activities.

constraints can be integrated into existing process and product design practices. It involves considering the environmental impact of all materials and processes that are involved in the entire life-cycle of a product. A company that implements DFE methods may emphasize the minimization of waste, energy, materials, and hazardous substances in its products and its manufacturing processes.

What is ECDM ? Environmentally Conscious Design and Manufacturing (ECDM) practices are developed for implementation of the objectives of industrial ecology (for example, the green product). The industry is showing increasing interest in the area of environmental or ecological product development. However, in our survey, so far, there is yet no common understanding of what ECDM really means. From the position papers and references, a sample of related descriptions are adapted as follows:

"*Environmentally conscious manufacturing (ECM) focuses on design, manufacturing, assembly/ disassembly, recycling, and reuse.*"

"*Environmental issues should be addressed in all design courses. In the concurrent engineering environment, every engineer should be able to assess the environmental impact of a decision as a design moves through the design/make process.*"

"*Alternative processes or more controlled, closely monitored processes may increase efficiency, reduce waste, and produce better products. Environmental impact must be added to the economic formulas.*"

"*ECM might automatically flag a certain design feature, telling the designer what the environmental implications are and suggesting a better alternative.*"

"*Green design (or environmentally conscious design, ECD) concerns two general goals: waste prevention and better resources management. By comprehensively accounting for resource and waste input and output, the LCA (life cycle assessment) technique can keep track of impacts that are typically shifted from one stage of the product's life cycle to another.*"

"*ECM refers to those processes that reduce the harmful environmental impacts of manufacturing, including minimization of hazardous waste, reduction of energy consumption, improvement of materials utilization efficiency, and enhancement of operational safety.*"

"*Environmentally Conscious Manufacturing involves developing and implementing manufacturing processes that minimize or eliminate hazardous chemical waste, reduce scrap, or are operationally safer. The benefits include safer and cleaner factories [green manufacturing], reduced costs for disposal and worker protection, reduced environmental and health risks, improved product quality at lower cost, and higher productivity.*"

"*Protecting the environment by reducing waste at the source is the goal of ECM...The new ECM paradigm must encompass cradle-to-grave technologies that achieve a balance between economics and the production of our environment...total system integration is essential for the cost-effective implementation of environmentally conscious manufacturing.*"

"*Approaches [to ECM] include substituting non-hazardous for hazardous materials, refining operating procedures, replacing existing processes and developing new, waste-free processes, finding innovative ways to redesign products, and increasing recycling opportunities.*"

"*...an integrated system [environmental information systems] is needed which provides engineers with information on the full impact of their decisions, during the manufacturing process.*"

"*ECDM refers to those processes that reduce the harmful environmental impacts caused by manufacturing, for example, minimization of hazardous waste, reduction of energy consumption, improvement of materials utilization efficiency, and enhancement of operational safety* [Watkins and Granoff, 1992]."

"*A Environmentally Conscious Design and Manufacturing (ECDM) strategy is described in which used products are demanufactured for potential reuse or remanufacture. A critical factor for the success of such a strategy is that significant value still resides in a product at the end of its life* [Vadrevu *et al.*, 1994]."

"*ECM is the transformation of materials into useful products through a value-added process that simultaneously enhances economic well-being and sustains environmental quality* [Darnall *et al.*, 1994]."

"*Concurrent engineering represents one of the most attractive opportunities to environmental design as the infusion of environmental knowledge of downstream activities into the design process will be the only way in which designers can generate 'green' product solutions rapidly and correctly* [Holloway *et al.*, 1994]."

The ECDM, above all, contains two parts: environmentally-conscious *design* (ecodesign) and environmentally-conscious *manufacturing* (eco-manufacturing). They become one in the term ECDM since product design and manufacturing issues are often considered simultaneously. This section describes the ECDM concept and how it is incorporated and employed in the ecodesign process. Articles that describe concepts of industrial ecology and the ecosystem, which defines the domain of ECDM problems and the LCA process, are also mentioned. This literature review shows, we believe, that the ECDM process is the next logical step to incorporating environmental issues and 'green technology' into the concurrent design process. However, as mentioned earlier, no standard or unified definition of ECDM

has been found in these articles and books, and no effective methodology has been proposed to implement the ECDM process.

Applications of Life-Cycle Analysis in ECDM. In association with the product/materials life-cycle, at least four analyses should be performed: material selection analysis, manufacturing process analysis, consumer use analysis, and product recycle analysis. In product design, *materials selection analysis* is concerned with the selection of materials to satisfy criteria of cost, performance, quality, time, and environment.

The design team should consider selecting both virgin and recyclable materials to meet criteria and to minimize hazardous wastes generated over the life-cycle. Materials selection must also consider the importance of compatibility. *Manufacturing process analysis* is concerned with the reduction of energy consumption and the minimization of wastes within different processes. Implementation of the ecomanufacturing process, one of the purposes of process analysis, can be conducted by screening the inputs and outputs of the manufacturing technologies available. *Consumer utilization analysis* may also be considered within the design and manufacturing environment. Deleterious environmental impacts that occur during product use should be considered by the design team in the early design stage. *Product recycle analysis* (or material recovery analysis) in the disposal phase is also a suitable consideration at the design and manufacturing stage. All potential opportunities for recycling (including internal recycling during the manufacturing process) should be considered. Possible considerations are design for recycling, remanufacturing, reuse and recovery of products, subassemblies, and components/parts. Within the IECDM methodology, all these efforts (analysis of material selection, manufacturing process, utilization, and product recycling) should be considered simultaneously in the early stage of product development cycle.

A General Scope and Features of Problems in the ECDM Domain. With regard to environmental improvement techniques, the Life Cycle Center at the Technical University of Denmark has worked on developing the methods/tools to assess environmental and occupational health and the resource consequences of the life cycles [Alting and Jørgensen, 1993]. The Life Cycle Center, as expected, is a multidisciplinary research and technology development institute, with three main technology areas of focus:

- Life-Cycle Strategies, Ecology and Control, including:
  - Total cost assessment of products in all life-cycle phases.
  - Control and monitoring systems and information systems to cope with life-cycle needs.
  - New business concepts and activities related to sustainable industrial production.

- Process and Production Engineering, with a focus on:
  - Guidelines for environmental and resource-oriented design of products, covering all life-cycle phases (production, distribution, usage/service, and disposal/recycling, primarily for mechanical, electromechanical, electronic and plastic products).
  - Eco-manufacturing system design, implementation of eco-factory (inverse factory), and automatic disassembly for demanufacturing and recycling.
- Environmental and Resource Technologies, including:
  - Life-cycle assessment and evaluation methods and tools for industrial products.
  - Cleaner techniques to reduce/minimize environmental problems of specific processes.
  - Environmental legislation and data as a general basis for development work and consultancy.

Industrial ecology can best be defined as the totality or the pattern of relationships between various industrial activities, their products, and the environment. ECDM may be viewed more as a techniques implementation consideration. The objective of developing ECDM technique is to achieve the goal of IE, that is,

- to maximize the use of resources and at the same time minimize negative impact on the environment,
- optimize the utilization of the resource,
- minimize waste generation during product realization and manufacturing processes,
- maximize reuse of waste resulting from manufacturing,
- maximize the ultimate recycling of the product,
- minimize consumption of energy throughout the process, etc.

This can be converted into six elements of industrial ecology that lead to the cradle-to-reincarnation production philosophy:

- use of materials that have the desired properties and are less harmful to the environment during their extraction or formulation stages;
- use of a just-in-time materials philosophy that would obviate the necessity of storage of hazardous or nonhazardous feed-stock materials;
- process substitution that eliminates toxic feed stock;
- process modification to contain, remove, and treat toxic materials in the waste stream by closed-loop recycling;
- engineering controls and systems approach to assume robust and reliable processes;
- end-of-life recyclability consideration.

Other production philosophies, of course, may add to this list elements from different production/operations perspectives. In the literature review, the ECDM are often discussed conceptually and in pieces. The lack of formal definitions and integration aspects of ECDM has motivated us to develop an IECDM methodology from an integration perspective.

2.3. STATE-OF-THE-ART TECHNIQUES APPLIED TO IMPLEMENT ECDM

Life-Cycle Design-related issues and approaches can be found in the critical review by Keoleian and Menerey [1994], which is titled "Sustainable development by design?" In this review the authors provide a comprehensive overview of Life-Cycle Design-related issues. Life-Cycle Design (LCD), Design for the Environment (DFE), Green design, and related initiatives based on product life-cycle are emerging as systematic approaches for integrating environmental issues into design. In order to effectively promote the goals of sustainable development, LCD must successfully address cost, performance, and cultural and legal factors. The integration approaches are merged in green product development. Unfortunately, a methodology or guideline is lacking to show how integration is achieved. In the literature review, we provide various perspectives on green design-related issues, and then propose our integration aspect for green product development.

In the literature review that follows, we will review the major issues that provide the context for design-based approaches that may be applied to environmentally sound product development. We have chosen to use the life-cycle framework as a template for a structured literature review. The main areas categorized in an attempt to emphasize the life cycle aspects of product design and development are:

[A] Life Cycle Assessment (LCA)

[B] Engineering System Design Theory/Methodology and Process (ESD)

[C] Design For "X" and Concurrent Engineering (DFX/CE)

[D] Design For the Environment (DFE)

[E] Quantitative Measurement (QM)

[F] Environmental Economics, Life-Cycle Costing, and Life-Cycle Cost Assessment (LCCA)

[G] Quality Function Deployment (QFD)

[H] Multiple Criteria Decision-Making (MCDM)

[I] Ecomanufacturing and Eco-factory with automatic disassembly

[J] Nontraditional Manufacturing Process (NTM).

A review of topics in categories [B] [C], and [G] can be seen in other articles, for example, the brief survey in Sullivan *et al.* [1994] and information on the Internet [QFD home page]; here, only that literature that considers environmental issues and is used as a reference in this research are listed. This

literature review serves to identify relevant articles and books that are major references for our research in the development of the IECDM methodology. Now, we introduce these techniques followed by their applications in the ECDM domain.

2.3.1. Life-Cycle Assessment

Life-Cycle (Environmental) Assessment (LCA) is one environmentally-conscious product development approaches; others include 'closing material cycle' approach, the energy indicator's approach, the pollution approach, the environmental economic approach, the environmental regulation approach, and the conceptual approach. All these approaches are used for green product development in the industrial ecosystem. This literature review will focus on the Life-Cycle Environmental Assessment approaches, or simply Life-Cycle Assessment (LCA).

What is Life-Cycle Assessment ? The Life-cycle analysis approach is useful in considering environmental issues in product design. Whereas Life Cycle Engineering (LCE) is the art of designing the product life-cycle through choices about product concept, structure, materials and processes, LCA is the tool that visualizes the environmental and resource consequences of these choices through product development [Alting and Legarth, 1995]. The ability of LCA, more precisely, Life-Cycle Environmental Analysis, to measure the environmental impact of a product throughout its life-cycle makes LCA a unique holistic tool for assessing the environmental and resource consequences of decisions made in product design [Wenzel *et al.*, 1994]. According to the Society of Environmental Toxicology and Chemistry (SETAC), LCA is defined as:

> "*the Life-Cycle Assessment is an objective process to evaluate the environmental loads associated with a product, process or activity by identifying and quantifying energy and materials used and wastes related to the environment, to assess the impact of those energy and materials uses and releases to the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials, manufacturing, transportation and distribution, use, re-use, maintenance, recycling and final disposal* [SETAC, 1993]".

In ISO 14000 , LCA is defined as:

> "*LCA is a systematic tool of assessing the environmental impacts associated with a product or service system to: build an inventory of impacts and outputs; make a qualitative and quantitative evaluation of those inputs and outputs; identify the most significant aspects of the system relative*

> *to the objective of the study. LCA considers the environmental impacts along the continuum of a product's life (i.e., cradle to grave) from raw materials acquisition to production, use and disposal. The general categories of environmental impacts to consider include resource depletion, human health, and ecological consequences. LCA is a tool to collect and interpret information for a variety of purposes. This information can be of assistance to those involved in: decision making, selection relevant environmental indicators for performance evaluation, marketing (claims or eco-label scheme).*"

More precisely,

> "*The basic objective of LCA is to guide decision makers, whether consumers, industrialists, or government policy makers, in deriving or selecting actions that will serve to minimize the environmental impacts while furthering other objectives.*"

In industrial practice, LCAs may only be used as inventory analysis. For example, the 3M company defined its life-cycle approach as looking at how waste can be reduced or eliminated, starting with the point of generation in the manufacturing operation, to its processing, treatment or ultimate disposal as a residual hazards waste. Procter & Gamble defines LCA as an *attribute* that displays an acceptance by manufacturers of consumer products of their share of responsibility for the environmental burden caused by their products from design to disposal. Procter & Gamble uses the LCA as a quantitative tool that ensures that real, rather than superficial, environmental improvements are identified. The fact is that a completed LCA process should include: goal definition, inventory analysis, impact assessment, and improvement analysis.

Industrial System and System Boundary for LCA Analysis. LCA is carried out within the well-defined system boundary. It is primarily concerned with the impact of industrial operations (activities) on the environment. It becomes a tool to predict the overall environmental impact of a product or service. Essentially there are two groups of potential problems: conservation of resources and minimizing environmental damage. These problems are formally converted to the problems on conservation of materials and energy as well as elimination of solid waste in practice. More recently, air and water pollution have been included in these problems. Before solutions to these problems can be found, information is needed about the scale of the problems in the industrial ecosystem, if indeed there are any, and the system boundary must be well defined. The analysis of any system and its boundary is therefore the first step to understanding these problems.

Figure 2.8 shows a schematic diagram of a simple industrial system (industrial chain in ecosystem). The boundary enclosed the system and the region surrounding the system is called the system environment. LCA is also a decision support tool that places "system boundaries" around the whole life

cycle of the materials and energy flows. It then balances the upstream inputs of energy and materials with the downstream emissions and residues of a product as well as the environmental effects directly associated with its manufacturer [Blua, 1995].

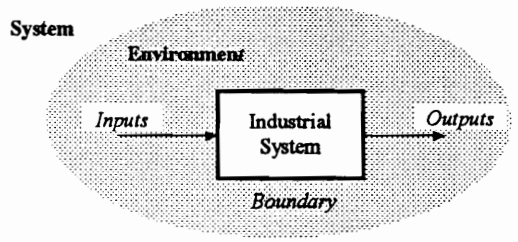


Figure 2.8. A simple industrial system

Figure 2.9 shows the type of overall system that is analyzed with the inputs and outputs broken down under the major headings of interest. The measurement or calculation of the inputs and outputs determines the impact of the system on its environment. Ideally, when all inputs are derived from raw materials in the earth and all outputs are returned to the earth, including the useful products at the end of their useful lives, the results of such calculations are frequently referred to as *ecobalances*, and the design of system for achieving ecobalances is referred to as *ecodesign*.

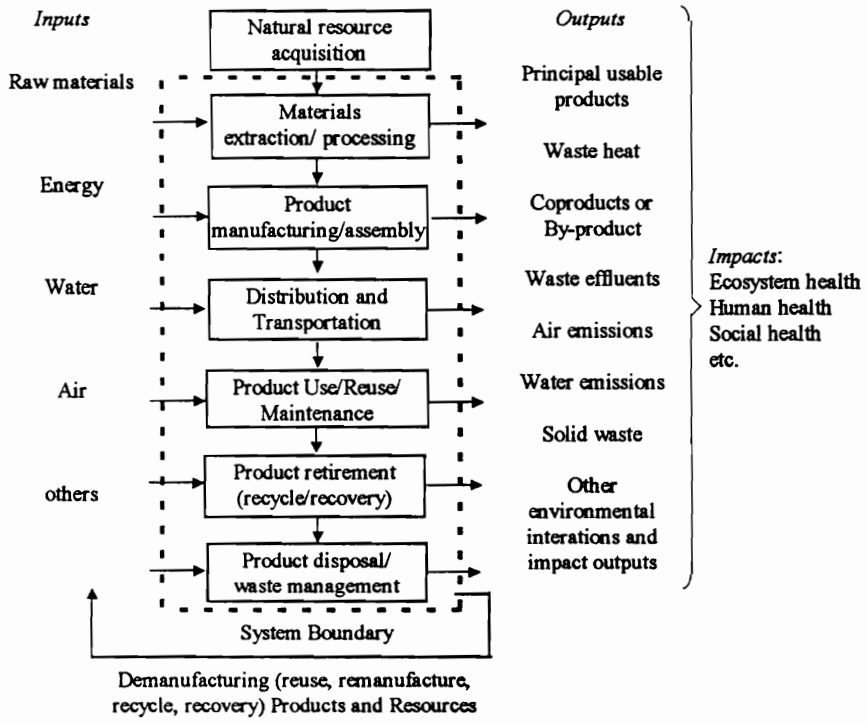


Figure 2.9. System boundary for whole LCA of a general product

As mentioned above, environmental problems to date are treated within three major areas: *environmental production*, *resource management*, and *eco-development*. A well-defined system boundary is essential to achieve successful eco-development of a new product and its manufacturing processes. Similar assessments have been conducted for some time under a range of different titles, including Ecobalances, Ecoprofiles, Resource and Environmental Profile Analysis (REPA), and Produktlinienanalyse (PLA), refer to White, P.R. *et al.* [1995]

Operationally, as shown in Figure 2.9, the LCA technique examines every stage of the life-cycle, from the acquisition of raw materials through manufacture, distribution, use, possible reuse/recycling and then final disposal. For each stage, the inputs (in terms of raw materials, energy, etc.) and outputs (in terms of emissions to air, waste as solid waste, etc.) are calculated, and these are aggregated over the life-cycle of the product. These inputs and outputs are then converted into their effects on the environment, i.e., their environmental impacts (or environmental loads). The sum (cumulating) of these environmental impacts then represents the overall environmental effect of the life cycle of the product, i.e., the environmental impacts profile. Conducting LCA as one of the measures for alternative designs (or products) thus allows comparison of their overall environmental impacts profiles and other factors such as cost, performance, quality, etc. This assessment will allow the tradeoffs associated with each option to be measured or assessed for each alternative, and between alternatives.

The Scope of the LCA. LCA, which is based on a material-specific flow approach, generally consists of four complementary components [Sullivan and Young, 1995]: (1) goal definition and scoping, (2) inventory analysis, the identification of energy and resource uses and environmental releases to air, water, and land; (3) impact analysis, the technical qualitative and quantitative characterization and assessment of the consequences on the environment; and (4) improvement analysis, the evaluation and implementation of opportunities to reduce negative environmental impacts, as illustrated in Figure 2.10. All aspects of the system's life cycle are considered in these four components including raw-material extraction, product manufacture, use, recycling, and disposal. Some life-cycle terminology adopted from White, P.R. *et al.* [1995] are listed in Table 2 3.

How does the LCA Operate ? MacAlasdair [1993] proposed eight steps that are typically involved in carrying out LCA of the environmental impacts of products and services. They are: (1) product/service life-cycle model formulation, (2) materials consumption determination, (3) basic process data accumulation, (4) energy and water consumption, (5) identifying, qualifying and quantifying environmental burdens (loading), (6) assessing the relative significance of the impacts of the environmental burdens identified, (7) developing potential improvements, and (8) reporting results. An

application of these steps to packaging products was given as an example by MacAlasdair [1993]. A more detailed LCA process is described by Keoleian *et al.* [1994] and Graedel and Allenby [1995]. A Critical review of life-cycle analysis and assessment techniques and their application to commercial activities can be found in the work of Young and Vanderburg [1994]; Vigon [1995]; and Lee, O'Callaghan, and Allen [Lee *et al.*, 1995]. Nevertheless, the basic steps presented are often placed in a decision-making framework that explains the main phases of the approach. According to the Society of Toxicology and Chemistry (SETAC), four components of the LCA framework have been defined and developed in the four main steps of LCA. These steps will be discussed below [Bloemhof-Ruwaard, *et al.*, 1995].

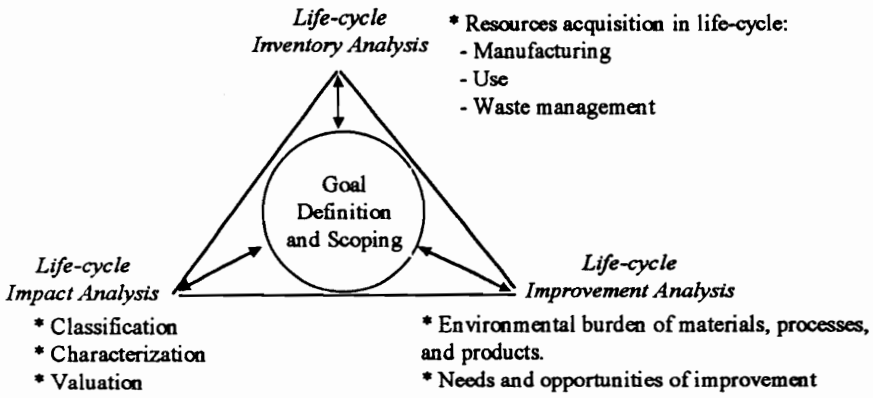


Figure 2.10. Scope of the LCA

Step 1: Goal Definition and Scoping: This first step defines the aim, the options to be compared, system boundaries, the target audience, the functional unit, the data requirements, and intended use of results. This step consists of three major decisions.

- To state the *goal* of study, for example, to obtain environmental information about existing products, to analyze strategies for product improvement or to compare products, either existing or new introduced products.
- To state the intended *depth* of the study and determine the system boundary being considered. To determine the possible and particular environmental effects to be investigated, and to decide the particular processes to be taken into account within the system boundaries.
- To establish the *functional unit* for the LCA. This unit is defined as a measure of performance which the system delivers. An example is the packaging used to deliver a given volume of beverage.

Table 2.3: Life-cycle assessment terminology [White, P.R. *et al.*, 1995]

Life-cycle assessment	A process to predict the overall environmental impact of a product or service, over the whole life-cycle 'from cradle to grave', i.e. from raw material mining to final disposal; currently considered to consist of 4 stages: goal definition; inventory; impact analysis; valuation:
Goal definition	Stage at which the functional unit for comparison is defined (normally per equivalent use), as well as the purpose, boundaries and scope of the assessment
Inventory	Process of accounting for all the inputs and outputs in the life-cycle; will result in a list of raw material and energy inputs, and of individual emissions to air, water and as solid waste
Impact analysis	Sometimes called 'classification'; conversion of the inventory of materials and energy into their actual environmental effects, e.g., ozone depletion; includes aggregation within such categories of environmental effect
Valuation	Evaluation of the overall environmental impact of the life-cycle by attempting to compare or aggregate the different categories of environmental concern resulting from the impact analysis; this stage is the least well accepted or defined, and involves subjective value judgments and determination of potential improvement
Life-cycle analysis	Sometimes used synonymously with life-cycle assessment; however, early life-cycle analysis involved only the first two of the presently recognized stages, goal definition and inventory, so current usage usually relates to these stages only
Cradle-to-grave analysis	Essentially any analysis that encompasses the whole life-cycle, but may not include impact analysis; life used nowadays
Life-cycle inventory	
Resource and environmental profile analysis (REPA)	Terms used by different practitioners for the first two stages of a life-cycle assessment, i.e. goal definition and inventory; they produce an inventory of materials and energy inputs and outputs
Ecobalance/Environmental balance	Terms used in two different ways; either equivalent to a life-cycle inventory (goal definition plus inventory stages) or to a life-cycle inventory with some subsequent attempt at impact analysis/valuation
Ecoprofile/Environmental profile	Equivalent to a life-cycle assessment, although usually combine impact analysis and valuation in one single phase with an expert making the value judgment
Product line analysis (PLA)	A broader assessment procedure, incorporating social and economic assessments as well as an environmental life-cycle assessment

Step 2: Life-Cycle Inventory Analysis (Data Acquisition and Aggregation): The inventory analysis estimates the environmental loads (or burden) associated with the entire life-cycle of a product, or processes, or activities. The various inputs and outputs, as illustrated in Figure 2.11, are quantified for each phases of the system life-cycle. LCI is an objective data-based process of quantifying energy and raw material requirements, air emissions, water-borne effluents, solid waste, and other environmental releases incurred throughout the life cycle of a product, process or activity. LCI should account for all materials and energy, inputs, and outputs throughout the whole life cycle of product or service.

Operationally, the product system is subdivided into individual process stages, connected by material (or products) flows either in open loop or closed loop process. A single stage flow diagram is

shown in Figure 2.11, where *i* represents life-cycle stages of product such as material acquisition stage, materials processing stage, production/assembly stage, product distribution and utilization stage, disposal stage, and recycle stage. Outflow from one process step will serve as inflow for the next one. By this way, the product system (e.g., manufacturing system) can be described as a process tree.

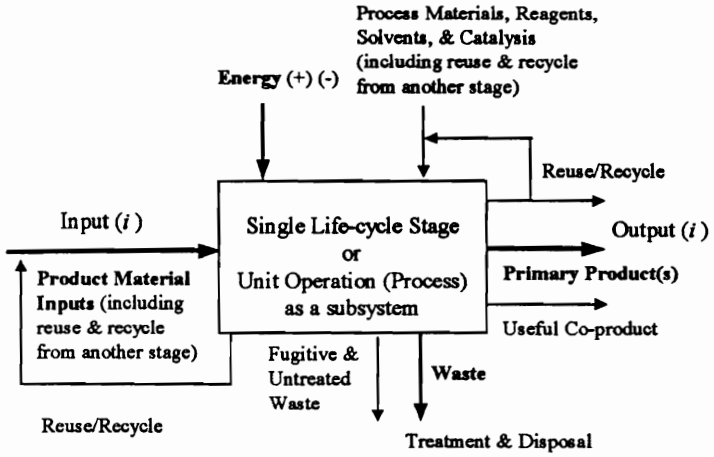


Figure 2.11 Single stage flow diagram for LCA [From: EPA, 1993a]

In the process flow diagram, flows extracted directly from or going directly to the environment are called *environmental interventions* (or *environmental loads* or *burdens*), for example, energy consumption and emissions to air and water. If a process step generates several useful products, the environmental interventions have to be allocated, which is usually based on mass relations of products in that process. The outcome (result) of this step is an *inventory table*, a detailed list with all environmental interventions belonging to the functional unit defined in the goal definition. If the functional unit can be transferred to monetary units, then the environmental costs for each individual process can be estimated.

In practical inventory analysis, the analysis can be employed hierarchically depending on the definition of system boundaries and product structure. The hierarchy of inventory analysis is as follows:

- Product-based inventory analysis focuses on entire product.
- Component-based inventory analysis focuses on particular component.
- Material-based inventory analysis focuses on particular material of a component or product.
- Resource-based inventory analysis focuses on particular resource required for the production of a material, component or product.

Step 3: Life-Cycle Impact Analysis (Classification and prioritizing options): The purpose of impact analysis is to evaluate impacts and risks associated with the materials and energy transfers. The impact assessment (or namely classification) characterizes the effects to human health and to the environment of the environmental interventions (loads) identified in the inventory analysis step. Data from the inventory table are grouped together according to their contribution to a number of environmental impacts. This is a process that converts the LCI into environmental effects (impacts), by which the environmental interventions identified in the inventory component of an LCA (i.e., LCI) are quantitatively or qualitatively characterized as to their effects on local and global environment. Impact analysis is achieved by methodology or impact analysis models which may or may not include hazard and risk analysis models. The conceptual framework for life-cycle impact analysis generally includes three steps: classification, characterization, and valuation.

Classification is used to aggregate the LCI according to effects being developed and classified, i.e., classification factors. It is the assignment of inventory items to impact categories based upon an elaboration of impact networks, which are the potential cause-and-effect linkages between interventions and ultimate impacts on human health, the ecosystem, and resources. Generally, such classification should address both ecological and human health considerations, as well as other effects such as habitual, modification and noise pollution. An example of classification of life-cycle impacts is shown in Table 2.4. Impact analysis evaluates impacts caused by design activities. Classification factors are then used to convert environmental interventions into contributions to environmental impacts, the so-called *effect scores*. The result of the impact analysis through classification is an *environmental profile*, a list with the quantitative contribution of the functional unit to the relevant environmental impacts.

Characterization is the process of aggregating and quantifying impacts within the impact categories, which involves an understanding of the environmental processes that lead from the interventions (inventory items) to the ultimate impacts of concerns. In life-cycle approach practice, the result of environmental profile is expressed as the sum or accumulation cumulating of effect scores of each individual process throughout the system life cycle. The environmental profile (i.e., aggregation of interventions) provides a useful measure index for evaluating and comparing environmental impacts of alternative process(es).

Valuation is the step where the different impact categories are considered in relation to each other in order to further aggregate the results of the impact assessment or to allow for further interpretation of the results. The valuation step is not an objective process, but depends upon social and cultural values and preferences. A valuation (i.e., a completed LCA) can help to: provide useful information to the consumer; identify the need for (or lack thereof) regulatory measures; identify opportunities for product improvements; and design better green products from the start [de Oude, 1993].

Table 2.4. Classification of life-cycle impacts [White, P. *et al.*, 1995, pp. 33]

Heading	Scale of environmental effect
Depletion problems:	
• Non-renewable resources	Global
• Energy carries	
• Others (minerals)	
• Scarce renewable resources	Global/local
• Space consumption	Regional/local
Pollution problems:	
• Global warming	Global
• Ozone depletion	Global
• Human toxicity	Continental/regional
• Ecotoxicity	Continental/regional
• Acidification	Continental/regional
• Photo oxidant formation	Regional
• Nutrification/eutrophication	Regional
• Final solid waste	Regional/local
• Radiation	Regional/local
• Dispersion of heat	Local
• Occupational health	Local
• Noise	Local
• Smell	Local
Disturbances problems:	
• Desiccation	Regional/local
• Landscape degradation	Regional/local
• Ecosystem degradation	Regional/local

Step 4: Life-Cycle Improvement Assessment (Evaluation and continuous improvement): The results of both inventory analysis and impact assessments are valuable in understanding: the relative environmental burdens resulting from evolutionary changes in given processes, products, or packaging over time; the relative environmental burdens between alternative processes or materials used to make, distribute, or use the same product; and the comparison of the environmental aspects among alternative products that serve the same use [Shen, 1995]. Improvement analysis systematically evaluates needs and opportunities to reduce the environmental burden associated with energy and materials use and waste releases throughout the life-cycle of product, process, or other activities.

The improvement analysis lists process or product modifications aimed at reducing the environmental loads and/or their effects, which is achieved through the evaluation process. This consists of two evaluations, using both quantitative and qualitative measures: the evaluation of the environmental profile, and the evaluation of the reliability and validity. The first evaluation assesses the environmental effect scores in the environmental profile. This leads to a multiple criteria decision making problem (MCDM). which can be dealt with quantitatively or qualitatively. Either way, weighing factors have to be

assigned to each of the environmental effects. Combination of weighing factors and effect scores yields an *environmental index*. The second evaluation assesses the consequences of uncertainties in the data (reliability) and the assumptions and choices made (validity). Sensitivity analysis can be a useful tool here for assessing these consequences.

The evaluation process is a process of balancing the important different environmental effects. It presents a process within LCA that leads to identifying chances or opportunities for environmental improvement by systematic evaluation of the need, i.e., using an environmental index. The environmental improvement is an activity of product-focused pollution prevention and resource conservation. The improvement analysis component of the LCA is defined by the Society of Environment Toxicology and Chemistry (SETAC) as follows:

> "*A systematic evaluation of the needs and opportunities to reduce the environmental burden associated with energy and raw materials and environmental releases throughout the whole life cycle of product, process, or activity. This analysis may include both quantitative and qualitative measures of improvements, such as changes in product, process, and activity design, raw material use, industrial processing, consumer use, and waste management.*"

As the matter of fact, it is difficult to define a unified tool to do improvement analysis and measurement. However, the philosophy of Design For the Environment (DFE) provides important guidelines to achieve the *life-cycle improvement* of products and to implement the industrial ecology.

With respect to life-cycle design, such improvement analysis is made through the concepts of DFE and eco-manufacturing. In other words, improvement analysis is often associated with DFE or Total Quality Management (TQM) through the entire life-cycle design engineering process. With these methodologies, environmental improvement proposals are combined with other performance factors and the life-cycle cost analysis in an appropriate design decision-making framework, such as Quality Function Deployment (QFD) framework.

LCA is an important tool for environmental analysis and for system design evaluation associated with environmental factors during the design process. Unfortunately, there is no single accepted method that is universally acceptable yet. It is becoming clear that each LCA conducted needs to be individually assessed since no two situations are ever the same [Lee and Allen, 1995]. In addition, it has been suggested that a comprehensive analysis cannot be carried out unless all aspects of the life cycle have been considered. In the product development or design evaluation viewpoint, the environmental index together with other measure indices such as cost, quality, and performance also leads to a top level Multi-Criteria Decision-Making (MCDM) problem, which is a trade-off process among environmental index, economic, and performance of system products.

The general stages of the LCA process are discussed above. In addition, it should be recognized that the critical issue in the LCA process (especially in LCI stage) is the data acquisition. The industrial ecologist should be willing to approach data needs with a broad perspective. Any methodology, whether applied to the LCA process, can often be most effective if qualitative rather than quantitative. An LCA information system should be non-prescriptive to maximize efficiency and avoid pre-judgment of normative issues [Graedel and Allenby, 1995]. In other words, a LCA information system should provide information that can be used by individual designers and decision makers given the particular constraint and opportunities they face. LCA information should provide not only relevant data, but also, if possible, the degree of uncertainty associated with data. This approach is particularly important in the environmental area, where uncertainty is unpredictable.

Applying LCA to Implement ECDM. Green product development and pollution prevention through LCAs is actually a departure from evaluating environmental (or waste) management options. With respect to the life-cycle design process, LCAs can assist in evaluating proposed changes to product or process designs so that trade-offs can be identified; that is, LCAs can be employed in continuous improvement of product and process design when focusing on reduction of environmental impacts caused by products and processes. In practical applications, Vigon and Curran [1993] proposed to incorporate the LCA concept into product improvement. They suggested that a decision-support method should be used for the aggregation of different types of information (e.g., ecodesign criteria and performance measurements) in determining the 'best' alternative options for implementation. On the trend of LCA, Fava [1993] also pointed out that "while the LCA methodology may have a few more years before it is widely and universally accepted, its concept is here today and may be applied to business and organizations as an alternative way of addressing environmental problems." LCA will move towards consolidation of baseline elements, while the objective is to develop a standard LCA methodology for meticulous analysis of environmental impacts of products and product-related processes. LCA should be considered as a perquisite and standard procedure in ecoproducts development. LCA should be used as a product design tool to assess the environmental impacts of IECDM methodology in industrial ecology.

Applications of LCA. According to Field *et al.* [1993], a wide range of potential users are interested in the application of the LCA technique (Figure 2.12). Consumers see LCA as a way to better inform the customer of the relative environmental impact of alternative products, which bring market pressures to bear upon manufacturers (producers). Regulators and policy makers see LCA as a tool that can guide environmental policy development and can provide a mechanism for enforcement of legislative objectives. Finally, forced by customers' preferences and environmental regulations, product designers

and processes planners should employ LCA as a way to incorporate environmental considerations into their ecodesign process, making it possible to anticipate and avoid potential environmental impacts.

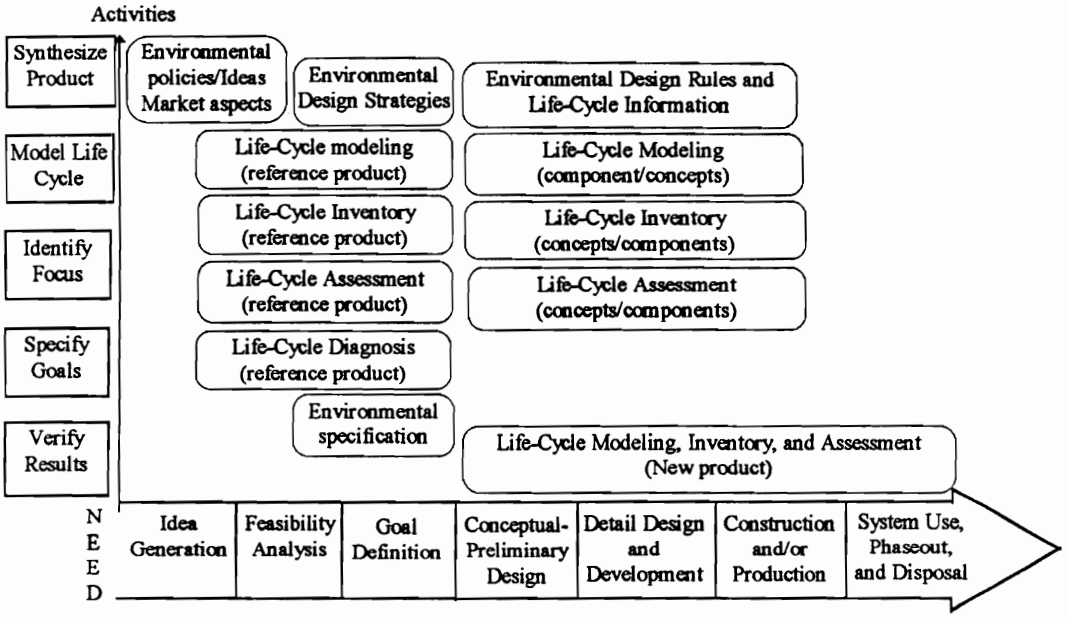


Figure 2.12. A simplified matrix for the use of environmental tools in product development

Industry use of LCA as a tool to improve environmental performance is increasing. Using LCA, designers and engineers can effectively use the approach to identify the consequences of their choices of materials, manufacturing processes, and product usage. Furthermore, LCA is an environmental management tool increasingly used to predict and compare the environmental impacts of a product or service, from cradle to grave. For a recent review, see P. R. White *et al.* [1993]. Many articles and books summarize the basic methodology of life-cycle analysis (assessment) techniques, which are aimed at evaluating environmental damage. However, none of them consider how LCA affects product design decisions.

From the life-cycle aspect, Figure 2.12 shows the key environmental methods (approaches) and tools in a general product development matrix, in which these main product development activities and the typical development phases are shown (refer to Wenzel *et al.* [1994]). LCAs are used throughout the product development procedure. The outputs from an LCA are the environmental profiles which are used in evaluation of product alternatives and product development. The matrix does not indicate a strictly stepwise procedure, but illustrates a principle of iterative development [Alting and Legarth, 1995].

Logistic Support (Distribution) System with LCA Application. Logistical systems have various impacts on the natural environment. For example, environmental impacts could occur during a logistical system's support efforts toward recycling purposes, including the collection and transport of used products, or decomposed components, or disassembled parts, or re-extracted materials. These used components and materials (with related information provided by logistic support) may transfer to the recycling industry or be taken back for the production of future products [Kriwet *et al.*, 1995]. Environmentally conscious supplier management is also considered in the logistical support life-cycle (see Beckman *et al.*, 1995 and Sarkis *et al.*, 1995). The basic concept of environmental logistics management has also been proposed by Ummenhofer [1994]. An ecological assessment (i.e., LCA) of logistical systems is required in the design evaluation process [Hilty *et al.*, 1994].

Limitations of LCA. The trend of LCA-related research is to develop a standard methodology for environmental impacts assessment in green product design. It has also been recognized that quantitative life-cycle assessment is not widely used for design decision-making. According to Shen [1995] there are four factors that restrict the use of quantitative LCA as a decision-making document:

- *Cost limitations* Industry or society can hardly afford it because LCA requires a large amount of data and has to answer endless questions.
- *Data limitations* Much of the critical data on product production is considered proprietary business information. Access to such data is severely restricted, even to government regulators.
- *Lack of common unit* No common unit exists for comparing different types of environmental impacts. Some researchers have gravitated toward monetary units as the common unit for certain studies, but the values assigned to environmental costs and benefits are often wholly subjective. Others use pounds of pollutants or Btu of energy to report impacts. The ecounit is the ultimate goal in LCA research.
- *Inability to quantify important environmental impacts* Even if agreement could be reached on a common unit and differing impacts could be converted to it, the problem of quantifying certain impacts would still exist.

In brief, LCA approaches are cumbersome in the early design stages where design is still evolving and changing dramatically. Hence, the efficiency of the LCA approach is low at the early stage of green design.

2.3.2. Engineering Design Theory/Methodology and Process for Product Development

Knowledge of engineering design theory/methodology and process also generally applies to environmentally conscious product development. A number of articles examine how the existing engineering design theory/methodologies and processes are adapted to the new research area of green product development. These articles describe life-cycle design and life-cycle engineering, the backbone of engineering design and product development.

From the life-cycle aspect, each methodology reviewed in the literature brings benefits to life-cycle engineering design during product development. Figure 2.13 classifies the methodologies in terms of the stage of the product life cycle they focus on (horizontal axis) and the stage of the product design procedure (vertical axis); see Ishii [1995]. Obviously, life-cycle engineering design requires the combination of all the viewpoints in the "*flexible engineering process.*" The figure does not indicate exactly how each tool is used in which phase, but illustrates the scope and principle for using these methodologies and tools. Nevertheless, combining the use of all the tools is not trivial. Currently, in practical design problems, (eco) design techniques are applied earlier in the pre-production stage and consider customer's needs as well as the following examples.

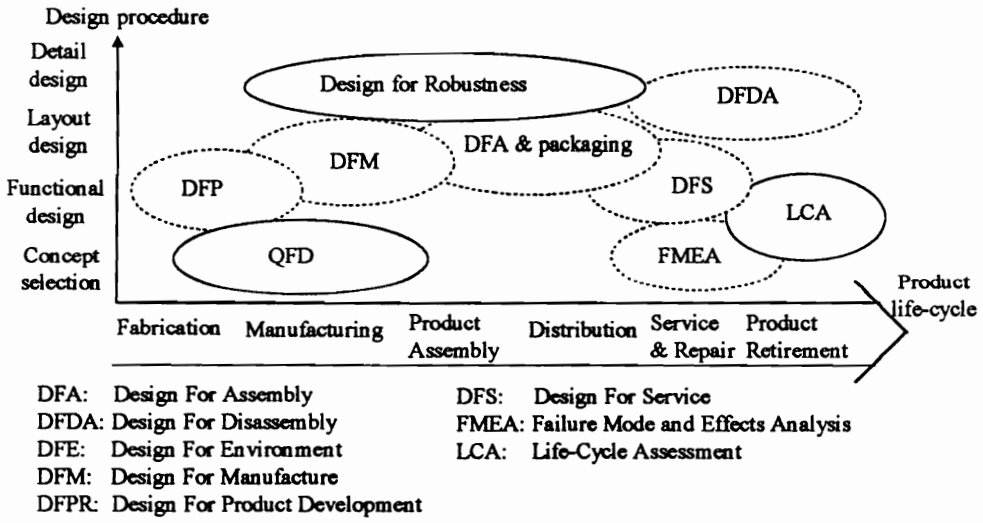


Figure 2.13. Methodologies used in the product design procedure throughout the product's life cycle

Product/Process Design and Customer Preferences. Product design and production planning are considered at the pre-production stage. Product/process design (or attributes determination) has long been a joint venture between the marketing and manufacturing functions of business. Market research identifies key variables (attributes) that are most desirable to a customer.

Based on these key attributes, product designers develop new product concepts to satisfy the desires of the customers, and manufacturing process planners translate these concepts into a product [Chakravarty and Baum, 1992]. Chakravarty and Baum have developed a coordinated planning approach to minimize the conflicts between maximization of market revenues and minimization of production costs by identifying product groups (in terms of attributes) that possess manufacturing commonalties. A unified, integrated product design model has been developed to illustrate the benefits of integrating the marketing design process simultaneously with manufacturing. Through this model, the authors have demonstrated methods for determining the optimum bundling of product attributes.

Raman and Chhajed [1995] have also provided a decision support tool for implementing an integrated approach that simultaneously determines product attributes and prices, and production processes in product-line design. On the basis of given customer preferences, the authors have presented a model for determining the number of new products to be introduced to market, the exact specifications of these products, and the production processes for efficiently delivering these specifications. These decisions are made in an integrated manner by simultaneously considering the interaction among the various choices. In their paper, a decomposition-based solution procedure is developed that iterates between the product-design and process-selection decisions while maintaining an effective link between them.

The integrated approach discussed above provides an opportunity to consider customer preferences in product/process design. Increasingly, environmental issues (e.g., environmental regulations and environmental impacts caused by the process) are considered in product/process design. When the environmental issues associated with product design and development are considered, it is common to focus efforts on the product design stage. Product design offers tremendous opportunities for achieving reduction of environmental impact, such as selection of recyclable material, use of sustainable material, and use of durable parts/components, or more commonly using techniques of Design For 'X' and Design for Environment (DFE).

Quality Loss Function Approach for Product Life Cycle Determination. Product quality in terms of value is an important measure during the product usage stage. Generally, value is a measure of those quantities that determine benefit, desirability, usefulness, or importance of the product, where profit can be expressed as the formulation: *profit = sales - cost*. It is believed that quality improvement is the most effective way of achieving a simultaneous increase in sales and cost reduction as well as an increase in total product value.

According to the design goal, the system is designed to satisfy the customer's requirements. However, due to manufacturing variation and environmental disturbance, the performance of the real

product may deviate from the ideal performance target. This deviation results in a quality loss. Accordingly, Taguchi and colleagues proposed two evaluators of quality: the Quality Loss Function (QLF) and the Signal-to-Noise (S/N) ratio. The QLF converts the variability into monetary terms that represent an estimate of the costs a customer incurs when a product fails to function as intended [Taguchi *et al.*, 1989]. Thus, Taguchi's loss function provides a quantitative measure of product quality, as related to the variation from the target specification. This measure provides a link between the economic and performance attributes of the product. However, Taguchi's QLF does not consider the time-varying factor in quality variation. In the real world, this deviation should increase with time in the product usage stage.

Recognizing the fact that variation of performance is a function of time, Vadrevu *et al.* [1994] have proposed the concept of a time-varying value of product in which the product value is defined as the cumulative sum of all the benefits and losses incurred by the customer during the use of the product until it fails. They developed a model for value over the life of a product based on the relationship between a time-varying quality characteristic and the associated benefit and loss. This time-varying value model was then employed to examine the potential reuse or remanufacture of used products that are demanufactured as part of the life-cycle design strategy. An example demonstrates how the time-varying value function model is used to determine that society has to pay for disposal of the product by observing the target value at the time of failure. It is time to pay for disposal when the product value becomes negative.

2.3.3. Design For "X" and Concurrent Engineering

Design for "X" is an acronym to represent all the concepts of downstream effects to be considered when designing products in the concurrent engineering environment. A life-cycle approach of DFX is illustrated in Figure 2.14. Each DFX has its own proactive effect on different phases downstream of the product life cycle. Concurrent or simultaneous engineering represents a multi-discipline teamwork approach towards completing the product design process. This section discusses articles on design for "X" and how concurrent engineering is used when environmental issues are considered in product design. Concurrent engineering, with its multidimensional and interdisciplinary orientation, considers environmental impact at every design decision point throughout product development. A true concurrent engineering approach addresses not only product performance but also manufacturing service and other downstream issues including environmental quality [Evanczuk, 1990]. Several studies works related to the concurrent-engineering paradigm can be found in papers by Kusiak [1993]; Gu and Kusiak [1993]; and Parsaei and Sullivan [1993].

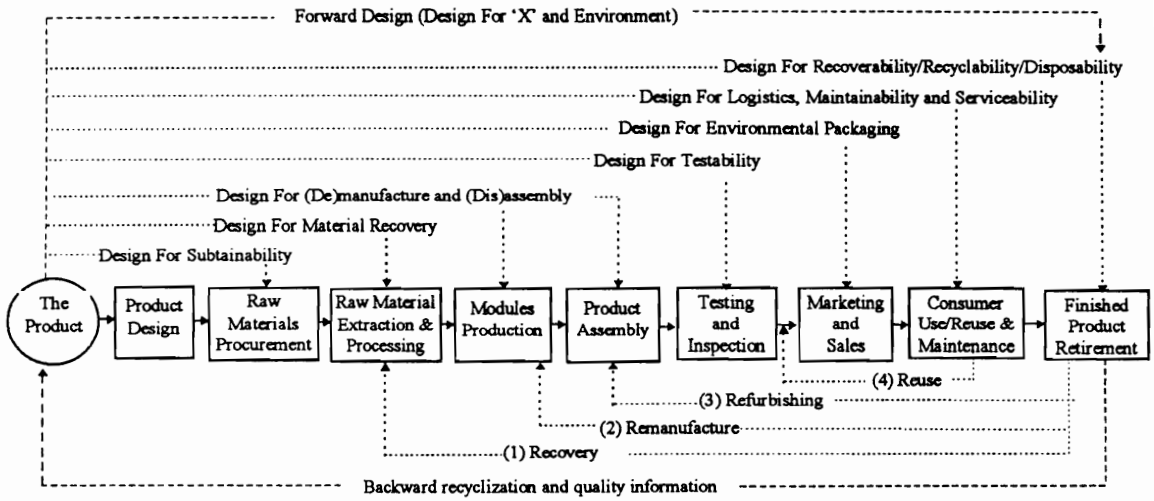


Figure 2.14. Life-cycle approach for DFX and DFE.

Moreover, the present trends towards concurrent or simultaneous engineering are very important since this facilitates environmental considerations becoming a natural part of the ECDM approach in industrial ecology. Design for environmental impacts reduction must be developed parallel to design for manufacture, design for assembly, design for environment, and so forth. Currently, Design for X or Life-cycle Design approaches focus on a single area of performance as the appropriate design driver, such as cost, and determine the functional relationships between design decisions and cost. Another approach, namely, Concurrent Engineering focuses on design evaluation as function of performance in multiple areas, but does not formally model the complex functional relationships between design decisions and performance in multiple attributes. Neither approach explicitly incorporates environmental considerations.

2.3.4. Design For the Environment

Increasingly, design engineers are promoting the concept of green engineering, commonly called Design for Environment (DFE). DFE can be viewed as the extension or as a partial design activity in DFX approaches [Lewis and Samuel, 1989], which are viewed as partial components of ECDM strategies.

What is "Design for the Environment" ? Design for the Environment (DFE) may be defined as the systematic consideration during new product and process development of design issues associated with environmental considerations over the full product life-cycle. According to Lent and Wells [1994], DFE, the first step in the renaissance of product development, is defined as:

> *"all efforts to include environmental criteria into product design: design for disassembly, design for recyclability, efforts to include life-cycle analysis in product development, efforts to map customer demand for environmental performance into new products, or efforts to reduce corporate risk by designing pollution out of products and processes."*

The key concepts here include life-cycle analysis and mapping of customer demand for new products. The DFE discipline maintains that not only recyclability, but also overall greenness, can be designed into the product without compromising the product's functional performance or integrity. Thus, a green product can be both environmentally compatible and economically viable.

Although the term Design for Environment (DFE) can be seen as deriving from the DFX process by adding environmental considerations into product design, a DFE methodology is fundamentally different from current DFX techniques. There is a need for decision support for DFE at the conceptual design stage. Such decision support must be based on a full life-cycle engineering model to allow members of a concurrent engineering design team to contribute data on their relevant fields for DFE, such as design, manufacture, assembly, packaging, serviceability, disassembly, retirement and disposal. In addition, it is likely that a DFE tool should directly use the output of other Design For "X" tools, as illustrated in Figure 2.10, as partial inputs to the model of the whole product life cycle. For example, information about product assembly is the best reference for design of the product disassembly processes. This situation is explained by Keys [1990] as:

> *"...while other researchers are addressing the need for improved design methodology understanding and improved DFA/DFM tools; it is important to keep a perspective that considers the total life cycle of the product and manufacturing process in continual view and focus. This is even more important today when the planning of new products includes second, and third, etc., generation product follow-on's; when the support to and through product lives must be part of an integrated life cycle strategy. In particular, such a thinking process and philosophy is a fundamental part of the effective management of technology."*

This statement suggests that DFE also requires life cycle thinking for the continuous design activities of Design For "X". In practice, two major parts of DFE are design for recycling (DFR) and design for disassembly (DFD). The DFE used in green product development are all efforts to include environmental issues (criteria) into product design: design for demanufacturing, design for disassembly, design for recycling, design for remanufacturing, and design for disposability.

DFE has been used in reference to a variety of practices and concepts. Another definition of DFE proposed by Lenox and Ehrenfeld [1995] is:

> *"Design for environment is the systematic process by which firms design products and processes in an environmentally conscious way based on industrial ecology principles across the entire product life cycle."*

There are three critical points in this definition of design for environment:

- Environmental impacts across the entire product life cycle are considered.
- Impacts are addressed during the product development cycle.
- Decision making is guided by a set of principles based on industrial ecology or some set of system-configured, integrative principles.

DFE is a new practice for making strategic decisions regarding environmental-oriented product design and development. Several studies examine how the critical features and rules that influence each DFE efforts are used in green product design, and represent DFE in practices: in practices of design for dissembling (DeFazio *et al.* [1987], Lee and Shin [1990], Homem de Mello and Sanderson [1990a], DeFlorani and Nagy [1989], Molloy *et al.* [1991], Struges and Kilani [1992], Tatikonda [1994], Rampersad [1995]), on design for manufacturing (Shu and Flowers [1993]), on design for reusability (Scheidt and Zong [1994]), on design for environmental quality (Ryberg [1993]), on design for disassembly and recycling (Kirby and Wadehra [1993]), on disassemblability analysis (Shin *et al.* [1995]), on disassembly planning and automated assembly (Lee [1982, 1992]), on automatic disassembly and assembling (Miyata [1992]), on design for product recycling and reuse (Kuuva and Airila [1993]), on design for recycling and remanufacturing (Steinhilper [1994]), on driving general design for environmental guidelines (Billatos and Nevrekar [1994]), in focus of engineers role in DFE (Hundal [1994]), in discussion of total approach to DFE (Berko-Boateng [1993]), among others.

A General Life-Cycle Design Framework for Green Design. Keoleian and his coworkers [1993] introduced a life-cycle design framework (Figure 2.15) that demonstrates the complexity of integrating environmental issues into design. The life-cycle framework provides a way to understand how environmental considerations are incorporated into the design process. The goal of sustainable development is located at the top, to indicate its fundamental importance. As the figure shows, both internal and external forces shape the creation, synthesis, and evaluation of design, the same as in the conventional design process. The related discussion is also found in the work by Keoleian [1995], Keoleian and Menerey [1994], and Keoleian *et al.* [1993].

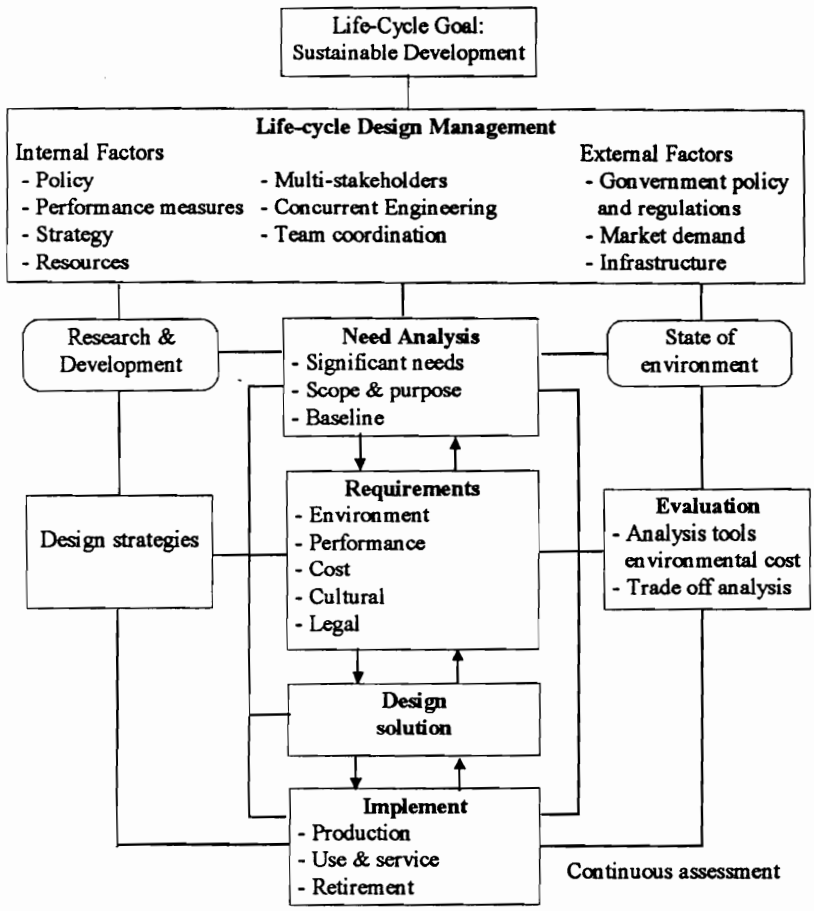


Figure 2.15. Life-Cycle design process [Keoleian and Menerey, 1993]

Design For Recycling. Recycling[4] strategy makes a significant contribution to improving total product value. The recycling of used materials must be considered at the product design stage. In other words, the product is designed not only from the viewpoint of function/quality, but by taking efficient recycling and minimum harmful waste discharge into consideration. Overby [1990] has presented a method embodying this concept, that is, design for environmental elegance for a product's entire life cycle.

Recycling and Design For Recycling Issues. Design for recycling (DFR) activity is the most important issue in DFE, which is applied in many practical industrial problems.

[4] In much of the literature, the term recycling has a broader meaning that includes reuse, refurbish, recovery, and remanufacture. Disassembly is a process for the implementation of recycling options.

On Recycling Production Planning. Remanufacturing schemes should be considered in traditional production planning when environmental issues are concerned. Considering how recycling and remanufacturing may affect a companies' operations management policies, Clegg, Williams, and Uzsoy [1995] developed linear-programming models of a production system with remanufacturing capability that can be used to explore the effects of different demand patterns, production and disposal costs, and government actions on the economic viability of remanufacturing schemes.

The decision variables in linear-programming models are the amount of products or components used in the different operation options (i.e., disposal, total disassembly, partial disassembly, remanufacturing, reassembling) and the inventory levels of the various intermediate items. The costs considered are production, disposal, and inventory-holding costs. The model determines a maximum-profits production and procurement plan, i.e., how much product to disassemble, how much of each component to reuse versus dispose of, how much of each product to remanufacture, and how much to make from scratch.

As the authors claim, the models can be used to examine the effects of different cost structures on the long-term economic viability of remanufacturing operations, as well as short-term operations management issues, by indicating which types of costs (e.g., disassembly, remanufacturing, disposal, or assembly) are the most important to implicate remanufacturing strategies successfully. However, the solution of the models did not appear in the paper. The authors also suggest that these types of questions can fruitfully be addressed using queuing network models, which they are still pursuing.

On Integrating DFR into Product Design. It is currently widely recognized that the most environmentally sound way to treat a used or worn out product is recycling. Since it is rarely possible or beneficial to recycle a product completely, the aim of recycling is generally to maximize the recycled resources while minimizing the effort that has to be invested [Kriwet, 1995]. In the context of life-cycle engineering and design for recycling, different paradigms are presented in studies by Alting and Jørgensen [1993], Züst and Wagner [1992], Kriwet [1995], Seliger *et al.* [1994], where the integration of recycling considerations into product design is suggested. Other studies present DFR guidelines for specific types of products, such as Burke *et al.* [1992]; or for general products for helping the design team to assess, compare, and make design decisions, such as Navin-Chandra [1991a, 1991b, 1993] and Beitz [1990, 1993].

Remanufacture and Disassembly Issues. Disassembly or separation is one of the critical issues for effective demanufacturing (e.g., recycling and remanufacturing) and is a key process in remanufacture. Therefore, as part of a study of life-cycle design, disassembly-related study is given much attention by researchers. With the emergence of environmental design initiatives such as DFE and green engineering,

Design For Disassembly (DFD) and Disassembly For Recycling (DFR) have become an integral part of enhancing product designs to facilitate servicing/reusing, recycling, and remanufacturing efforts. Some studies have been done related to DFD and DFR, both conceptually or analytically.

In the paper "A Key Issue in Product Life Cycle: Disassembly", Jovane and co-workers [1993] have presented an overview of disassembly research at universities, research centers and industrial companies, pointing out ongoing topics and trends for future activities. Among them, major attention has been paid to basic technological development, product design (e.g., design for disassembly), process design (e.g., selection of disassembly strategy and automation level) and system design (e.g., configuration of manual and automated disassembly facilities, design of disassembly tools). The authors conclude that the life cycle concept should be used to develop suitable ways of dealing with information related to environmental protection and resource optimization during disassembly of the existing product.

On disassembly sequence's generation and disassemblability. Little research has been completed on disassembly sequence generation and the economics of material recovery. Generally, according to Miller [1995], two main approaches to the disassembly planning problem have resulted as follows. In the first approach, methods rely on the designer to provide precedence information, than an appropriate algorithm determines all the possible disassembly schemes. The disassembly schemes are then stored as lists of sequences, precedence diagrams, AND/OR graphs, etc. Such storage methods hold precedence information but not explicit contact or constraints information. The second approach requires the designer to model the product with a liaison graph which contains connectivity/constraint information, then, algorithm search the model for all possible disassembly combinations; the plans are then stored as precedence relations in the same manner as in the former approach.

In addition, design tools for disassembly should also consider the objectives of present tools for assembly design such as those proposed by Boothroyd and Dewhurst [1987]. Based on the representation-of-disassembly diagram by either of the approaches, Subramani and Dewhurst [1991] developed an algorithm for generation of the disassembly sequence from a serviceability viewpoint. Laperriere and ElMaraghy [1992] developed a method for integrating assembly sequence generation with various aspects of disassembly. Navinchandra and Bansal [1994], and Ishii *et al.* [1993] have extended disassembly modeling to incorporate environmental and other life-cycle considerations to aid designers on planning and design. Johnson and Wang [1995] were concerned with the generation of an optimal disassembly sequence in terms of the economic considerations of material recovery opportunities at the end of the product life cycle.

In the context of disassemblability, the difficulty of the disassembly problem is the inherent complexity of possible solutions. R.W. Chen and his coworkers [1994] developed a separability algorithm to find a heuristic disassembly sequence to remove a component out of a structure by a parallel

disassembly procedure. The time complexity of their algorithm is Max{ $O(N^3), O(E)$ }, where N is the number of components and E is the total number of mating edges. Separability testing is incorporated to determine whether the query components can be disassembled and moved to infinity without obstruction, i.e., the separability of the disassemblable components. The onion-peeling algorithm is used to investigate the 'multi-translation' case because, if the components are disassembled but inseparable, physical disassembly may yet be feasible if multi-translation is allowed.

In the concurrent engineering environment, product design is a process of synthesis in which a variety of product attributes at different levels are attempted to be satisfied simultaneously. Wang and Johnson [1995] proposed a structured procedure, namely *Design for Disassembly and Recyclability*, which incorporates environmental attributes into the product design process. Combined with the other conventional attributes (such as functionality, cost, and consumer satisfaction), they claimed that the structured design procedure gives a better product design that can then be selected to assure reduced cost and ease of manufacturing. A methodology is established for incorporating "disassemblability" into life-cycle design, which is structured using a four-level disassembly analysis: (1) disassembly cost analysis, (2) optimal disassembly sequence generation, (3) disassembly optimization, and (4) DFD guidelines. A detailed example of using this four-level methodology was proposed in the work of Johnson and Wang [1995], in which economic analysis for optimization of the disassembly sequence is described in detail.

With respect to automation, the most challenges in this field of disassembly include automatic generation of product disassembly sequences (Subramani and Dewhurst [1991]), disassembly of product automatically (Woo and Dutta [1991], Warnecke *et al.* [1992]). In contrast to the state of the art of flexible assembly automation, disassembly for recycling today is mainly a manual and, to some extent, mechanized process. Focusing on electrical and electronic devices, Warnecke and his co-workers [1992] introduced the concept of a flexible disassembly cell based upon the industrial robot, which was installed for recycling telephone sets. A methodology was also presented to approach both disassembly system design and disassembly sequence control based upon a product line analysis and a disassembly technology database. They also concluded that flexible disassembly system design should be concerned with the parallel development of a methodology to implement design for disassembly (DFD).

On design for remanufacture. It has been known that product design for ease of remanufacture could be a means for realizing resource conservation and waste disposal minimization, which in turn is a way to reduce environmental impacts. Unfortunately, few design-for-remanufacture guidelines are available so far. By using the principles of axiomatic design proposed by Suh [1990], Shu and Flowers [1993] have performed the overall remanufacturing operation as well as specific remanufacturing processes: disassembly, part identification and sorting, cleaning, assessment,

refurbishment, and transportation. Axiomatic Design is applied to remanufacturing processes to gain insight into how products should be designed to facilitate each remanufacturing process.

On tools to support DFR. Several research works have addressed the need for a formalized evaluation tool to support design for recycling. Navin-Chandra [1991] addressed the necessity of supporting the designer with quantitative information about process options for the end-of life. A software 'ReStar' has been developed to assist the designer in identifying recycling-friendly design solutions. Wallace and Suh [1993] have illustrated the implementation of environmental and recycling efforts into the general framework of axiomatic design.

On product's end-of-value. The basic concept of DFD and DFR is to increase the end-of-life value (or recycling value) that depends on an efficient DFR process during product demanufacture and effective DFD at the early product design stage. Zussman *et al.* [1994] have demonstrated a formalized quantitative evaluation of product recyclability, supporting the design team in evaluating and improving their designs based on the evaluation/assessment of the end-of-value of the product being disassembled.

Hentschel and his co-workers [1995] present an approach based on group technology to recycling system planning for used products at their end-of-life phase. Their approach employed design and process attributes for group information in manufacturing; they focused on designing cellular recycling systems by using group technology for dealing with uncertain product and process characteristics associated with recycling issues.

Other Product Design-Related Methods. Many research efforts can be employed in the product design process that are viewed as iterative: design, evaluate, and redesign. Such efforts include life-cycle engineering, concurrent engineering, design for X, design for assembly, design for disassembly, and "Design for Environmentability" [Navin-Chandra, 1991b]. These efforts take an important step into the design process; however, they do not help incorporate environmental considerations along with others into the design process for reduction of environmental impact.

2.3.5. Quantitative Measurement

Quantification of environment quality plays an important role in green system development. As pointed out by Fiksel [1994]:

> "*...without a quantitative basis for understanding the relative contribution of environmental quality to profitability and customer satisfaction, it is difficult to make meaningful trade-off decisions in the development of new products.*"

This statement suggests that analytical tools are required to evaluate the cost benefits of business decisions from an environmental perspective. Consequently, tools for environmental quality measurement are required in a quantitative sense to evaluate and improve the environmental impact while minimizing the life cycle cost. The following survey provides an overview of different measurement tools for life-cycle analysis.

In general, eco-product and eco-factory can be evaluated by various factors. Ecoproduct will be evaluated by factors of design for disassembly, design for recycling, economy, and function. In eco-product design, the trade-off between maximization of recycling rate, function, and economy, and minimization of environmental loads of end-of-life products should be solved. The eco-manufacturing system will be evaluated by factors of ecological load, energy saving, resource saving, industrial waste, hazardous waste, productivity, economy, performance, and marketability. In the design of the eco-factory, the trade-off between maximization of productivity, performance, and economy, and minimization of ecological loads should be solved.

In the context of LCA, eco-balance calculations generally produce large amounts of data and information about the associated different units. In practice, Boustead [1995] concluded that

> "*...the total number of different parameters needed to describe fully the environmental performance of a system is large and they cannot be aggregated in any meaningful way to produce a single parameter that could be used as a measure of the overall environmental effect.*"

This difficulty is even larger when different industry systems are considered. Therefore, it is meaningless to say that one system is "better" than another. Another potential research topic is to develop ecounits from various environment-related measurements.

In the context of DFE, environmental performance matrix are parameters used to measure ecodesign improvement of a product and its processes with respect to environment goals that are derived from customers' needs and wants (requirements). According to Fiksel [1994], environmental performance matrix are useful in three ways:

- as parameter indicators of environmental performance for the purpose of external communication;
- as a basis for setting internal design objectives related to design of product and its processes;
- as linkage information of environmental factors for development of an ecounits set or ecounit.

The last usage is especially important. Ecounits must be developed based on environmental performance matrices so that the interrelated environmental measures can be aggregated into a set of ecounits, or even one ecounit. These ecounits are used as factorized units for constructing ecodesign evaluation functions and modeling optimization ecodesign problems.

To introduce environmental performance matrix and development of ecounits into ecodesign of product and processes, a systematic process of environmental quality measurement is essential. Fiksel [1994] established a systematic process for such purposes, which involves the following steps:

Step 1.) Development of matrix:

- Identify key company goals and objectives relevant to environmental performance (quality) in new product development;
- Select a reasonably small set of QFD matrices (DFX matrix and DFE matrix) that reflect the critical environmental goals/objectives of product-performance and EH&S requirements, so that these matrices are manageable;
- Derive corresponding operational function dependency matrices that are measurable and controllable for modeling optimization design problems with ecodesign evaluation functions.

Step 2.) Implementation of matrices:

- Establish systematic measurement tools for each of the DFX and DFE matrices selected from QFD matrices;
- Develop an appropriate aggregation and weighting scheme by benchmarking;
- Assess the baseline environmental performance (quality) of existing products and processes;
- Track environmental quality improvements relative to the baseline;
- Develop ecounits for modeling the optimization ecodesign problem.

Step 3.) Trade-off Analysis

- Trade-offs among economics, performance, ecology and quality;
- Trade-off techniques are applied.

Step 4.) Continuous improvement:

- Institutionalize the metrics and associated tools using computer support as appropriate;
- Benchmark environmental quality progress against competitors by the QFD method;
- Periodically establish new objectives for environmental improvement.

This process motivates us in development of the QFD-based methodology for environment-oriented product design and development.

2.3.6. Life-Cycle Cost Assessment

The growing importance of including environmental issues in design has forced companies to more formally consider the entire life cycle of a product, from cradle to grave or even to reincarnation through recycling and reuse. A crucial issue is the assessment of costs (or profit) related to pursuing environmentally conscious product and product-related processes. Besides the quantitative measurement in environmental considerations, the economic considerations and models are also needed to be developed in green product design. Hence, as stated by Bras and Emblemsvåg [1995], the following two questions should be answered:

- *What is the life-cycle cost associated with pursuing or developing environmentally conscious products and processes*?
- *Which aspects of both the product and process ecodesign have the largest influence on these life-cycle costs*?

In the ECDM practice, Life-Cycle Costing (LCC) and Activity-Based Costing (ABC) are related to justifying environmentally responsible product development. In this section, we investigate various methods for developing cost models to aid designers in answering these or similar questions in the context of IECDM methodology.

Incorporating Environmental Issues into LCC Model. Life-Cycle Cost (LCC) is best considered along with environmental and other performance factors in a Life-Cycle Design (LCD) or Design For the Environment (DFE) framework, or in the process of life-cycle design (see also Sullivan and Young [1995]). Design of new products/processes that are ecologically (environmentally) friendly requires capital investment, but the pay-back can come sooner rather than later. Mallik and Ross [1993] have pointed out that

> "*...engineering economy (life-cycle costing) can be useful in evaluating and justifying environmental projects, but many environment-related factors other than engineering economics must be considered simultaneously. For example, investment in industrial energy conservation and waste management (elimination) systems can reduce utility costs, manufacturing overheads, environmental emissions, cleanup costs, and reliance on foreign energy sources.*"

This statement implies that the traditional life-cycle costing approach must be concerned not only with engineering costs but also with costs for developing environment-friendly systems. In the context of green engineering, i.e., designing products simultaneously for environmental compatibility and economical viability, a cost-benefit model is often useful to assess costs of the design for environmentability issues (e.g., recycling and disassembly), and to balance between the cost (e.g., cost of

the recycling process) and benefits (e.g., revenues from recycling). The survey includes the impact of ecological issues on the environmental economics in terms of life cycle costing, and provides a knowledge background for Life Cycle Cost Assessment (LCCA). However, an integrated model that considers cost-benefit analysis along with production/ manufacturing costs, recycling/demanufacturing costs, and recycling/remanufacturing benefits is lacking. We later use the concept LCCA to evaluate product design alternatives in a cost-benefit analysis model.

In practice, companies can effectively use a LCC approach similar to LCA approach by implementing three important steps [Cohan and Gess, 1993]:

- Define or bound the scope of the product, process, or systems to be addressed;
- Assess or measure the pertinent costs (e.g., by LCCA) or impacts (e.g., by LCA) throughout the life cycle of a product, process, or activity; and
- Make decisions based on the assessment of impacts and costs.

Several methods have been developed for assessing or measuring the environmental impacts and costs of products/materials, processes, and activities throughout their life cycle. These methods include LCA, such as in the work of Fava *et al.* [1991] and Vigon [1995]; the study of Life-Cycle Costing (LCC) and pollution prevention in Bailey [1990]; discussion of Life-Cycle Cost management for chemicals and materials by Choan *et al.* [1992]; using Total Cost Assessment to advance pollution prevention in A.L. White *et al.*, [1993]; integrating a life-cycle cost model in design for recyclability (DFR) methodology in Rose and Evans [1993]; and using Activity-Based Costing in demanufacture cost assessment by Bras and Emblemsvåg [1995]. Generally, the purpose of these methods is to measure or assess impacts, in units of emissions, resources, dollars, or other metrics. The major differences between these methods involve the following considerations:

- how they define life cycle--cradle to grave, cradle to cradle, product or material, upstream inputs, downstream outputs, etc.;
- how they measure environmental impacts--costs, volume, weight, activities, etc.;
- the extent to which indirect costs or impacts are included; and
- who is responsible for impacts--individual, company, government, society, environment.

Nevertheless, companies are facing increasing pressures to reduce or even eliminate the environmental impacts associated with their operations while improving quality and reducing costs. A comprehensive model for life-cycle costing can help companies address these pressures by reducing costs while gaining opportunities for reduction of environmental impacts.

Commentary of LCA and LCC Models. Both LCA and LCC models are used for analysis of product and process. LCC assessment is based on product-specific costs that occur within the life-cycle framework. The purpose is to measure or describe costs that can help reduce environmental impacts (or pollution prevention) in product-related decisions. Products must have an attractive price to be successful. Fortunately, some strategies for reducing environmental impacts can also lower costs while meeting all other critical requirements [Shen, 1995].

To assist in life-cycle design, cost-assessment practices need to be modified to reflect the actual (true) costs of development, including environmental related costs which are often hidden in the traditional LCC model. An accurate estimation of costs to develop and use a green product are central to life-cycle green design. Materials and energy flows identified during the life-cycle inventory analysis provide a detailed template for assigning costs to individual products. In an effort to be more complete, life-cycle costing analysis also uses an extended time scale [Keoleian et al., 1994]. On the other hand, the limitations of LCA are also the limitations of the LCCA model. Some hurdles to developing an environmental impact and cost model are similar to limitations of the LCA model (see section 2.3.1):

- there is a lack of both hard test data and past experience;
- new and different technologies are integrated with unknown effects; and
- designs are incomplete and evolving at the stage where the largest reduction in environmental impact and cost can be made.

Applying LCC Concepts to LCCA Methodology. In the context of the ECDM domain, LCC should be a tool used to measure cost-effectiveness with respect to environmental goals. Also, life-cycle costs associated with environmental issues are another important index for selecting the better ecodesign system alternative. In practice, environmental performance (quality) is not just one aspect of total quality for system ecodesign but is also an unavoidable cost of doing business. That is, a business needs to integrate environmental quality metrics and life-cycle assessment (LCA) tools, as well as developing a system that recognizes environmental costs and benefits, namely, the LCCA model. Recently, life cycle costing for environmental issues, or environmental life cycle costing, has increasingly been studied (Mallik and Ross [1993]; Tipping [1991, 1993]; Züst and Wagner [1992]; A.L. White *et al.* [1993]; Cohan and Gess [1993]; Popoff *et al.* [1993]; Bailey [1991]). However, there is no unified approach or model for integrating environmental economy in conventional life-cycle cost methods.

Regarding the design of a LCCA model, according to Cohan and Gess [1993]: A complete LCCA model should achieve the following.

> *"A LCCA model should enable companies to assess the product' life cycle costs, to reduce costs while identifying opportunities for waste minimization and pollution prevention. In the context*

of the LCCA model, managing life cycle costs requires not only that firms identify and estimate the elements of such costs [costs of resources usage in the product life cycle], but also that employees throughout the firm be provided with the means to actually put this understanding of life cycle costs into action to make better decisions that will ultimately save money and reduce environmental impacts."

LCC in Practice. Overby [1991] points out that Taguchi's "loss functions" are related to the "life-cycle costs". Taguchi loss functions are used instead of the LCC calculations to include environmental 'losses' incurred by society in the course of producing, using, and disposing of goods and services [Overby, 1991]. There is no surprise that "loss functions", where dollars of *loss* for the life cycle of the product are related to some measurable quality characteristic, are used in the field of green product development, such as in determination of product life time with respect to product end-of-life value [Vadrevu *et al.*, 1994], and in the evaluation assessment of the end-of-life value of the product being disassembled [Zuseman *et al.*, 1994]. Other LCC-related studies include cost-benefit analysis for recycling process implementation [Chen R. *et al.*, 1994]; applying Activity-Based Costing (ABC) in demanufacturing practices [Bras and Emblemsvåg, 1995]; and using a cost-effective approach to determine the degree of disassembly [Alting and Legarth, 1995]. We will briefly discuss these applications of LCC associated with environmental considerations:

Life-Cycle Costs and Taguchi Loss Functions: Overby [1991] points out that Taguchi's "loss functions" are related to the "life-cycle costs". It is no surprise that "loss functions", where dollars of *loss* for the life cycle of the product are related to some measurable quality characteristic, are used in the field of green product development; such as in determination of product lifetime with respect to product end-of-life value [Vadrevu *et al.*, 1994]; and in the evaluation assessment of the end-of-life value of the product being disassembled [Zusemann *et al.*, 1994].

Conceptually, if it is not possible through market research or other economic cost modeling to generate specific economic loss models for a given situation, Taguchi recommends using rather simple quadratic equations to approximate relationships between "losses to society" and some measure of quality. In the context of life-cycle design, as we mentioned, the topic of 'product life-cycle assessment' and 'life-cycle costs assessment' have been paid increasing attention by researchers in order to determine whether or not changes in the design of products and processes will in fact produce net positive improvements in terms of environmental concerns [Overby, 1991]. They are supposed to give designers the information to evaluate design or redesign the products. Needless to say, LCC calculus is further complicated by the fact

that environmental and pollution costs are often 'external' costs[5] not easily factored into the 'internal' cost calculations that determine what gets produced and how it gets made. Therefore, Taguchi loss functions are used instead of LCC calculation to include environmental 'losses' incurred by society in the course of producing, using, and disposing of goods and services [Overby, 1991]

Total Cost of Disposal in a Disassembly Scenario: The degree of disassembly (disassembly depth) often displays a cost-effective (or benefit) optimum, where further disassembly and the disposal of the remainder costs more than is gained by selling the disassembly parts [Alting and Legath, 1995]. When a used product enters a disassembly station it may no longer be exactly the product that was initially manufactured. The possibility to disassemble products into recycling fractions and the issue of material quality preservation is the heart of the matter in optimal recycling. The trade off analysis cost and disassembly depth becomes an important issue in optimal recycling. This idea in shown in Figure 2.16 where the total cost of disposal is determined with respect to disassembly depth. The diagram helps the decision-maker decide the best recycling policies associated with disassembly depth. In practical ECDM, the cost-effectiveness analysis is still an effective way to find the 'best' design solutions, because the elements of costs are more complex and appropriate effectiveness attributes are difficult to define in green product development.

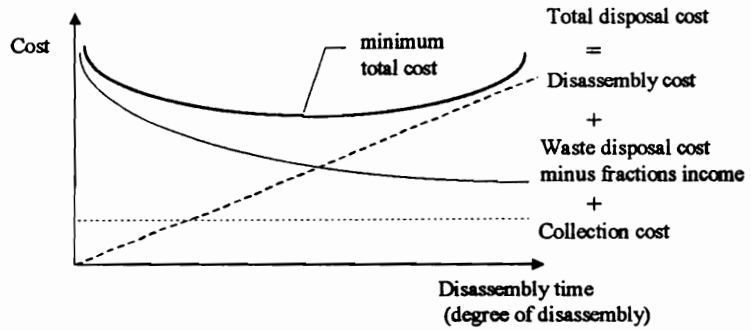


Table 2.16. Total disposal cost with respect to disassembly depth

Product Recycling Costing in Design For Recyclability Methodology: Focusing on end-of-life value of product can be realized by two means related to recycling activities (remanufacture, reuse, refurbish, recovery) processes:

[5] Disposal and pollution costs are usually 'external' costs whereas 'use' costs (losses) during the useful life of a product are usually 'internal' costs (losses). Broadly speaking, the internal environmental cost is used to reflect the environmental control cost to the manufacturer and issuer, whereas the external environmental cost is used to reflect the social environment impact of the product and materials. Both 'external' and 'internal' life-cycle costs associated with the product should be factored into an effective decision-making model.

- Improvement of Recycling processes by developing more sophisticated product recycling technologies; and
- Improvement of product design to be product recycling-friendly.

Costing Design For Services (DFS): Design for service involves both disassembling time and reassembling time. The service costs include labor, operation, parts and replacement. Therefore, as an example, a serviceability (or DFS index) can be defined as a cost index:

$$\text{DFS Index} \equiv I_{DFS} = \frac{C_s}{C_s + C_r + (T_d + T_a + T_g)L + C_t}$$

Where C_s is the cost of service item(s) which may be part(s) to be replaced because of failure or wear, or other service goals, e.g. cleaning or adjustments. C_r is the cost of items which cannot be replaced once removed, e.g. consumable like gaskets, seals and fluids. T_d is the disassembly time. T_a is the reassembling time. T_g is the diagnostic/ verification time. L is the applicable labor rate for OEM, service center or technician, or, in the case of owner service, the value of leisure time. C_t is the cost of special tool or equipment use per service task. Notice that the disassembly time and reassembling time are strongly dependent on results of upstream design for disassembly (DFD).

Total Retirement Costs: In the product's retirement phase, one has to decide to either dispose of the discarded goods or recycle them. End-of-life value of a product is estimated to help make such a decision. Basically, if the end-of-life value of a product is greater than the total retirement cost, then the discarded goods should be recycled.

Total retirement cost (complete disposal cost)is given by:

$$\text{Cost}_{\text{Retirement}} = \text{System disassembly cost} + \sum_{i=1}^{n} (\text{clump reprocessing cost})_i$$

where n is the total number of clumps.

The total disassembly time for system (with no clump) in terms of cost depends upon the degree of disassembly that results from design for disassembly. As an example, this total disassembly cost may be given by:

$$\text{Cost}_{\text{Disassembly}} = \left\{ \sum_{i=1}^{l} C_i + \sum_{j=0}^{m} (f_n \times F)_j + \sum_{k=0}^{n} (P_n \times P)_k \right\} \times \text{Labor cost}/\text{Time}$$

where the first term is the total time to remove components, C_i is the individual time to remove i^{th} component; the second item expresses the total time to remove parts (e.g., fasteners), f_n is the number of fasteners, F is the time to remove one fastener, m is the total number of components required to remove fasteners; and the third term is the total time of disassembly links within fastener, P_n is the number of links, P is the time to deal with disconnecting links, n is the number of fasteners that require being disconnecting. Notice that the degree (or number of levels) of disassembled product depends on the efforts of DFD and product analysis.

The Cost-Benefit Analysis of Recycling [Chen *et al.*, 1994]: According to the recycling processes implemented by individual company, the cost function of recycling is different from system to system. Nevertheless, a basic cost function of recycling can be defined as [Chen R., *et al.*, 1994]:

$$\begin{pmatrix}\text{Cost of}\\ \text{Recycling}\end{pmatrix} = \begin{pmatrix}\text{cost of}\\ \text{disassembly}\end{pmatrix} + \begin{pmatrix}\text{cost of}\\ \text{shredding}\end{pmatrix} + \begin{pmatrix}\text{cost of material}\\ \text{recovery}\end{pmatrix} + \begin{pmatrix}\text{cost of}\\ \text{dumping}\end{pmatrix}$$

or

$$C^R = C_d + C_s + C_r + D_c$$

$$C_d = C_{dh}\left(\sum_{j=1}^{n}\sum_{i=1}^{m-g} T_{ij}\right);\ C_s = C_{sh}(S_t)(W_s);\ C_r = \sum_{i=1}^{k}(R_{ci})(W_{ri});\ D_c = d_c(W_d)$$

where,

C_{dh}	hourly cost of disassembly
C_{sh}	hourly cost of shredding
T_{ij}	time for disassembling *i*th of *j* type joint
m	number of same type of joints in the product
n	number of different types of joint such as screws, etc.
g	number of joints that connect parts of the same or compatible materials
S_t	time to shred one ton of material
W_s	weight (ton) of material to be shredded
R_{ci}	material recovery cost of one ton of type *i* material
W_{ri}	weight of type *i* material to be recovered in a product
k	number of different type of materials in the product
d_c	cost of dumping one ton of solid waste

On the other hand, the benefit of recycling may be defined as:

$$\begin{pmatrix}\text{Total benefit}\\ \text{from recycling}\end{pmatrix} = \begin{pmatrix}\text{revenue from}\\ \text{used parts}\end{pmatrix} + \begin{pmatrix}\text{revenue from}\\ \text{recovered materials}\end{pmatrix} + \begin{pmatrix}\text{benefit of emission}\\ \text{reduction}\\ \text{from energy saving}\end{pmatrix}$$

or

$$R_e = R_p + R_m + E_r$$

$$R_p = \sum_{i=1}^{x} P_{u_i} \; ; \; R_m = \sum_{i=1}^{y} P_{m_i} \; ; \; E_r = \sum_{i=1}^{y} E_{S_i} \sum_{j=1}^{h} E_{m_j}(E_{C_j})$$

where,

P_{u_i}	revenue of reusable parts
x	number of types of recycled material in a product
P_{m_i}	revenue of type *i* recycled material
y	number of types of recycled material in a product
E_{S_i}	energy saving of recycling type *i* material
E_{m_j}	type *j* emission reduction.
E_{C_j}	external cost of type *j* emission.
h	of types of emissions such as SO_2, particulate etc.

Based on these information, the cost-benefit analysis model of recycling is defined as following:

$$R_{b/c} = \text{benefit / cost ratio of recycling} = \frac{R_P + R_m + E_r}{C_d + C_s + C_r + D_C}$$

$$R_{b-c} = \text{net benefit of the recycling} = (R_P + R_m + E_r) - (C_d + C_s + C_r + D_c)$$

Activity-Based Costing in Demanufacture Practice [Bras and Emblemsvåg, 1995]: Activity-Based Costing (ABC) has received its name because of the focus on the activities performed in the realization of a product. Costs are traced from activities to products, based on each product's consumption of such activities.

The idea of using ABC model in green product design issues is the following: if the consumption of activities relevant to environmental consideration can be traced throughout a product's life cycle, then the cost-tracing efforts become useful in green design. In-depth discussions of ABC can be found in Cooper [1990a, b], Turney [1991], O'Guin [1990]. With respect to environmental costs, Dieffenbach *et al.* [1993] proposed a method used in modeling costs of plastics recycling. A motivating example can be found in Brooks *et al.* [1993] where the authors presented an example to show how ABC and

environmental aspects can be combined in order to give companies the ability to identify more accurately those plants and products which are driving up their environmental expenditures.

In their paper, Emblemsvåg and Bras [1994] concluded that the ABC approach has the best potential for efficient and effective cost assessments in the context of life-cycle green design, based on their review of relevant life-cycle costing approaches. The ABC model was developed in designing the life cycle in the works of Emblemsvåg [1995]; Bras and Emblemsvåg [1995]. In their papers, the authors presented the development of an ABC model that is used in design for demanufacture under the presence of uncertainty. Demanufacture, in their model, is defined as the process opposite to manufacturing, involved in recycling materials and product components after a product has been taken back by a company. The crux of developing an ABC model is to identify the activities that will be present in the demanufacturing process of a used product, and afterwards to assign reliable cost drivers and associated consumption intensities to the activities. Bras and Emblemsvåg concluded that the use of an ABC approach may overcome some of the difficulties associated with conventional LCCA tools; e.g., the lack of common standards. In the long term, a ABC method can be utilized not only for monetary cost assessments, but also for life-cycle assessment of environmental impacts in terms of matter and energy consumption of activities throughout a product's life cycle.

2.3.7. Quality Function Deployment

Quality Function Deployment (QFD) is typically used to evaluate quality elements of a system or product over all phases of the system life cycle. The QFD provides a means of building desired levels of quality into a system, which is conducted early in the design process to enhance the design quality and minimize design changes. This section provides a comprehensive understanding of QFD from various perspectives.

What is QFD ? Quality Function Deployment (QFD) is a planning methodology for translating customer needs into appropriate product features. QFD has been described in excellent articles by Sullivan [1986] and by Hauser and Clausing [1989]; and introduced in books by King [1989], Akao [1990], Cohen [1995]; it is also rapidly gaining acceptance in many applications including ECDM. Quality Function Deployment (QFD), as defined by Akao [1990], is:

> *"converting the consumers' demands into quality characteristics and developing a design quality for the finished product by systematically deploying the relationships between the demands and the characteristics, starting with the quality of each functional component and extending the*

deployment to the quality of each part and process. The overall quality of the product will be formed through this network of relationships."

QFD is a method for developing a *design for quality* aimed at satisfying the consumer and then translating the consumer' requirements (needs) into design targets in terms of product characteristics and technique requirements throughout product development. According to Sullivan [1986], QFD is the mechanism used by the manufacturing company to bring new products to market sooner than the competition with lower cost and improved quality. QFD is a structured methodology/process, and a set of inter-linked engineering (with systems engineering and concurrent engineering) and management charts that use the seven management tools for product development and production planning.

QFD and TOM. Quality support techniques can be generally divided into on-line and off-line approaches [Swift and Allen, 1992]. On-line systems, like statistical process control (SPC) and shop-floor quality circles, have been widely used in the manufacturing industry over many years.

On the premise that prevention is better than detection and correction, the off-line techniques are developed, including QFD, Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Taguchi Methods, and Poka Yoke. These techniques are briefly reviewed by Swift and Allen [1992]. Linking on-line and off-line approaches, QFD is a quality support tool that is often examined to show how QFD and Design of Experiments (DOE) help implement Statistical Process Control (SPC) to achieve the goal of TQM [Wahl and Bersbach, 1991]. In practice, Lorenzen and his coworkers [1993] integrated QFD, DOE, SPC and process capability into a process for achieving total quality of electronic multichip modules. Similar efforts are referred to [Parvey, 1994]. In the context of environmental considerations, if we see the environmental quality as one of quality factors, then ECDM can be viewed as one quality support technique to increase environmental quality through green engineering process and DFE rules. QFD is then examined to show how QFD can help incorporate environmental factors and requirements into product design process.

In addition, the prioritization is always a problem in practice. Analytic Hierarchy Process (AHP), as one of tools for prioritization, has recently been related to QFD; see Zultner [1993] and Armacost *et al.* [1994]. Linking QFD, SPC and AHP, Xie *et al.* [1995] applied (AHP) technique to prioritize an SPC planning through QFD-process.

Using Fuzzy Set Theory in QFD Planning Matrix. In QFD operation, relationship matrices are used to describe the relations between different customer needs, between different design requirements and between customer need and design requirements. These relations may be expressed using linguistic need or crisp variables. Linguistic variables are characterized by ambiguity and

multiplicity of meaning. In such cases, the so called Fuzzy Quality Function Deployment (FQFD) approach is employed [Khoo and Ho, 1996]. Based on possibility theory and fuzzy arithmetic for QFD operation, Knoo and Ho developed the FQFD approach to handle both linguistic and crisp variables in a ratings generation. With the resultant ratings expressed in terms of ranges of values, the FQFD approach was able to provide an overall picture about the design requirements and could help to ensure that the decision made in the selection would not be biased. FQFD approach-related works are referred in Wasserman and his colleagues [1993], Verma [1994], Bahrami [1994], and S. K. Lee [1995].

Applications of QFD with Environmental Considerations. QFD is typically applied to small subsystems. In addition to the linkage among QFD, DOE, and SPC, Dean [199?] describes efforts to extend QFD to large-scale systems. It links QFD to the system engineering process, the concurrent engineering process, the robust design process, and the costing process. The effect is to generate a tightly linked project management process of high dimensionality. Similar efforts on QFD-integration can be found in the book by Bicknell and Bicknell [1995]. They integrate QFD with other methodologies: system engineering process, concurrent engineering, business reengineering, process improvement, design for experiments, and integrated product design, as the so-called the *Repeatable Success Method*™ (RSM™), where QFD is the heart of RSM™ because it provides that link between strategy and implementation.

To date, QFD has been used as a decision-making analysis tool in environmental compliance, waste reduction, and environmental processes. Bicknell and Bicknell [1995], in their book, illustrate how QFD analysis is employed to solve specific problems in: a small business, an educational setting, the manufacturing process, and in manufacturing safety compliance, waste reduction, environment clean-up, and new product development. These real-case studies demonstrate that not only is QFD used, but it is used to great advantage in diverse businesses and organizations, especially in environment-related applications. Taking the advantages of QFD that play as coordinator of different methodologies, the approach of QFD-based environmentally-conscious product design and manufacturing will be proposed in our research.

The life cycle approach is required for applying QFD in the ECDM approach thereby, incorporating environmental requirements into the QFD-process to achieve the goal of ECDM. As stated by Overby [1991]: because of a rising tide of environmental concerns these days, customer 'wants', a beginning point in QFD, now include a desire for clean land, air, and water--such that we increasingly hear of consumer demand for 'clean', 'green', and 'environmental-friendly' products and manufacturing processes. Based on understanding the QFD-process, the manufacturing planning phase plays an important role in process design that aims at reduction of environmental impacts [Bicknell and Bicknell, 1995]. By building environmental dimensions into the QFD matrices system, design teams can streamline

their responses to the customer's environmental requirements [Hochman and O'Connell, 1993]. Berglund [1993] argued that QFD can be used to encourage breakthrough thinking about new concepts and technology that focus the environmental activities of the firm to best meet the interests of the stockholders. Another example at the sub-system level (or tactical and operational decision-making levels) can be seen in the work of Hochman and O'Connell [1993]. Doukas *et al.* [1995] addressed a QFD methodology for understanding and integrating user quality factor requirements (usability, reliability, technology, safety, environment, and cost) into system design. A modified AHP is then used to determine the relative importance of each requirement. In a practical design problem, Halbleib *et al.* [1993] applied QFD to the design of a lithium battery, where environmental requirements (personnel safety, ease disposal, and ECM implementation) have been incorporated into a QFD/HoQ matrix. However, none of the above examples consider the integration of QFD and LCA for measurement of environmental impacts.

QFD can be seen as a methodology partly based on, or as a practical addition to, the "Principles of Design" by Suh [1990]. Other studies include one using the Axiomatic Design approach and applications (Albano and Suh [1992]), one on a performance-based design tool (Albano *et al.* [1993]), and one on information-based design involving environmental issues (Wallace and Suh [1993]). A number of other references to the application of Suh's design axioms in both product design and manufacturing process design can be seen in Gebala and Suh [1992]; King and Suh [1991]; Kumar and Suh [1988]; Park and Suh [1993]. This is also a potential research topic to show how environmental requirements can be incorporated into the requirement matrices of Suh's design equations. Bascaran and Tellez [1994] address the apparent inconsistency between QFD and Axiomatic Design, then describe how both concepts can be used in harmony to improve the conceptual product design process.

Formulation of QFD-based Optimization Problem. QFD-based optimization means the formulation efforts using QFD-related information to construct a mathematical model of the optimal design. In such an approach, the question is how can QFD be used in this optimization problem setting and what elements of QFD represent design variables, constraints and objectives. In order to extract and interpret the information useful for the optimization problem, Prasad [1994] has proposed an general QFD-based optimization problem, which is formulated as a multi-objective program. Locascio and Thurston's [1993 and 1994] work, based on multi-attributes theory application, also formulates the optimal design problem by using QFD information, where the objective function is expressed by a multi-attribute utility function. We believe that a QFD-based optimization approach can provide a systematic and useful way to formulate an optimal design problem.

2.3.8. Multiple Criteria Decision-Making

Design is typically a decision-making process. Decision-making methods can be employed in solving the engineering systems-design problems. The idea of design decision-making in general and in the IECDM methodology in particular is the selection of the 'best' alternative or of an optimal combination of alternatives to satisfy the desired objective and requirements, for example, customer preferences, environmental regulations, or a company's profit. The main sources of difficulty in achieving proper evaluation of the alternatives are:

1) *uncertainty*, the difficulty in predicting the results following design action and in the complexity of the analytical solution for evaluation of alternatives; and
2) *multiple attributes* (*or multidimensional*), which make it difficult (i) to establish a common scale for the multidimensional outcomes of the problem and (ii) to make value trade-offs among variable levels of different attributes. For example, the difficulty in design evaluation based on environmental impact assessment is to find ecounits of different environment-relevant attributes.

In the green engineering context, ecological product development plans should be evaluated in terms of criteria (or factors) of economy, function, technology, and ecology. Therefore, Multiple Criteria Decision-Making (MCDM) methods, by their nature, are useful tools in IECDM methodology. In this section, MCDM and its relevant characteristics are briefly reviewed.

The Types of MCDM Problems. The problems of MCDM are widely diverse. However, as mentioned by Hwang and Yoon [1981], all the MCDM problems which are considered share the following common characteristics:

1) *Multiple objectives/attributes*: A decision-maker must generate relevant multiple objectives/attributes for each MCDM problem setting.
2) *Conflict among criteria*: Multiple criteria usually conflict with each other. For example, in ecological system design, the objective of lower environmental impacts might increase the system cost in the short term.
3) *Incommensurable units*: Each objective/attribute has a different unit of measurement. For example, in the environmental loads measure, material stream is expressed by kg per kg material stream, and energy flow is by kg per kj of energy stream, and environmental costs are by dollars, etc.
4) *Optimization design/Alternative selection*: Solutions to these MCDM problems are either to design the best alternative in search space constructed by design decision variables or to select

the best one among previously specified finite alternatives in design space established by dependent parameters. The (eco)design process may be viewed as a MCDM method that involves iterative designing/searching procedures for the most attractive alternative.

The MCDM problems are broadly classified into categories: 1) Multiple Attribute Decision Making (MADM), and 2) Multiple Objective Decision Making (MODM). In actual practice, this classification is well fitted to the two facets of problem solving: MADM is for alternative selection which goes through the design evaluation process within design space, while MODM is for searching which goes through the design optimization process within search space. This widely accepted classification has the following major contrast features (Table 2.5).

Table 2.5. General comparison of MODM and MADM features in design decision-making

	MODM	MADM
Objective	Explicit	Implicit
Attributes	Implici[t]	Explicit
Constraints	Active constraints	Inactive restriction
Alternatives	Infinite number, continuous	Finite number, discrete
Solution space	Search space	Design space
Usage	Design optimization	Alternative selection/evaluation
Interaction with decision maker	Mostly	Not much

(1. Attributes may be incorporated into objectives in function equation form. 2. Constraints may be incorporated into attributes.)

MCDM problems can be solved using several solution principles, depending on the characteristics of the problem [Korhonen *et al.*, 1992]:

- If only few alternatives are considered under a small list of criteria, it is possible to check all possibilities.
- If the problem has few criteria and many alternatives, a possible solution method can be multiple objective programming or goal programming.
- If the problem has few alternatives and many criteria, the Analytic Hierarchy Process (AHP) is a widely used method.
- In the case of many alternatives and many criteria, the problem may become too complex for analytical models.

Multi-Attribute Decision Making (MADM) Problems: In MADM problems, there is usually a limited number of predetermined design alternatives. The design alternatives have associated with them a set of achievement of attributes with levels, which may not necessarily be quantifiable and same scale (unit), based on the final design decision is to be made through an appropriate process or methods (e.g., Analytical Hierarchy Process, AHP). The set of attributes might generally include three

major grouping factors: economical factors (e.g., life-cycle cost, manufacturing cost, environmental costs), functional factors (e.g., reliability, maintainability), and ecological factors (e.g., pollutants, energy, waste, and air emissions), etc. Because multiple attributes are involved, the outcomes for the design decisions are multidimensional (i.e., no unified scale). Thus, this type of decision problem becomes naturally a problem of multiattribute design evaluation under uncertainty. The final selection of design alternatives is made based on inter and intra attribute comparisons. The common characteristics of MADM methods are that they generally process: (1) an expression of the MADM problem, generally represented as a structured attributes diagram and expressed in a decision matrix form; (2) a weighing of attributes for prioritization; and (3) a series comparison among attributes.

The MADM problem is characterized by a set of distinct alternatives $\left(C_1,\ldots,C_j\right)$ evaluated on a number of attributes $\left(E_1,\ldots,E_j\right)$. Mathematically the MADM problem can be represented as follows:

$$\text{Select } \left\{\text{Alternative } C_1,\ldots,\text{Alternative } C_j\right\}$$

$$\text{Subject to } \left\{\text{Attribute } E_1,\ldots,\ \text{Attribute } E_k\right\}$$

The selection is always based on maximizing a mult-attribute value or utility function. In the literature [Korhonen *et al.*, 1992] MADM is also known as a multiple criteria decision analysis, a discrete MCDM, or evaluation problem (either for design or project evaluation).

Multi-Objective Decision-Making (MODM) Problems: MODM is not associated with the design decision-making where the feasible design alternatives are predetermined and overdesigns are preavoided. The motivation of these models is to design the 'best' design alternative by considering the various interactions within the design constraints (search space). The set of separating objectives might include economical issues, functional issues, and ecological issues, which makes multidimensional outcomes for decision-making possible. The final 'best' design alternative satisfys the decision maker by attaining some acceptable levels of a set of some prespecified quantifiable objectives. The common features of MODM methods are that they process: (1) a set of quantifiable objectives; (2) a set of well defined constraints; (3) a process of obtaining some tradeoff information, implicit or explicit, between the stated quantifiable objectives, and also between stated or unstated non-quantifiable objectives [MacCrimmon, 1974].

Mathematically the MODM problem can be expressed as follows:

$$\text{Maximize } \left\{f_1(\overline{E}),\ldots,f_l(\overline{E})\right\}$$

$$\text{Subject to } g_l(\overline{E}) \le B_l,\ \ l = 1,\ldots,m$$

where $\overline{E} = (e_1, \ldots, e_n)$ denotes n decision variables which are a kind of attribute, $f_i(\overline{E})$ represents i conflicting objectives, and $g_i(\overline{E}) \leq B_i$ represents m constraints. MODM is a mathematical programming type and it is also known as continuous MCDM, or design search problem. The MODM problems are solved by finding efficient solutions. An efficient solution is a feasible solution which is not dominated by any other solutions in terms of the achievements of the objectives [Korhonen *et al.*, 1992].

Design Using MCDM Approaches. Applying Multiple Attribute Utility Theory (MAUT) in the context of Design For Recycling (DFR), Zussman *et al.* [1994] have developed a quantitative assessment methodology to support product design for the 'end-of-life' or recycling phase. Two aspects are critical for this assessment: First, it is necessary to combine multiple design objectives such as cost minimization (or profit maximization) and waste reduction in terms of multiple-objective utility functions. The choice of objectives depends on the designer and the goals of the company. Second, the uncertainty regarding future recycling conditions such as the price for raw materials, the refinement of process technologies, and the development of dumping fees and regulations need to be considered. Both of these aspects have been dealt with by integrating probabilistic design methods into the concept of utility theory to incorporate both future uncertainties of recycling options and multiple recycling objectives in the design evaluation.

Applying the fuzzy set for Multi-attribute Decision Making (MADM) in the context of recycling, since the disassembly process of a product is characterized by uncertainties due to usage influences on the product, the methods of MADM under uncertainty can be used. Hentschel *et al.* [1995] have introduced an approach to the planning of cellular recovery systems for worn-out products. In their paper, the formulation of the part families is based on usage attributes in addition to the design attributes. Grouping is done by a fuzzy algorithm, allowing a description by membership functions to what degree a special group belongs to a certain part family for recovery options.

Applying the Loss Function for decision-making in the context of recycling, disposal costs were identified to have a significant effect on the economic viability of ECDM. The cost of disposing of a product is very difficult to estimate in the development phase [Züst and Wagner, 1992]. These costs can be calculated only if the condition of the product at the time of disposal is known ahead of time. But this can be known only if the value of the product during, and at the end of its life can be estimated. Therefore, by extending Taguchi's loss function, Vadrevu *et al.* [1994] have proposed a model for value over the life of a product based on the relationship between a time-varying quality characteristic and the associated benefit and loss, in order to determine the time of product disposal; however, the model is only for that single quality characteristic. This model may give the direction for developing a more general,

time-varying multivariate loss function for evaluating the value of the product in general and the value of its environment-relevant quality.

Lately, a number of authors are using more decision analysis methods to assess the trade-off considerations of life-cycle analysis in ECDM implementation. Among them, Analytical Hierarchy Process (AHP) technique is most used. The AHP has received considerable attention by research groups in product system design, such as the U.S. Environmental Protection Agency [EPA, 1993a], Sandia National Laboratories (SNL) [Gockel and Watkins, 1993], and the ECDM Laboratory of the University of Windsor [Johnson and Wang, 1994]. This well-structured method of decision analysis does provide a sound method of evaluation in a hierarchical approach. During their AHP-relevant research, Salo and Hamalainen [1993] developed a new preference programming method, drawing from the classic AHP method. Adapting Salo and Hamalainens' method, Johnson and Wang [1994] provide their methodology to allow the design group to negotiate the trade-off considerations of product design. In their model (Figure 2.17), both traditional aspects and the newly considered life-cycle criteria may be negotiated among the concurrent engineering team to determine an appropriate design that fulfills the traditional elements of design (e.g., performance and reliability) as well as environmental criteria and specifications. This approach provides a way to aggregate the compatible design factors and negotiate the non-compatible factor group.

Multi-attributes Evaluation Approach on Product Design and Material Selection. The environmental compatibility of a product must be viewed as an important aspect (attribute) of the design process. However, unavoidable tradeoffs must often be made between environmental impact, economics, customer preferences, reliability, manufacturability, and other attributes. In addition, tradeoffs between environmental impacts that occur at different phases of the life cycle might be necessary.

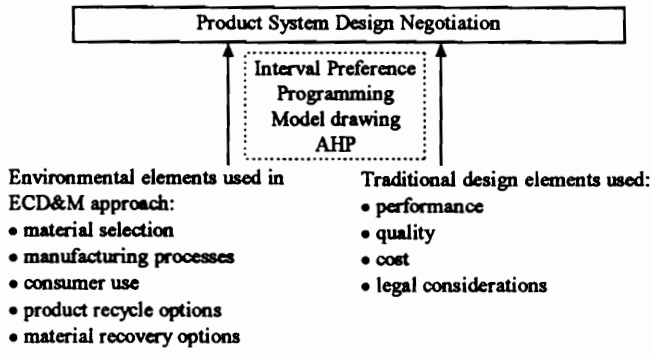


Figure 2.17. Product design negotiation and environmental compatibility [Johnson and Wang, 1994]

It is generally believed that the primary driving force in the engineering design process, especially in the life-cycle design process, should be the *overall value* of the manufactured product. Determining this value, according to Thurston [1994], requires simultaneous consideration of traditional engineering design issues and manufacturing costs, along with environmental impacts. Rather than post-activities (e.g., detect, assess, and respond) to the environmental impact after the fact, the design process associated with pre-production activities should be continually driven by an (eco-design) evaluation function that recognizes potential environmental impacts. Like the conventional design evaluation function for trade-off analysis, this eco-design evaluation function must reflect the fact that tradeoffs between economic (e.g., manufacturing cost and environmental cost), functional (e.g., product performance), ecological (e.g., environmental impact), and technical (e.g., green techniques) requirements of the system must be made. Such trade-off issues can be achieved by several methods, including Pugh's method [Pugh, 1991], weighted sum methods, multi-attribute utility analysis [Thurston, 1991], fuzzy set analysis, and the Analytic Hierarchy Process (AHP) method [Satty, 1988]. These methods offer varying degrees of ease-of-use and sophistication, but each method helps the designer deal with conflicting attributes by separately defining multiple attributes or characteristics of a design and addressing their relative importance or the willingness of the decision-maker to make tradeoffs between them [Thurston and Blair, 1993].

By extending the Evaluation Driven Analysis (EDA) methodology, which directly incorporates multiple attributes into the design decision-making process, developed by Thurston *et al.* [1991], Thurston and Blair [1993] have presented a multiattribute-based methodology that directly integrates environmental considerations into the engineering decision process (see also Thurston [1994]). The authors' approach is to perform concurrent multi-attribute design evaluation early (i.e., AHP) in the design phases (for doing trade-off analysis between 'Design for Environmentability' attributes and different phase of the life cycle) to simultaneously consider all conflicting and non-conflicting attributes. The end result is the determination of the overall value of each design alternative. An example of material selection based on this multi-attribute evaluation approach is also illustrated in the work of Thurston [1994].

Material selection is normally based on optimizing material preference according to functional requirements, geometry, and the properties of the material [Ashby, 1992]. Accordingly, Ashby has developed sets of tables that summarize the relationship between material properties and engineering requirements. On material selection, Zenger [1993] has also conducted research to develop a materials/process ranking system that makes the decision based on the combination of material property and manufacturing process. In the context of environmental impacts considerations, the environmental impact due to processing materials has been increasingly noticed. Appropriate material selection and processes design can largely reduce impacts (e.g., pollution) on the environment. Thurston and Blair

[1993] and Thurston [1994] have begun to incorporate environmental issues into concurrent design to perform concurrent material selection in the early design phase by using multi-attribute evaluation methodology. On the basis of the cost-benefit analysis model [R.W. Chen, *et al.*, 1993], a systematic methodology of material selection has been proposed by Chen, Navin-Chandra, and Prinz [R.W. Chen *et al.*, 1994], which has involved consideration of the impact that products have on the natural environment. Nevertheless, materials/processes selection has been recognized as an important way to reduce environmental impacts. It should be integrated into life-cycle design approaches.

Design Using Selection Decision Approach. With respect to design decision-making, to support the design-decision process, the crucial research in environmentally conscious design is to provide engineers the following key elements [VerGow and Bras, 1994]:

- attribute metrix for assessing environmental aspects such as matter and energy consumption, economic cost, quality, etc.
- associated engineering design models (processes) to compute these metrix, and
- decision support tools based on these metrix and associated models to support trade-off assessments and decision-making in environmentally conscious design.

Certainly, these key elements must also be suitable to the traditional aspects of design criteria, models and trade-off analyses, since the environmental and traditional criteria are considered simultaneously in green product design.

Among the design decisions approaches, Decision-Based Design (DBD) is offered as a starting point for the creation of design methods that are based on the notion that the principal role of engineers, in the design of an artifact, is to make decisions [Mistree *et al.*, 1990]. Based on the requirement of these key elements for design decision-making, a selection Decision Support Problem (DSP) model for design, which can be viewed as the process of implementation of MADM, has been proposed by Mistree and his co-workers (Bascaran *et al.* [1989] and Mistree *et al.* [1990]). DSP is being developed and implemented to provide support for human judgment in designing systems that can be manufactured and maintained. The selection DSP model facilitates the ranking of attributes based on multiple attributes of varying importance. In DSP selection both science-based information and experience-based soft information can be used. The structure of a selection DSP is given as following:

Given A set of feasible alternatives	
Identify	The principal attributes influencing the selection.
	The relative importance of these attributes.
Rate	The alternatives with respect to each attribute.

Rank The feasible alternatives in order of preference based on the attributes and their relative importance.

The steps for solving a selection DSP are as follows:

Step 1: Describe the alternatives and provide acronyms

Step 2: Describe each attribute; specify the relative importance of the attributes and provide acronyms.

Step 3: Specify scales, rate the alternatives with respect to each attribute.

Step 4: Normalize rating.

Step 5: Evaluate the merit function for each alternative.

Step 6: Post-solution sensitivity analysis.

Further details on formulating and solving selection DSPs is provided in the book by Mistree and his co-workers [Mistree *et al.*, 1995].

The DSP model has been applied to fasteners for recycling [Mistree *et al.*, 1990]. As an example of selection DSP in design for assembly, Simpson and his coworkers [1995] adapted the DFA method for use in conceptual and embodiment design through the use of DSP. In another example of using DSP in recycling issues, VerGow and Bras [1994] showed how DSP is used in the selection of recycling-oriented fasteners. In product recycling (also refereed to as reuse) non-destructive disassembly is desired, whereas in materials recycling destructive disassembly is allowed. This distinction has an impact on the selection of fasteners. Using the selection DSP model, the authors evaluated the selection of fasteners in the context of product recycling and material recycling, by adopting "fastener selection table" elements as the attribute metrix in the DSP model. As a result, the appropriate fastener can be selected for three design scenarios, namely, design for material recycling, design for product recycling, and design for strength and ease of assembly.

2.3.9. Ecomanufacturing and Ecofactory

When the environmental issues associated with industry are considered, it is common to focus on the waste generated during the production process and to classify and manage industrial waste and associated environmental problems by the physical state of the waste. To reduce the waste and pollution during production stage, manufacturers may set up "greener" production systems, such as implementing a "eco-factory".

Essential Definition of Eco-Factory (Inverse Factory). Recycling of products to obtain raw materials or reuse components is an important means of reducing disposal costs and increasing total

product value. In demanufacturing processes, remanufacturing involves refurbishing and/or partially rebuilding a product returned from the market at the end of its life to give it the functionality of a new product, and has been identified by a number of companies as a major-source of cost saving and thus competitive advantage [Berko-Boateng, *et al.*, 1994]. Effective recycling and remanufacturing require ease of product recovery through disassembly or separation, performance and market acceptance of the recycled materials and components, and the environmentally responsible disposal of non-recovery remaining after recycling [Henshaw, 1994]. Reuse in demanufacturing schemes is the highest form of waste reduction and has the potential to reduce end-of-life cost for products. Reuse may be easily justified in the case of components with high manufacturing costs, long innovation cycles and long life times [Jovane, *et.al.*, 1993]. All of these issues should be considered in design of the *Eco-factory* or *Inverse Factory*.

The concepts of eco-factory come from the Japanese. The major driving force for the development of ECM practices and technology for the Japanese is not only for competitive advantage, but also because of environmental necessity, primarily due to Japan's limited geographical area and natural resources. The eco-factory practices are increasingly incorporated into manufacturing strategies of major companies. The environmentally (or ecologically) conscious manufacturing system, the Eco-manufacturing system or Eco-factory, could contribute significantly to reducing ecological (or environmental) loads, such as energy and resource consumption, industrial waste, and use of harmful materials, and could contribute to the solution of environmental problems. The aim of designing a Eco-manufacturing system is to harmonize manufacturing activities within the global ecological loop. According to Hattori and Inoue [1992], the Eco-factory can be evaluated by the following:

> "*reduction of its influence to environment damage than today, no declination of productivity and economy of manufacturing process, and high added value products.*"

This implies that the closed-loop Eco-factory should be evaluated both by environmental (ecological) criteria and by conventional criteria such as economy, productivity, performance, and marketability. Environmental loads have seldom been taken into consideration in conventional manufacturing activities. The closed Eco-manufacturing system that aims at reduced consumption of energy and resources, and enhancing the recycling process, is desirable and necessary. An overview of the Eco-manufacturing system is illustrated in Figure 2.18.

A similar concept is proposed in the work of Dario *et al.* [1994]. They defined so-called 'inverse' factories that, by operating in symbiosis with the more traditional factories, would close the loop of the production cycle (design-assembly-utilization), open new perspectives of development for industrial automation and eventually affect even some macro-economic aspects of the industrial world. As they claimed, the inverse factory could lead to the full implementation of the concept of 'integrated design,'

that is the design of products that are conceived not only to be assembled and used, but also to be totally and efficiently disassembled and recycled.

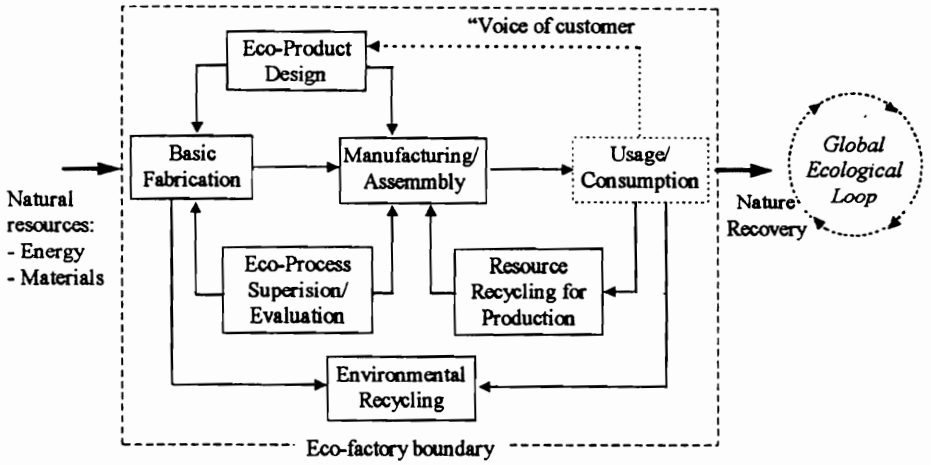


Figure 2.18. Overview of environmentally conscious manufacturing system

Technology-oriented Eco-factory and Demanufacturing Strategies. The concepts of Design For Environment are also employed in design for manufacturing processes in the factory, called *eco-factory*. Ecofactory's initiatives focus primarily on various manufacturing technology strategies. The major emphasis for manufacturing technology is on production systems, restoration systems, and control and assessment technology [Sarkis, 1995]. Eco-factory technology is aimed toward the protection of the environment and the effective use of the world's resources in industry. In a sense, eco-factory is viewed as a physical system derived on the basis of the ECDM approach to implement Industrial Ecology. Various technologies within each of these groupings are shown in Figure 2.19. These technology-oriented strategies are currently driving some of the domestic corporate ECM research and development.

Manufacturing Systems with Recycling Application. Recycling has been recently recognized as one of the effective tools for solving environmental problems. Therefore, in the design of future manufacturing systems, the recycling of materials used should be taken into consideration.

Hoshino, Yura, and Hitimi [1995] constructed an optimization model that is used to maximize two measures of performance: total profit and recycling rate, for a recycle-oriented manufacturing system. Then the model was analyzed by a goal-programming method with the objective of enhancing the recycling rates as well as optimizing the firm's profit. Different recycling rates were defined, corresponding to three types of parts: re-usable part, not re-usable but re-producible part, and not reproducible/not reusable part.

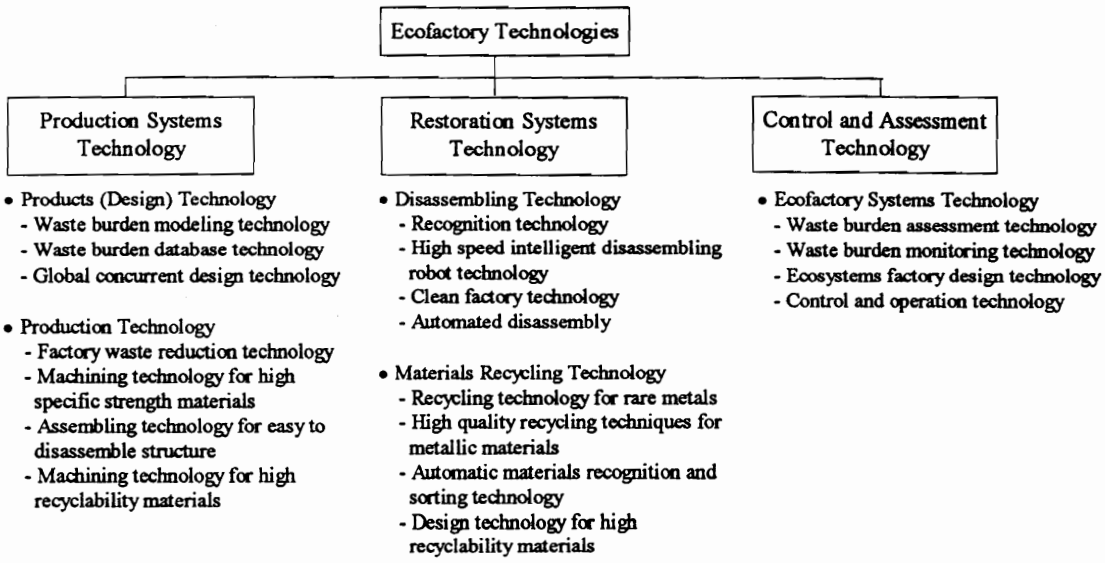


Figure 2.19. Eco-factory technology-oriented strategies.

Ecology-based CIM System. In the research field of life-cycle design, one of the important issues in manufacturing will be how to harmonize manufacturing activities with global ecology. A new concept of an ecologically-conscious manufacturing system, namely an ecology-based CIM system (or Eco-factory), is proposed by Hattori and Inoue [1992]. As defined by the authors, the basic requirements for an Eco-factory are small size, energy-consumption oriented, no use of rare natural resources, and recycling-oriented. Therefore, the Eco-factory can be evaluated by the following: reduction of its influence to damage the environment, no decline in productivity, economy of the manufacturing process, and high added-value products. In the Eco-factory, the manufacturing system consists of a product design technology that aims to develop and design products with a low ecological load, and a production technology that aims for low ecological load production methods. As part of the eco-factory concept, a new estimation and compensation method for determining thermally induced machining error using a neural network technique has been investigated.

Optimal Recycling Number During the Material Extraction Process. Recycling activities could occur during the production stage. One of the features in a plastic extrusion production process is that waste materials are created, reground, and mixed with virgin plastic raw materials for use in subsequent (extrusion) production cycles. The recycling of these waste materials helps to reduce the cost of using the more expensive virgin raw materials. However, the yield from the overall extrusion process

decreases as a result. Therefore, Ladany and So [1994] developed a model to determine the optimal number of regrinding cycles efficiently reusing these waste materials during the extrusion production process. The objective is to maximize the average profit per production batch.

(Intelligent) Automated Disassembly. Disassembly activities are critical in Eco-factory for use in the demnaufacturing process. As a part of the Eco-factory technology as shown in Figure 2.14, an automates disassembly system is proposed for ecologically conscious manufacturing to protect our environment and to recycle the resources [Shibata and Tanie, 1994]. They used the multi-task-fusion technology for achieving automated disassembly by multiple robots and suggested a concept of an automated disassembly automation system for production.

As a consequence of uncertainty of disassembly characteristics, an automated disassembly system should deal with environments characterized by a higher degree of uncertainty than in the case of assembly tasks. Dario *et al.* [1994] have suggested the 'integrated design' as a power tool for reducing such uncertainty: if a specific product has been designed properly, an automated system for disassembly could be considered as operating in a partially structured environment. However, such integrated design is not always possible. Therefore, intelligent techniques are applied to design an automated disassembly system. Other works can be found in Shibata and Tanie [1993]; Dario and Rucci [1993]; Fukuda and Shimojima [1993].

2.3.10. Nontraditional Manufacturing Processes

Advances in recent years in science and engineering present new and significant challenges to the materials-processing industry. There is an acute need to develop new manufacturing methods and to improve existing techniques that are capable of economically and ecologically manufacturing advanced materials in order to reduce impacts on the environment. Research has increasingly been conducted for integrating different nontraditional manufacturing (NTM) and traditional manufacturing processes into CAD/CAM and FMS systems under the concerns of the Eco-factory environment.

Why Nontraditional Manufacturing Processes ? According to Rajurkar *et al.* [1992], customer requirements have imposed the following three major conditions for the development of manufacturing technology, namely nontraditional manufacturing or machining (NTM) processes, in the middle and late 1990s:

1) Rising overhead, capital equipment, and labor costs dictate that production operations be automated as far as possible;

2) The vastly superior properties of innovative materials such as superalloys, composites, and ceramics require new manufacturing techniques; these materials simply cannot be processed with traditional machining methods; and
3) The soaring of the disposal of industrial waste and increasingly stringent environmental regulations necessitate the development of environmentally self-contained processes which generate a non-toxic waste stream.

Obviously, these conditions (especially the third) are also major reasons for implementing ECDM strategies for eco-manufacturing. The special need for NTM has existed for some years and its importance continues to grow. For example, many advanced materials cannot be machined by traditional means. The complexity and required surface quality of machined parts, tools, and dies have increased. The environmental impact concerns of machining materials have also dramatically increased.

Characteristics of NTM Processes. NTM processes may be broadly categorized in two ways [Rajurkar *et al.*, 1992]:

(1) Manufacturing processes in which there is a nontraditional mechanism of interaction between the tool and the workplace; and
(2) Manufacturing processes in which nontraditional media are used to effect the transfer of energy from the tool to the workplace.

Nontraditional interaction mechanisms include chemical, electrochemical, thermal, and mechanical with high impact velocity. Nontraditional media include solids, abrasives, non-Newtonian fluids, aqueous and non-aqueous liquids, gas, plasma, ions, electrons, and electromagnetic waves (photons). Table 2.6 lists the NTM processes and their general characteristics [Kalpakjian, 1995]. The last column points out a potential investigation on environmental impact concerns for each NTM process. Little work has been done on estimating the adverse environmental impacts of the NTM process so far; however, we believe that more attention should be paid to such research, because, in the context of DFE, materials design and selection affect not only the choice of traditional manufacturing processes but also the choice of NTM processes and recycling strategies.

As mentioned earlier, the subjective elements in the ECDM model are: Pollution prevention, Waste minimization, and Energy consumption reduction. These may be achieved by raw materials selection, operating procedures, process modification, recycling, and the use of NTM processes. For example, the Abrasive Water-Jet (AWJ) process offers environmental benefits versus traditional methods of machining graphite aerospace structures with lowered noise levels, complete elimination of dust and maintenance of ambient air temperature in the shop; thus, AWJ manufactures a broad spectrum of traditional and nontraditional materials with minimal adverse environmental impact. NTM processes

Table 2.6. General characteristics of NTM processes [Cf.: Kalpakjian, 1995; with modifications]

NTM processes	General Characteristics	Process parameters and Typical material removal rate or cutting speed	Ecological, quality, and economic concerns
Chemical machining (CM)	Shallow removal (up to 12 mm) on large flat or curved surfaces; blanking of thin sheets;	0.0025-0.1 mm/min.	Low tooling and equipment cost; suitable for low production runs.
Electrochemical machining (ECM)	Complex shapes with deep cavities; highest rate of material removal among nontraditional processes;.	V: 5--25 dc; A: 1.5--8A/mm^2; 2.5--12 mm/min., depending on current density.	Expensive tooling and equipment; high power consumption; medium to high production quantity
Electrochemical grinding (ECG)	Cutting off and shaping hard materials, such as tungsten-carbide tools; also used as a honing process; high removal rate than grinding.	A: 1--3 A/mm^2; Typically 1.5 cm^3/min. per 1000A.	
Electrical-discharge machining (EDM)	Shaping and cutting complex parts made of hard materials; some surface damage may result; also used a grinding and cutting process;	V: 50--380; A: 0.1--500; Typically 300 mm^3/min.	Expensive tooling and equipment.
Wire EDM	Contour cutting of flat or curved surfaces;	Varies with material and thickness.	Expensive equipment.
Laser-beam machining (LBM)	Cutting and hole making on thin materials; heat-affected zone; does not require a vacuum;	0.50--7.5 m/min.	Expensive equipment; consumes much energy.
Electron-beam machining (EBM)	Cutting and hole making on thin materials; very small holes and slots; heat-affected zone; requires a vacuum;	1--2 mm^3/min.	Expensive equipment.
Water-jet machining (WJM)	Cutting all types of nonmetallic materials to 25 mm and greater in thickness; suitable for contour cutting of flexible materials; no thermal damage; noisy.	Varies considerably with materials.	WJ is an environmentally safe manufacturing process.
Abrasive water-jet machining (AWJM)	High speed waterjects for single or multilayer cutting of metallic and nonmetallic materials.	Up to 7.5 m/min.	AWJ is very attractive economically due to operating time reduction; and with minimal adverse environmental impacts.
Abrasive-jet (or flow) machining (AJM or AFM)	Cutting, slotting, deburring, deflashing, etching, and cleaning of metallic and nonmetallic materials; manually controlled; tends to round off sharp edges;	Varies considerably with material.	AJM processes are finishing operations which presently account for approximately 15% of total machining cost; a hazardous process.
Rapid prototyping (StereoLitheography)	A manufacturing process for rapid production of 3-D parts directly from computer models to reduce time required to bring a product to market. (Technology such as model-making, low-volume manufacturing, free-form fabrication.)		

such as EDM, ECM, and LBM can machine advanced materials independent of their properties; thus they provide more flexibility in material selection in the DFE evaluation process. In addition, ultrasonic assembly[6], a nontraditional assembly technology (NTA), is a clean method commonly used in industry recently.

2.3.11. Integration Approach Issues

Much attention is now being paid to the widespread, chronic lack of integration in design and manufacturing, not to mention integration with demanufacturing/recycling into manufacturing systems and integration of LCA for environmental impact assessment in manufacturing systems. As illustrated in this brief literature review, the impact of environmental issues on product development covers everything from production planning, product production, to product disassembly and recycling, both economically and ecologically. However, none of the above works considers the life-cycle design problem as a whole throughout the product/material life-cycle. In many ways the above types of problem and solution are simply parts (or subproblems) of the whole DFE problem. Systematic integration of environmental considerations into life-cycle engineering and design is needed.

Ecology-oriented product development is not limited to production and marketing. The entire product life-cycle must be considered. Besides green product design, companies have to consider the environmental impact of the product-related processes and of the logistic support. Therefore, an integrative approach is desired that considers three elements (i.e., products, processes, and logistic support) during the whole life-cycle including the recycling phase [Kriwet, 1995]. A number of papers have discussed the importance of the integration approach in green product development throughout the life-cycle; however, there are still no analytical methodology being developed for integration of design decisions throughout a product's life-cycle phases.

Most recently, Reman and Chhajed [1995] provided a decision support tool for implementing an integrated approach that provides a model for determining the number of new products to be introduced, the exact specifications of these products, and the production processes for efficiently delivering these specifications. These decisions are made in an integrated manner by simultaneously considering the interaction among the various choices. By use of conjoint analysis, a decomposition-based solution procedure is developed that iterates between product-design and process-selection decisions while

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[6] Ultrasonic assembly [Lieu and Waskom, 1995] is a fast, clean and efficient method of assembling or processing rigid thermoplastic parts, films or synthetic fabrics. Various ultrasonic assembly techniques are used by all segments of industry to join plastic to plastic, plastic to metal parts or other non-plastic material. Ultrasonic welding can replace or preclude the use of solvent, adhesives, mechanical fasteners, or other consumables which, in turn, may reduce waste and environmental impact.

maintaining an effective link between them. However, this model does not include environmental issues (i.e., environmental regulations and life cycle assessment) and LCA in the product design and process selection. By investigation of various approaches to environmentally-conscious product development and various design paradigms for a green product, a conclusion is made that it is possible to develop a new methodology that combines various approaches and design tools for ecological product development.

Bloemhof-Ruwaard *et al.* [1995] present a methodology to use environmental information within the decision process of formulating fat blends. They have combined three analysis tools sequentially: Life Cycle Assessment (LCA), Multiple Criteria Decision Making (the Analytic Hierarchy Process is used), and Linear Programming (LP). The structure of the methodology is illustrated in Figure 2.20 in which LCA provides a method for calculating the environmental profile of refined oils. AHP is used to transform the environmental profile into an environmental index. LP blending models, containing environmental indices, can improve the environmental impact of fat blends. With this combination of methods, the environmental aspects of products can become part of product portfolio management between purchasers, producers, and marketing people on the issue of green edible fats.

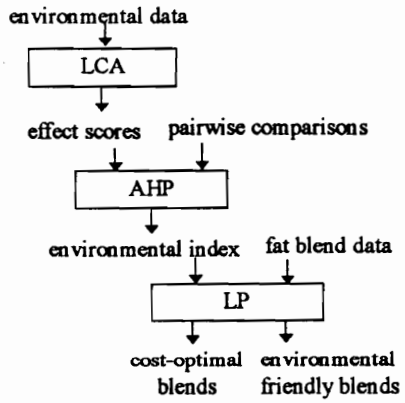


Figure 2.20. Structure of the LCA/AHP/LP methodology [Bloemhofo-Ruwaard *et al.*, 1995]

2.4. SUMMARY OF LITERATURE REVIEW

We summarize Industrial Ecology (IE) and ECDM approaches that are employed in design and ecoproducts and product-related processes in order to prevent environmental impacts. We also show how the literature review helps in the research. Finally, we propose our integrative aspects that are templates of the development of IECDM methodology.

2.4.1. On Industrial Ecology Approaches

The goal of Industrial Ecology (IE) is to eliminate the causes of environmental problems rather than to work to solve them after they become apparent. IE is proactive, not reactive; it is a design-in, not an added-in, approach; it is flexible, not rigid for different system boundaries; it is encompassing, not insular. Environmental concerns in Industrial Ecology are classified as: Global scale concerns, Regional scale concerns, and Large scale concerns [Graedel and Allenby, 1995]. Whereas ECDM is an evolutionary design paradigm that has been developed to achieve the goal of industrial ecology, the ECDM approach is holistic, for the design of eco-products and eco-manufacturing processes to reduce existing and potentially harmful environmental impacts from within manufacturing [Johnson and Wang, 1994]. An environmentally-conscious company determines its own ECDM strategies depending on the boundaries designed in industrial ecology. Implementation of ECDM strategies in a company should be considered as environment-driven design and manufacturing problems that are characterized by:

- The problem should be considered at least company-wide.
- The problem should be broader--crossing throughout the product/material life-span.
- The problem should be treated in a multi-cycles loop system.

In such circumstances, the integrated approaches of system-oriented (e.g., concurrent engineering), life-cycle scheme(life-cycle analysis), and closed-the-loop concepts (recycling concerns) are applied in the ECDM paradigm.

The system-oriented approach requires that the design team consider eco-product design and eco-manufacturing processes simultaneously in the early design stage to achieve a balanced industrial ecosystem. Life-cycle analysis is a tool to evaluate the environmental consequences of a product or process over its entire life from raw material acquisition to final disposal. These is also a growing use of LCA as an evaluation tool. As part of life-cycle analysis, LCA is an environmental assessment technique. LCA has been classified as both a conceptual and a technical framework used to evaluate the environmental performance of a product, process, or activity over the entire product life cycle from the first stage of procuring raw materials to the final stage of waste management. Recycling analysis within a closed loop system requires information from other efforts such as material selection analysis, manufacturing processes analysis, and product utilization analysis; all these efforts incorporating environmental considerations are performed as life-cycle analysis in the ECDM approach.

Within the context of ecodesign of products and processes, the ECDM seeks to discover product innovations that will result in reduced harmful environmental impacts at any or all stages of the life-cycle, while satisfying cost and performance as well as quality objectives. ECDM should be practiced in balance against other design considerations to get the 'best' design. In order for ECDM to be implemented and

integrated effectively into the ecoproduct development process, the following key elements are required throughout the life-cycle stages: life-cycle synthesis, life-cycle analysis, and life-cycle design (evaluation), in order to determine the best alternative with balance among the various design considerations (Figure 2.21).

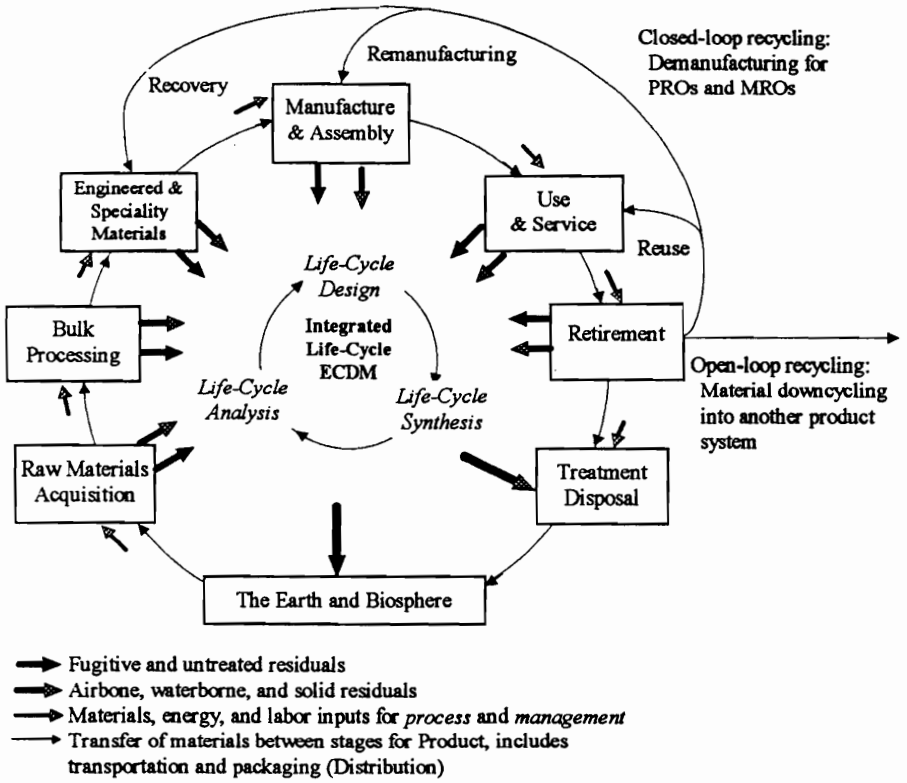


Figure 2.21. A life-cycle approach for implementation of IECDM approach
[Keoleian and Menerey, 1993, with modification]

In the synthesis step, the design team seeks to incorporate environmental issues into other design considerations. Various performance measurements are aggregated together for trade-off analysis. In general, a variety of metrix, driven by fundamental customer needs or corporate goals or environmental regulations, are used to support measurements for products design in various industries. In the analysis step, appropriate methods are used to assess proposed design alternatives with respect to the measurement metrix and to analyze measurements (cost, performance, environment, and quality) trade-offs. In the design step, different designs (either concepts or physical products) may satisfy the customer needs or corporate goals based on an understanding of relevant technologies. The design team needs to determine the best design among them. These interactive efforts (synthesis, analysis, and design) are performed at any stage of the life-cycle.

In addition, it is important for design teams to have an information infrastructure that supports the ongoing application of life-cycle synthesis, analysis, and design efforts. We believe that the successful implementation of the ECDM (and also the LCA) paradigm starts with the acquisition of the necessary data/information and related knowledge. Some of this information is straightforward and related to ECDM, but other data are not. Therefore, industrial engineers (who may become industrial ecologists involving ecological issues) should be willing to approach knowledge needs with a wide perspective. Any methodology (also method and tool) whether or not it applies to ECDM, can often be most effective, if it is adopted appropriately during different stages, either qualitatively or quantitatively.

Summary of ECDM and DFE Scope. The objective of ECDM is to minimize aggregate environmental impacts and risks over the life-cycle of the product system; in order to achieve environmental friendliness in industrial ecology.

The framework for IECDM methodology should be developed to be applicable for all product domains. In addition, the objective of IECDM, and also the goal of industrial ecology, can only be attained through the balancing of environmental, performance, economic (cost), cultural (consumers), legal (regulation), and technical requirements of the product system and service. Concepts such as environmental impacts analysis and life-cycle assessment (section 2.3.1), concurrent engineering and design 'Design For X' approaches (section 2.3.3), design for environment and design for demanufacturing (section 2.3.4), cross-disciplinary design teams, Total Quality Management (TQM) and Quality Function Deployment (section 2.3.7), multi-criteria decision making and trade-off analysis (section 2.3.8), and environmental economics and life-cycle cost assessment (section 2.3.10) are essential elements of the IECDM approach that help meet the goal of industrial ecology.

2.4.2. Observation and Applications from the Literature Review

The categorized literature has been investigated and used in the research. Table 2.7 depicts how categorized subjects are applied, corresponding to each chapter in the dissertation. The problem statement has been presented in the previous chapter. In this chapter a literature review has been briefly provided to show how existing studies relate to ECDM problems. It provides a potential knowledge in modeling for development of the IECDM methodology (Chapters 3 and 4) and modeling methodology for integrating LCA into product development (Chapter 5). A more critical literature review will be described in more detail as necessary during methodology development.

Table 2.7. Subject classification

Subject classification	Purpose of survey	Main finding and application	Number of literature references
Environmental strategies, Industrial ecology, and ECDM	- to provide comprehensive understanding and knowledge on study of the field of environmentally-conscious design and manufacturing - to define the scope of ECDM clearly - to survey papers and articles that are relevant to ECDM, including concepts, planning management, and specific applications	- ECDM is more practice-techniques applications than theoretical approach, which includes both design and manufacturing efforts - no unified definition of ECDM in reviewed articles and books - green design is the focus study of ECDM - life-cycle approach is critical issue in ECDM - it is possible to define a reasonable process for considering environmentally-conscious design and its manufacturing process simultaneously	Industrial Ecology: 9,12,13,16,18,21,42,43,114,143,150,181,195,196,198,199,245,299,306,354,364,368,392,403,408,437,472,484,525,538. ECDM: 1,2,10,15,23,51,58,63,65,69,73,78,84,92,93,94,95,103,104,106,108,112,113,117,128,133,136,149,168,197,219,228,254,269,274,279,288,297,300,301,327,332,337,349,350,359,361,367,373,380,397,399,402,423,428,442,454,461,462,470,473,475,477,485,488,502,512,514,515,516,517,527,529,530.
Life-Cycle Analysis and Assessment	- to understand the concept of industrial ecology and its domain - to review various approaches on environmentally-conscious product development - to study the life-cycle assessment and its applications	- the concept of industrial ecology is the domain of ECDM - LCA techniques are critical in estimating environmental loads of product ant it process - LCA can be a way to integrate other approaches for green product development - any new methodology concerning environmental issues should involve various approaches, especially LCA	3,22,40,74,80,81,125,135,155,167,169,180,192,204,212,234,241,247,259,273,293,312,374,391,409,419,420,431,447,455,480,493,495,520,523,524,544.
Life-cycle design and engineering, Design theory and methodology	- to study various design processes and design methodologies - to study theories that are used in design process and methodology - to study the fundamental design methods and tools - to study design-related	- life-cycle engineering is a key issue in all modern design process and methodologies - no existing single design methodology to date has involved environmental issues in the design process - integrating various design tools and various methodologies is the way for the ECDM	Life-Cycle Design and Engineering: 24,25,26,27,28,29,30,90,154,162,166,176,237,238,242,256,257,258,260,261,262,318,347,357,369,474,494,499,543. Design Theory and Methodology: 6,7,33,36,46,53,70,98,107,124,134,142,147,156,157,163,170,179,184,185,251,252,276,298,307,317,325,328,329,333,344,346,353,356,360,377,387,388,393,401,413,445,446,450,451,456,460,469,483,487,496,501,504,505,532.

	management	process	
DFX, DFM, DFA, and CE	- to review the DFX approaches and applications including assembly issues - to study life-cycle design concepts - to review concurrent engineering concept	- concurrent engineering is also useful to treat the ECDM problem - DFX are proactive design activities that consider downstream activities of product life cycle at as early design stage as possible	DFX: 68,86,130,131,138,145,158,177,183,186,187,262,371,452,518,526,528. DFA: 76,77,132,160,224,225,226,227,290,291,292,331,384,390,417,436,448,459. CE: 8,96,97,100,109,110,111,122,159,189,202,236,239,240,244,246,264,265,282,331,345,362,370,382,389,394,400,457,458,410,411,438,497,513,519,546,547.
DFE, DFR, and DFD	- to study the impact of environmental issues on conventional engineering design process and methodologies, including disassembly issues - DFE paradigms are studies for 'green' product development	- DFE are also proactive design activities, and can be a special area of DFX - DFE involve two major parts: design for disassembly and design for recycling (reuse, remanufacture, recover)	DFE: 11,14,17,19,20,37,64,67,72,79,144,150,161,171,172,173,174,175,189,190,200,206,216,221,222,223,233,250,253,270,296,305,322,323,326,338,448,339,340,341,342,343,351,355,365,398,412,535,414,421,423,424,434,441,443,465,489,500,531. DFR: 32,59,60,88,90,101,140,141,191,210,213,214,243,271,277,283,284,287,319,336,348,389,395,405,415,418,432,435,443,550. DFD: 34,44,45,57,75,105,137,139,146,248,249,267,278,286,289,308,324,379,406,407,427,449,498,503,551,552.
Measurement	- to study tools required for quantitative measure of environmental-related - to study ways to unify the environmental units (ecounits)	- matrix in terms of unified units for life cycle assessment is required for different scope (e.g., area, state, country) - matrix form is still a useful way to express the environmental-impacts factors	8,31,49,71,173,175,429,430,439,440,444,536,537.
LCC and LCCA	- to study the impact of environmental issues on economic of product development - to study the concept and application of life cycle cost	- environmental issues will affect conventional life cycle costing by including environment-related costs such recycling and disposal costs - in green product design, tradeoffs exist between ecological and economic factors	LCC and LCCA: 13,48,102,116,118,123,153,164,207,211,217,218,232,268,295,315,320,372,403,476,482,486,507,521,522. ABC: 82,89,120,121,151,152,201,376,481.

	assessment (LCCA)		
QFD	- to get comprehensive knowledge of structured QFD methodology - to study the potential application of QFD on green product development - to study environmental TQM	- QFD can provide a sound framework for generating a new product design methodology/process by incorporating environmental requirement in the QFD matrix - QFD can be modified as a decision-cooperating system for green product development in generating product-related attributes - structure of the QFD process is suitable for the life cycle ECDM/DFE process	QFD: 4,5,38,39,41,52,54,55,56,61,62,66,83,85,91,115,119,129,148,178,194,203,205,209,220,255,266,272,303,304,311,314,316,321,345,357,358,363,375,378,383,385,396,453,478,479,492,510,539,540,541. Fuzzy QFD: 47,263,294,491,511,545,548. QFD/AHP: 35,302,309,509,549.
Eco-factory and automatic disassembly	- to investigate the design of eco-manufacturing system, eco-factory implementation, and automatic disassembly for demanufacturing and recycling	- intelligent techniques are applied to design automatic disassembly system within eco-factory to deal with uncertainty issues.	Eco-factory/Eco-manufacturing: 182,188,208,215,229,230,285,310,334,335,352,359,366,433. Automatic disassembly: 126,127,330,425,426,490,506,533,534.
Multi-Criteria Decision-Making	- to study how decision-based tools can help in design process while incorporating environmental impacts	- design is a decision-making process - MCDM process can help decision-making in green product development in dealing with multiple attributes simultaneously and design selection	50,87,99,165,193,231,235,275,280,281,313,328,329,386,404,416,422,464,466,467,468,470,471,508,542.
Nontraditional manufacturing	- to find out other factors that affect the environmental impacts	- NTM processes have effects on environment	381.

From the literature review, we present our integrative aspects on ECDM-related problems, which become the template in developing our IECDM methodology. Industrial ecology provides a framework for thinking systematically about environmental problems during the product development process. It looks at the flow of energy and materials through industrial ecosystems: firms, industries, or industrial society as a whole. This whole system approach is key to moving towards environmentally sound industrial development or industrial systems that are sustainable. When adopting industrial ecology to companies, we consider factors of environment, economics, technology, and performance over the full life-cycle of the product or service being provided. The IECDM approach provides an engineering process for ecoproducts design and for achieving the goals and principles of industrial ecology. Integration is the key to successful IECDM development.

2.4.3. Learning for Literature Review: Integration Aspects

Industrial Ecology is currently a broad umbrella of concepts rather than a unified theoretical construct [O'Rourke *et al.*, 1995], which is developed to improve the current state of industry and the environment. In our integration approach, different integration aspects are considered, as shown in Table 2.7, which have led to the complete IECDM approach: QFD-based IECDM methodology, mathematical Cost-Benefit Analysis (CBA) methodology, and Integrative Design Decision-Support (IDDS) system, the first two components are the focus of the research.

Environmentally conscious product/process design problems are a new area and should be treated with care in order to incorporate them in the existing and used product design/development process. Due to the impact of the ecodesign paradigm on the conventional system for engineering design process and evaluation (Chapter 3), a new methodology is required for the green design of a product and its manufacturing processes, which integrates various methods in the engineering design process and various approaches for environmentally-conscious product development. An analytical model is also needed for simultaneous determination of product and processes' design decisions.

Since various tools could be employed for solving the complicated problems in the environmentally conscious industry, we believe that ECDM problems must be developed within an integrated system framework in order to provide useful guidance (or direction) for design decision-making during environmentally sound product development. With the knowledge obtained from the literature review, we will construct an effective integration approach for implementation of ECDM strategies in a firm in order to deal with ECDM-related problems. The integration approach is a useful way to deal with ECDM-related problems of engineering systems design and manufacturing. Such an integration framework is considered from different aspects, as shown in Table 2.8.

The integrative requirements for green product/process design motivates us to develop an IECDM methodology. The literature review provides information for exploring the means for developing the IECDM methodology to support the ecoproduct/processes design and development. Because it has been recognized that recycling issues have effects on product/process design decisions, IECDM models should incorporate issues such as recycling and demanufacturing at the product's end-of-life. Therefore, our approach to development of IECDM methodology is divided into development of the QFD-based IECDM process, the optimization-based Cost-Benefit Assessment (CBA) model, and the design selection-based Integrative Design Decision-Support (IDDS) system. All of them demonstrate how environmental issues (e.g., customer preferences and environmental regulations) affect ecoproduct and eco-processes development and how environmental requirements are incorporated into the ecodesign process. The QFD-based IECDM (Chapter 4) serves as an aid tool for engineering design process and evaluation of a product and its processes, based on the well-defined interactive design evaluation and optimization procedure in the well-structured QFD framework. The optimization-based Cost-benefit Assessment (CBA) is developed based on an unified approach that conceptually defines the integration problem that involves marketing research (customer preferences), environmental requirements (environmental regulations), product design, and system of manufacturing processes with demanufacturing/recycling capacity (Chapters 5) in order for simultaneous determination of product configuration, process selection, and recycling options.

Table 2.8. Integration aspects for IECDM approach

Integration Factors	Extension of Integration Environmentally-conscious Industry	Corresponding research approach (Chapters)
Approaches integration: • Life-cycle (Cradle-to-Grave) • Product flow approach • System-oriented approach	• Industrial ecology • Industrial ecosystem approach • Product/Materials closed loop • Life-cycle thinking (Cradle-to-Cradle)	Design activities integration: • Reviews from various aspects are integrated (Chapter 2) • ECDM is viewed as a green evolution based on life-cycle system engineering to support Industrial Ecology (Chapter 2). • Integrating product design and manufacturing through product life cycle, including recycling phase (in Chapter 3), in engineering system desig process--synthesis, analysis, and evaluation.
Decision factors integration: • Costs (Economic) • Function (Effectiveness) • Technology (e.g., CAD/CAM)	• Life Cycle Cost Assessment (LCCA) • Function (Effectiveness, Greenness) • Technology (e.g., green engineering) or environmentally conscious design • Ecology (Life Cycle Assessment, LCA)	Structured decision-making integration: • Identification of the Integrated ECDM -- IECDM • The model is developed to show how QFD helps the design team on identification system attributes (including greenness attributes) and decide the candidate alternative (Chapter 4).
Product design and development integration: • Marketing research • Product (attributes) design • Production/Manufacturing • Recycling/Demanufacturing	Integration of design decision throughout a product's life cycle phases: • Customer preferences • Ecodesign (green design, DFE) • Materials/Processes selection or environmentally conscious manufacturing • Demanufacturing/Recycling process.	Mathematical integration: • Considering product design, process design, demanufacturing process, and inventory control simultaneously in a production system with recycling capacity. • Integrated cost-benefit model through marketing, product attributes design, process selection with recycling capacity (in Chapter 5 and 6)
Integrative decision support: • System attributes • Environmental factors • Multi-attributes decision-making • Mathematical programming	• Quality Function Deployment • Life-cycle Assessment • Analytic Hierarchy Process • Cost-Benefit Analysis programming or Value-Impact Assessment	QFD-IECDM decision-making process: • A tentative IDDS is developed to integrate QFD, LCA, AHP, and CBA model for dealing with integrative design decision-making support problems. • An example is used to illustrate how environmental information is incorporated into design evaluation and optimization. (Chapter 6)

CHAPTER 3

INTEGRATING ECDM EFFORTS INTO LIFE-CYCLE SYSTEMS ENGINEERING PROCESS THROUGH SYNTHESIS, ANALYSIS, AND EVALUATION

3.1. LIFE-CYCLE ECDM ENGINEERING

3.1.1. Definition of Life Cycle ECDM Engineering

3.1.2. Recycling-Oriented System Engineering Process

3.2. THE IMPACT OF THE ECDM EVOLUTION ON SYSTEM ENGINEERING DESIGN

3.2.1. The Impact of The ECDM Evolution on Conventional System Engineering Design

3.2.2. Qualitative Basis for Green Design Evaluation

3.2.3. Quantitative Basis for Green Design Evaluation

3.3. APPLICATION OF THE SYSTEM MODELING TOOL FOR INTEGRATION

Based on the literature review, the problem in the ECDM domain initially seeks to reduce the environmental impact of design activities and manufacturing operations. It involves a paradigm shift from end-of-pipe control, to meet environmental regulations, and to avoid pollution (impacts) on the environment before the ecodesign products are produced and their manufacturing processes are actually facilitated. Many concepts and approaches related to the ECDM have been proposed and discussed. No common definition of the ECDM, however, has been found to date, nor is there a practical methodology that can be used to implement ECDM strategies for a firm. This lack stimulated the development of an Integrated Life-Cycle ECDM (IECDM) engineering process.

In Chapter 1, we defined our own ECDM problem (see Figure 1.7) within Industrial Ecology, that is, to maximize the product's total life-cycle value (TLCV) while considering environmental issues. The purpose of this chapter is to define an IECDM engineering process, based on Concurrent Engineering (CE) and Life-Cycle Design (LCD), for designing environmentally sound products and processes simultaneously. Then, we will discuss influences on the conventional design evolution process caused by environmental concerns., Both qualitative and quantitative design evaluation techniques are introduced. Finally, we introduce a system modeling tool (i.e. IDEF0) for implementing the ecoproduct realization system to address the relationships among activities of product design, manufacturing, and demanufacturing. This IDEF0 modeling tool also provides a way to develop a mathematical Cost-Benefit Assessment (CBA) model in Chapter 5

3.1. INTEGRATED LIFE-CYCLE ECDM ENGINEERING

Attempts to deal with ECDM problems that associate environmental efforts within the product's life-cycle has led to the need to modify the traditional engineering process in order with to cope the environmental impacts in the product design and development cycle. Simply adding environmental factors, such as disassembability and recyclability, has led to direct analogies of ECDM with the System Engineering process [Fabrycky and Blanchard, 1991]. Therefore, the term IECDM engineering, that embeds environmental factors into the system engineering process, is used in this research.

3.1.1. Definition of IECDM Engineering

IECDM engineering is characterized not only by increasing environmental considerations but also by the extending life-cycle framework. IECDM engineering emphasizes effects to integrate the related-activities of product design, fabrication/manufacturing, assembly/disassembly, demanufacturing[1], and recycling, and to incorporate environmental requirements together with other design factors (such as economic, quality, performance, and time) in green product development. Furthermore, based on the literature review, we believe that life-cycle related works (such as LCA and LCD) and economic evaluations (such as LCCA) should be strongly integrated. Therefore, we denote the IECDM as an engineering methodology that concurrently associates the environmental impacts of a product and its processes, as well as its logistic support, throughout the entire product's life cycle (from cradle to cradle).

Components In IECDM Engineering. The aim of IECDM engineering is to produce an environmentally-friendly system while maintaining other function and quality factors of the system. The environmental impacts of a product during its life cycle are largely determined by its design and by the selection of its manufacturing processes as well as by the design of the operational logistics systems that support it.

Typically, a system is defined as an assemblage or combination of elements or parts forming a complex interrelation [Blanchard and Fabrycky, 1990]. The product system includes four components: product system, manufacturing processes, logistic support, and information/ management (Figure 3.1). On the other hand, in order to make the ecodesign activities better understood, the life-cycle has been extended to a recycling (or demanufacturing) phase for each product system component. These

[1] Demanufacturing is the reduction of a product to its individual parts with the goal of recycling usable parts, remanufacturing certain parts, and reducing the remains to another form. The disassembly processes are of particular concern in the design for demanufacturing. Demanufacturing of a product requires controlled disassembly. Disassembly processes are to recover reusable parts for use in future products. The main demanufacturing costs come from disassembly-related activities.

components should be considered simultaneously while following the system life cycle during the acquisition, utilization, and recycling phases. With respect to IECDM engineering, the last phase of system engineering is not yet fully recognized as a part of the life-cycle in most manufacturing companies, but is becoming increasingly important. We call this last phase the *recyclization phase* (or the demanufacturing phase, or the recycling/disposal phase). Note that the added recycling phase results from environmental considerations and efforts; therefore, it also has interactive impacts with activities of other phases in IECDM engineering.

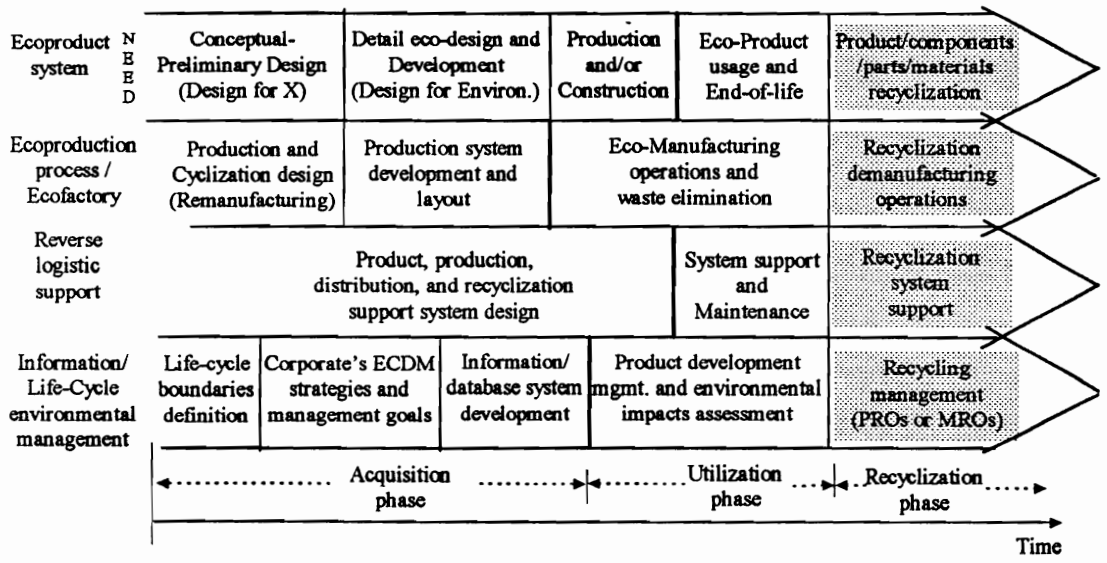


Figure 3.1. Life-cycle ECDM focus system engineering

The recyclization phase, generally, deals with problems related to used and/or returned products and materials at product's end-of-life. Recently, companies are increasingly paying attention to environmental impacts, as shown when they try to reduce waste generation and energy consumption. Governmental regulations also impose on companies a responsibility to plan for taking back, recycling, or disposing of their products. Consequently, there will be an increased emphasis on engineering not only to provide for more recyclable and renewable materials in products, but also to assist in the design of post-usage (after-market) disposal or recycling/demanufacturing procedures, thus, to design for the environment.

As Figure 3.1 shows, in addition to extending the time horizon into account in ecoproduct design, companies have to consider the environmental impacts of product-related processes, of logistic support, and of information/management. Therefore, an integrated approach that simultaneously

considers the product-system's four components (i.e., product, processes, logistic support, and management) during the entire extended life-cycle will lead to the IECDM engineering template. The four components may be described as follows.

Ecoproduct and Materials Life-Cycle: The product component consists of all materials constituting the final product and includes all forms of those materials in each stage of the life cycle. With respect to recyclable products, the product component of a complex commodity such as an automobile consists of a wide range of materials and parts. These may be mix of primary (raw) and secondary (recycled) materials. The product life cycle begins with the identification of the needs, especially environmental performance and design requirements, and extends through design, production, usage, end-of-life, and recycling stages. The most influential phase is the design for environmental considerations.

Design for the Environment (DFE) techniques (e.g., design for recycling and for demanufacturing) are required in the early design phase, so as to determine the demanufacturing/recyclization options and the ratio of products, components, and parts being recycled during these processes (in both the manufacturing and the demanufacturing processes). DFE techniques also influence the options for the production and recyclization processes and for logistic support during the product's end-of-life stage. Environmentally conscious engineering, or green engineering, has increasingly been concerned with ecoproduct development. The added recycling processes cause increases in material flows that require environmental-impact analysis, such as Life-Cycle Assessment (LCA) methods. For this reason, it is important to study the relationship of material within a logical system to the logistical processes taking place in product development. The purpose is to find a way for environmental-impacts analysis either for production systems or for logistical support systems (e.g., the life cycle assessment of packaging).

Production Process Life-Cycle: The eco-manufacturing process life cycle begins with the definition and planning of the production process according to the product design. It contains the design of the production and recyclization systems and equipment as well as product-related processes (for example, material extraction, component fabrication, product assembly, and disassembly). With regard to environmental improvement, production process planning has to deal with waste elimination and reduction in energy consumption, and must find ways to recycle used products and resources. In most cases, environmental loads are generated from production processes (i.e., material extraction, material manufacturing, and product assembly). For this reason, consideration of environmental impacts is critically important during production/construction phase. In addition, in regard to recyclization system

design, the aim is to find the processes that lead to the maximum end-of-life value, such as reusing components, recycling parts, recovering materials, and regaining energy for further use, either in closed or in open recycling loops, while minimizing product recycling efforts and costs. Environmentally conscious manufacturing system design with automatic disassembly application, or so-called *eco-factory* or *inverse factory*, is facilitated once the eco-production planning and processes are defined.

Logistic Support (Distribution) Life-Cycle: In the product development cycle, the logistic support system links all stages of the life cycle, for both physical product/materials distribution and information linkages. The logistic support life-cycle covers support during the design and production phases, customer support and maintenance during the product usage phase, and support for the product recycling phase.

The term *logistical system* is used generally for man-made systems of coordinated materials, energy, and information. In most cases the logistic support system, such as a material-handling system or an inventory system, provides operational production and recycling processes. In such cases, energy and information have supporting functions: energy is needed for the calculated transformation of goods within a space and time, and information is necessary to coordinate these transformation processes. Operating logistical systems may have various impacts on the natural environment. For example, environmental impacts could occur during the logistical system's support of efforts to recycle, including the collection and transport of used products, or decomposed components, disassembled parts, or reextracted materials. These used components and materials (with related information provided by logistic support) may transfer either to the recycling industry, or kept for the production of future products.

In the context of industrial ecology, companies assume responsibility for collecting, transporting, processing, and marketing recyclable or reusable materials (i.e., secondary materials). Increasingly, *reuse distribution systems* are designed to recycle shipping packaging and to a lesser extent recover products and primary packaging. Managing reverse distribution systems for shipping waste is likely to become a routine logistics support function [Transmode and ICF, 1993]. Reverse distribution systems have reflected a fundamental shift in waste management responsibility from the private waste management industry and local governments toward manufacturers, distributors, and retailers.

Integrated Life-Cycle (Environmental) Information Management: Life-cycle management (LCM), or eco-management, includes the entire information/ management network that supports decision-making throughout the life cycle. LCM is management in a way that fully considers life-cycle costs, benefits, and environmental impacts. Management responsibilities include administrative, service, financial, life-cycle costs and assessment, personnel, purchasing, marketing, customer services, legal

services, and other related issues, especially LCA and waste management. With respect to the environmental focus, LCA should include both economic and environmental dimensions. In addition, LCA is increasingly viewed by many companies as one of the management tools needed for environmental-conscious product development and waste management system.

From the engineering management viewpoint, eco-management is about managing the flows of information generated by moves towards greener design and production, and about managing the upstream and downstream changes required by corporate environmental strategies on the basis of that information. Its key feature is the development and application of auditing tools (e.g., life-cycle assessment) to assist in the implementation of the best available environmental options for process, products and suppliers, for evaluation of green product and processes design, and evaluation of process towards greener production.

IECDM engineering involves design and analysis of a product and its associated processes. As our ECDM problem definition, an integrated approach is needed for simultaneous design-decisions with the objective of maximizing the manufacturer's profit and maximizing the product's TLCV while minimizing environmental impacts. To cope these situations, IECDM focuses on green design that contains two major efforts: product design and process selection.

Designing a product through IECDM engineering process requires determining the product alternatives to be selected, setting the active level for each attribute within each product, and specifying processes that associate each identified attribute. Process design and selection refer to determining the processes that need to be opened, and assigning the chosen attribute levels, including environment-related attributes, to these processes. In process design decisions, the focus is on understanding the impact of the process attributes (e.g., flexibility) on profitability and the environment in the face of uncertainties in parameters such as demands for the product over its useful life-cycle, interest rate changes, or financial impact of technological innovations of environmentally conscious manufacturing. This operational design activities are the basis of design decision-making process that will be constructed in Chapter 6.

Formulation of IECDM Engineering and Related Issues. As environmental factors increasingly affect competitiveness worldwide, designing products and their manufacturing processes (from concept through material reclamation) for the environment becomes of significant importance. To most effectively implement waste minimization and front-end pollution prevention, it is necessary to apply a total life-cycle engineering approach to the IECDM. Processes and products provide value to the manufacturer and the consumer, respectively. However, there is also an environmental impact associated with all products and their processes. Unfortunately, one can rarely maximize the product's total life-

cycle value while minimizing all negative environmental impacts. Both manufacturers and consumers are forced to make tradeoffs.

As we concluded in the literature review (Chapter 2):

- In spite of the diversity of opinions and descriptions in ECDM-related works, there are more common denominators than otherwise; and
- in order to obtain environmentally improved products, all the various approaches must be involved in the ecodesign process.

These points may be summarized in the definition of IECDM from the system engineering viewpoint:

> *Integrated (Life-Cycle) ECDM (IECDM) engineering is a parallel execution of different environmentally-oriented, system development activities by multidisciplinary, cross-functional teams with the aims of reducing environmental impacts caused by the product and production operations, of increasing the product's total life-cycle value, and of providing an environmentally-improved product system with respect to functionality, quality, producibility, and environmentability.*

This generic definition implies that the need for the IECDM is driven by the need for environmental compatibility. Based on this description, a conceptual IECDM model is formulated as:

$$\left\{\begin{matrix}\text{Life - Cycle}\\ \text{Framework}\end{matrix}\right\} + \left\{\begin{matrix}\text{Concurrent}\\ \text{Engineering}\end{matrix}\right\} + \left\{\begin{matrix}\text{Environmentally Improved}\\ \text{Issues and Green Techniques}\end{matrix}\right\} = \left\{\begin{matrix}\text{Integrated (Life - Cycle)}\\ \text{ECDM approach}\end{matrix}\right\}$$

- Life-cycle thinking
- Life-cycle concepts
- Product/material life cycle
- Life-cycle approach

- Time-to-market
- Life cycle engineering
- Design For X:
  - Manufacturability
  - Assembly
  - Maintainability, etc.
- Life-cycle costing
- Simultaneous product design, manufacture, and demanufacture.
- Life-cycle Design

- Design For Environment
- Demanufacturability
- Disassembility
- Recyclability
- Resources conservation
- Waste elimination
- Green design techniques
- Life-cycle Assessment (LCA)
- Life-cycle Cost Assessment (LCCA)

- Ecology: industrial ecology
- Environment: produce green and high quality systems (product and processes)
- Energy: minimize waste and develop clean energy resources
- Economy: minimize life-cycle costs
- Efficiency: develop high performance systems

In this descriptive model, the life-cycle based system approach is the backbone of the IECDM engineering process. Time-to-market involves shortening the time from the creation of an idea until its presentation as a product on the market for the customer to buy. Life-cycle engineering implies the parallel consideration of product, function, design, material, production process, and cost with regard to later (downstream) stages of product life-cycle such as testing, service, maintenance, operation, repair, destruction, and further product development. Through this IECDM formulation and its domain, we recognize the following facts:

- Technologically, IECDM is the application of the Concurrent Engineering process and Life-Cycle design in order to incorporate environmental considerations (or environmental design requirements) into the design of a product and product-related processes through its entire life-cycle, in order to prevent negative environmental impacts caused by the product and its processes.
- Economically, IECDM is the transformation of materials into items of greater value with minimum production and environmental (external and internal) costs; in addition, IECDM increases product's total life-cycle value (including the product's end-of-life value) through life extension and recycling-related activities.
- Environmentally, IECDM is an ecodesign and ecomanufacturing strategy that aims, through environmentally-oriented product development, to reduce environmental pollution (impacts) caused by the product and its processes.

Therefore, the economical goal for IECDM approach is to maximize the product's total life-cycle value (including end-of-life value) as experienced by customer, manufacture, and the society, while the ecological goal for IECDM is to minimize the aggregate life-cycle environmental burden (impacts) associated with meeting societal demands for products. The ultimate technological goal for IECDM is to develop an Integrated Design Decision-Support (IDDS) system for environmentally-conscious product design and development. This computer-based IDDS system is beyond the scope of this research.

According to our definition, the strategy of the IECDM refers to the simultaneous pursuit of two or more activities (approaches) in the ecodesign of product and manufacturing as well as demanufacturing processes. The implementation of IECDM engineering will vary on an industry and regional basis. However, we believe that there exist common goals in the IECDM approach for environmentally friendliness, thus:

- to enhance the *effectiveness* of system-product development by incorporating all relevant knowledge and factors at the design stage;
- to increase the *efficiency* of the system design process (i.e., analysis, synthesis, and evaluation) by reducing the turnaround time from product conception to market delivery; and
- to improve the *environmental compatibility* of the system product and its manufacturing processes as well as of the demanufacturing processes for used products.

The first two goals are directly driven from concurrent engineering efforts, while the third goal is conducted from consideration of environmental problems and green technique requirements.

To achieve these goals in a full IECDM approach, our research addressed these challenges:

- Development of a QFD-based IECDM methodology for producing a feasible, environmentally-oriented product;
- Development of a mathematical Cost-Benefit Assessment (CBA) model for observing system behavior in the IECDM; and
- Development of a temporary Integrative Design Decision-Support (DSS) system for design selection and design changes.

The first two components of the IECDM system are the focus and are presented in the research.

3.1.2. Recycling-Oriented System Engineering Process

How and when does the IECDM approach interact with the phases of System Engineering Life-Cycle, and what tasks does it undertake? The primary function of the IECDM is to define the environmental requirements for the product, throughout the product's life cycle. An obvious first application of the IECDM is in the initial exploration of the environmental aspects of the system engineering process, the environmental consciousness of the customers, and the environmental regulations imposed by the government. For a complete understanding of the use of the IECDM approach in System Engineering, comprehensive recycling-oriented task and design criteria are fulfilled in the System Engineering Life Cycle phases illustrated in Figure 3.2, since recycling activities are critical issues in the IECDM approach.

Phase 1: Definition of Need and Concept Exploration. Figure 3.2 shows how the IECDM approach corresponds to the Systems Engineering Process with emphasis on recycling issues. In the figure, the Concept Exploration phase is actually preceded by a definition-of-need step, which looks to applied research to determine if a need even exists for the product design.

This step allows for an understanding of the marketplace need, customers' preferences, and environmental regulation. An industry has to explore its concepts, including environmental considerations, in order to design 'green' products. Ecology-oriented (e.g., recycling-oriented) products are increasingly created rather than technology-oriented products when the environmental consciousness is recognized. Concept exploration involves the completion of the interactive matrix between product attributes preferred by customers and product design attributes put together by engineers, including recycling issues. These tasks can be done using other tools, life, Quality Function Deployment (QFD). The customers' needs are transferred into requirements of green techniques, operations with a smaller environmental impact, maintenance with recycling process, and recycling issues.

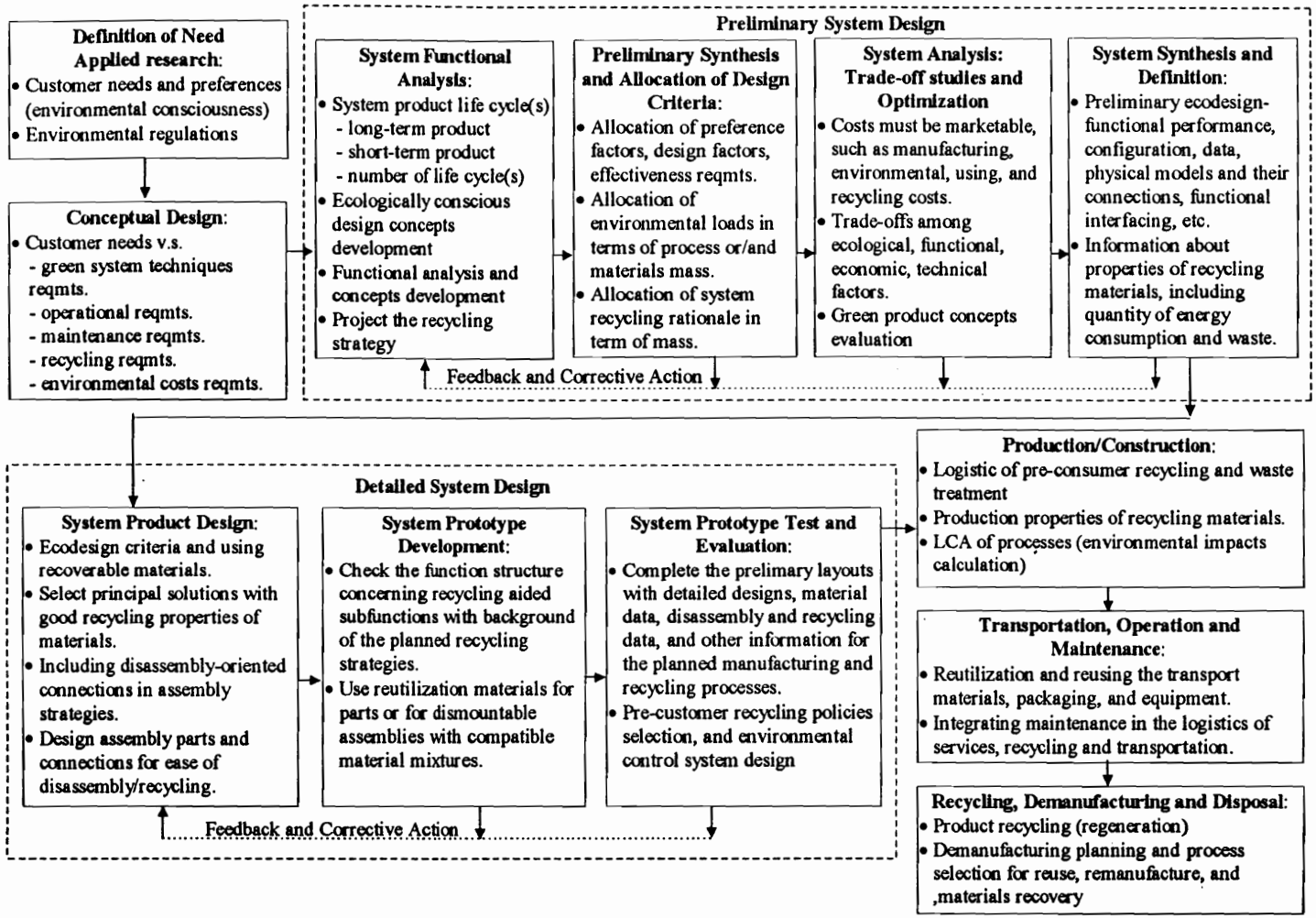


Figure 3.2. Using the IECDM approach in the system engineering process (recycling emphasis)

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Phase 2: Preliminary System Design. The preliminary system design phase is divided into four activity sub-phases: (1) System functional analysis and Life cycle analysis; (2) Preliminary synthesis and allocation of design criteria; (3) System analysis trade-off studies and optimization; and (4) System synthesis and Definition.

System Functional Analysis and pre-production Life Cycle Analysis: This involves developing the functional flow and the system alternatives, and determining the life cycle(s) of product alternatives, that is, long-term product and/or short term product. During the system engineering stages, all aspects of the systems life-cycle must be accounted for. Functional analysis helps to define the extent of the design in terms of alternative concepts, and life cycle analysis helps to define the lifetime of the product/components in order to decide the recycling strategy.

Preliminary Synthesis and Allocation of Design Criteria: This involves allocation of preference factors, ecodesign factors, and effectiveness requirements. It also includes allocation of the environmental loads in terms of product/component unit or mass unit in order to estimate the total environmental impact of the product and to determine opportunities for 'green' improvement and recycling priorities.

System Trade-off Studies and Optimization: System trade-off studies involve tradeoffs among factors of system function, economy, technology, and ecology. The costs (i.e., manufacturing, use, and recycling costs) must be marketable, environmental criteria must be met, and the green design concepts must be further tested and evaluated.

System Synthesis and Definition: Preliminary design comes out in this phase, including performance, configuration, materials selection, possible environmental impacts, and pre-consumer recycling system design. The synthesis focuses on functional interaction and the physical connections between the subsystem/components and parts.

The preliminary system design illustrated in Figure 3.4 contains a 'Feedback and Collective Action' loop indicating the iterative nature of the process. The feedback recognizes the fact that changes will be necessary (e.g., environmental criteria are changed from time to time, from area to area), but within the confines of the preliminary design. Completion of the preliminary design allows further definition of the recycling plans and disassembly strategies and helps to maintain a framework and tractability for the entire process.

Phase 3: Detail System Design. Like the Preliminary System Design phase, the Detail System Design phase contains three sub-phases and a feedback loop. The three sub-phases are: (1) System-product design, (2) System prototype development, and (3) System prototype testing and evaluation.

System Product Design: This sub-phase involves development of the complete product with design criteria using recoverable materials; selection of the principal solutions with good recycling

properties; assembly strategies; disassembly-oriented connections; design of assembly parts and connections for ease of disassembly and recycling.

System Prototype Development: In this sub-phase processes and procedures are refined as the prototype is developed in order to reduce environmental impacts as low as possible. The tasks include checking the function of recycling-aided sub-functions in the background of the planned recycling strategy, and using reutilization materials for parts or for discountable assemblies with comparable material mixtures.

System Prototype Testing and Evaluation: The final testing and evaluation of the prototype is to determine if the design is meeting the target specifications. Also, this sub-phase should complete the preliminary layouts with detailed designs, material data, disassembly data, pre-customer recycling issues, and other essential information for the planned recycling process during the product's production.

The final system design is completed during this phase, and the feedback loop represents a further refinement of the design.

Phase 4: Production/Construction and Operation and Maintenance. Pre-consumer recycling and its logistics are required during the production/construction phase of Systems Engineering. System design must consider the production properties of recycling materials in order to eliminate waste during production.

If the 'green' design has been properly performed, no design changes (e.g., using other type of materials) are required during this phase. This is the stage at which process and environmental control, collection of material waste, reduction of energy consumption or recycling energy, and recycled component feedback are all taken into consideration in determining whether or not the as-built product is being produced within the specifications. It also determines whether or not the as-built manufacturing process is being set up within the environmental requirements, which is expressed in terms of environmental loads during the production process. LCA is used for detailed estimation of the environmental impacts during the product production/construction process. Environmental control may be required to improve the environmental quality and to eliminate waste.

Phase 5: Operation and Maintenance. In this phase, transportation criteria include reutilization of the transport materials and equipment. System operation should integrate maintenance into the logistics of service and recycling. In addition, ease of maintenance becomes one of the objectives of Design for Disassembly (DFD) in the IECDM engineering.

Phase 6: Demanufacturing and Recycling/Disposal. The policy of product/material recycling is implemented in this phase. Demanufacturing determines the recycling process, plans, and even the recycling rate in order to meet the environmental requirements.

Using the IECDM approach offers many benefits. For example, when the IECDM approach is used as an integral part of the process, System Engineering is more complete from the environmentally-conscious viewpoint. The tasks and criteria of system design results from the system engineering process making 'green' product development possible.

3.2. THE IMPACT OF THE IECDM APPROACH ON SYSTEM ENGINEERING DESIGN

Design synthesis, analysis, and evaluation are required throughout the product design and development cycle. Typically, system (product and/or process) design can be viewed as a sequential decision-making process. During the ecodesign process, firms need to be able to compare the environmental impacts of different product design alternatives. In addition to design for performance and functionality, designers are constantly faced with choosing among materials and processes, as well as among the end-use characteristics of their designed products, such as the degree of energy efficiency and recyclability. These design choices are performed through the system engineering design process and the design synthesis, analysis, and evaluation activities.

If environmental requirements for the product-system are well specified, design alternatives can be checked against these requirements together with other requirements. Tools for design evaluation range from comprehensive analysis tools such as LCA to the use of single environment metrics. In each practical design case, design solutions are often evaluated with respect to a full spectrum (multiple dimensions) of criteria (factors) which include cost, performance, environment, time, and quality. This section will discuss how the IECDM approach affects the conventional engineering design and evaluation process. Conversely, the IECDM methodology should be developed on the basis of traditional design activities--synthesis, analysis, and evaluation.

3.2.1. Impact of the ECDM Evolution on Conventional System Engineering Design

Environmental factors have an impact on traditional design problems. In this section, traditional design problems and their classification are described first; then the impact of environmental issues on the system design process are discussed.

Characteristics of Design and Engineering Design Problems. Design problems in general, and engineering designs in particular, are typically open-ended and ill-structured, by which we mean [Dym, 1994]:

- Design problems are said to be *open-ended* because they usually have many acceptable solutions. The quality of uniqueness, so important in many mathematics and analysis problems, simply does not apply.
- Design problems are said to be *ill-structured* because their solutions cannot normally be found by routinely applying a mathematical formula in a structured way.

However, from a system and systems engineering viewpoint, design problems can be solved through an integrative process of definition, synthesis, analysis, design, and evaluation. Environmental issues have effects throughout this integrative design process. There are two ways for classification of system design problems: by theoretical and by practical classification.

(1) By The Theoretical Classification of System Design Problems: The IECDM is developed as a generic methodology that can deal with any design problems in the ECDM domain. According to life-cycle design activities--synthesis, analysis, evaluation--problems in ECDM domain can be classified.

Characteristics of the Analysis, Synthesis and Evaluation Process: Analysis and synthesis are composite words of Greek origin (ana-lysis, syn-thesis). *Ana* is a preposition implying distribution while *lysis* is a noun denoting resolution. Thus, analysis is the resolution of a complex whole into its constituent elements. On the other hand, *syn* is the preposition with, while *thesis* is the noun position. Thus synthesis is the composition of elements into a complex whole. Every synthesis activity is initiated once a need has been identified. These elements may be synthesized in different ways (or alternatives). Evaluation is then employed to choose the best alternative that meets the objectives and criteria, and addresses the identified needs. Design tasks typically require several iteration of synthesis, analysis, and evaluation. Based on that, a complete IECDM methodology is proposed.

Problems Classification for Analysis, Synthesis, and Evaluation: To clearly represent the system design problem, an example of a dynamic system with feedback is illustrated in Figure 3.3. Definition of the basic problems in a dynamic system is always the first step of system analysis. Figure 3.3 illustrates that systems problems are generally classified based on the objective of the system study. The dynamic system under control operates on a sequence of inputs $U(t)$, yielding a sequence of outputs $Y(t)$. The outputs at any time are a function of the state of the transfer function $F(t)$ and system state X itself. On the basis of this perspective, different approaches for different goals are possible:

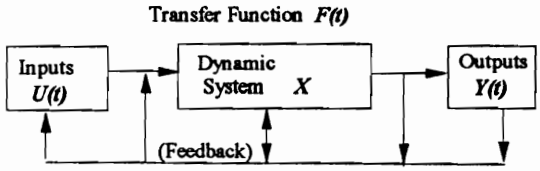


Figure 3.3. A general system with feedback

Problem I: *System synthesis* (or *identification*)-- Given U and Y, determine a suitable F model.

Synthesis is the assembly of primitive design elements or partial designs into a configuration that satisfies a few key specifications and constraints. Before a system can be configured or designed and analyzed, system research is often required for a nonexistent system. System research involves applied mathematical efforts to modeling a real-life problem that will be described by a system (equations or physical). For system research, the desired transfer function F is a function of states X, inputs $U(t)$, and outputs $Y(t)$ that are often obtained from observation of real problems:

$$F(t) = q\ (X,\ U,\ Y) \tag{3.1}$$

To a large context, synthesis involves the identification of attributes (elements) that are used to configure the desired system. In green design, product-related attributes should contain environmental factors. Environmental regulations and customer preferences can be viewed as constraints in the QFD-IECDM methodology (see Chapter 4 for details).

Problem II: *System analysis*-- Clarify contents of F, U, and Y.

System analysis concerns the investigation and study of the elements (or components) which constitute in a system. In other word, system analysis typically seeks to obtain an understanding and description of how a system performs or behaves. Generally, analysis involves computations or deductions based upon attributes of the current synthesis to assess the extent to which the synthesis satisfies other, more subtle or complex specifications and constraints. In a black box representation of a system, system analysis involves obtaining a description of operations inside the black box that transform given inputs into known outputs. In such a sense, input and output are functions of the transfer function $F(t)$ and the system state X; and the problems concerned are:

(a) *System inversion*: Given F and Y, find U.

$$U(t) = f\ (F, X, Y; t) \tag{3.2}$$

(b) *System operation*: Given F and U, find Y.

$$Y(t) = g\ (F, X, U; t) \tag{3.3}$$

In the context of IECDM, the behavior of the product system is analyzed throughout each stage. The analysis includes study of the environmental impacts caused by product, process, and design-related activities. In other words, the degree of environmental impacts and waste generated (outputs) depends on the energy consumption and materials used (inputs) of the system, efficiency of the system, and the system itself.

Problem III: *System evaluation (optimization) process*-- Pick U, Y, or F so that the specified evaluation criteria are optimized or designed.

System design evaluation concerns the configuration and/or reconfiguration of activities that comprise a system according to a set of predetermined specifications and constraints. Generally, evaluation is the process of comparing the analysis of the current synthesis against the specifications and constraints for the artifact (e.g., the product) to determine whether that synthesis is acceptable (i.e., configuration is acceptable).

An evaluation that a given synthesis is unacceptable will typically prompt a new synthesis aimed at improving that system's performance to satisfy the violated specifications or constraints (i.e., reconfiguration). In the system block box, system design involves the normative analysis of the box, so that given inputs will yield the outputs desired by system designer. In view of system design, system X is the function of a given transformation function $F(t)$, inputs $U(t)$, and desired outputs $Y(t)$:

$$X = h\,(F, U, Y, t) \tag{3.4}$$

Analysis and evaluation are required throughout the product-development process. If environmental design requirements for the product system are well specified (through the help of the QFD-process), design alternatives (or product alternatives) can be checked directly against these requirements. In such a case, environmental impact assessment can be viewed as a design evaluation problem. In a sense, inputs $U(t)$ are raw materials and energy consumption, outputs $Y(t)$ are waste and emissions, $F(t)$ can be expressed as environmental transformed metrics. Ideally, the system alternatives X with the smallest environmental impact is selected. In design practice, optimization efforts are often employed together with evaluation processes to find out the optimal solution of an evaluated system (see Chapter 4 for details).

For illustration, we suppose that the functional equation (or objective), E, can be expressed by corresponding functional requirement (or attributes), Y and decision variables, X, as

$$E = f(x_1, \ldots x_i, \ldots, x_n\,; y_1, \ldots, y_m) \tag{3.5}$$

Then, in the system analysis stage, x_i is known and E is to be determined (formulated) to ensure the functional requirement Y. On the other hand, in system synthesis, the functional requirement Y is known (given) and x_i is to be determined from objective function (for example, minimized cost). Clearly, system synthesis is much more difficult than system analysis, because the former needs an appropriate criterion for allocation of the system parameters allocation. In the system design stage, a system candidate is selected based on the set of evaluation criteria.

Keeping these classification of ECDM problems in mind, the problems of dynamic system design can be easily understood. As a matter of fact, a control system is often defined as a design problem that involves the three activities -- synthesis, analysis, and evaluation -- conducted in an iterative manner, evolving with increasing resolution. This procedure is depicted in Figure 3.4. In other words, the design of a new system involves the design of an iterative process and a decision-making process. The iterative process provides data for the decisions taken by the decision process with increasing resolution. In this chapter, we will develop the IECDM for green design that cope these fundamental design processes: analysis, synthesis, and evaluation.

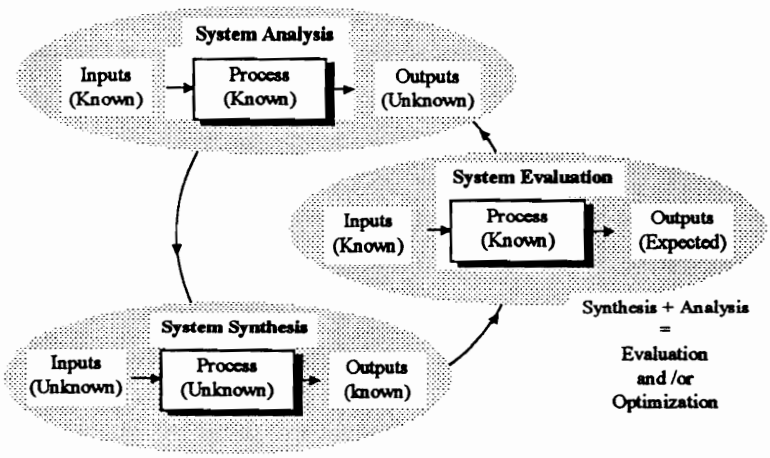


Figure 3.4. System analysis, system synthesis, and system evaluation

(2) The Practical Classification of System Design Problems. Design is viewed as a problem solving process. According to Ullman [1992], product-system design problems can be basically categorized as: selection design, configuration design, parametric design, original design, and other types of design. Most design situations are a mix of various types of design problems as follows.

Selection Design involves choosing one item (or maybe more) from a list of similar items. This type of design is used every time designers choose an item from a catalog.

In a *Configuration Design* (or packaging) type of design problem, all the components have been designed and the problem is how to assemble them into a completed product. For many problems, some of the components to be used in the assembly can be altered in various attributes such as in sign, shape, or function. This alternation gives the designer more latitude in determining potential configurations and makes the problem solution more difficult. Any product configuration may be assembled (or constructed) by a set of attributes with different levels that generate alternative product designs to be selected.

Parametric Design involves finding values for the variables, or parameters, that characterize the object being studied. Basically, some values are found to fit a simple equation, or a whole set of equations and rules govern the design. Design-evaluation-function is a representative way of parametric design. Constrained mathematical programming is also used in parameteric design problems to search for the 'best' design.

Original Design is used any time when the design problem requires the development of a process, component, or assembly not already in existence, for example, new-green product development. Actually, while most selection, configuration, and parametric design problems can be represented (formulated) by equation(s), rules, or some other logical scheme, original design problems cannot be reduced to any algorithm. Each one represents something new and unique.

In many ways other types of design problems are simply constrained subsets of original design. When solving a design problem, the potential results (solutions) may be limited to a list in an arrangement of components, or a set of related, characterizing values in the feasible design space. Thus, if designers have a clearly systematic methodology for performing original design, then they should be able to solve any design problem by having a more limited set of potential solutions. Motivated by this advantage, the IECDM approach is implemented in the well-structured QFD framework in order to help designers constrain the potential solutions of complex design problems (see Chapter 4).

The Role of Designers in A general System Ecodesign Process. A general design process is illustrated in Figure 3.5. By definition, engineering systems are made up of interrelated subsystems. A system is often so complex that it is difficult to handle the entire system at one time. The inherent complexity and diversity of engineering system design inhibit the formulation of a general methodology that covers the entire spectrum of engineering decision-making activities in different design phases. Fortunately for a major class of problems in the real-world, the system design process can be treated as a hierarchical and iterative procedure from the conceptual design to the detail parameter's design phases.

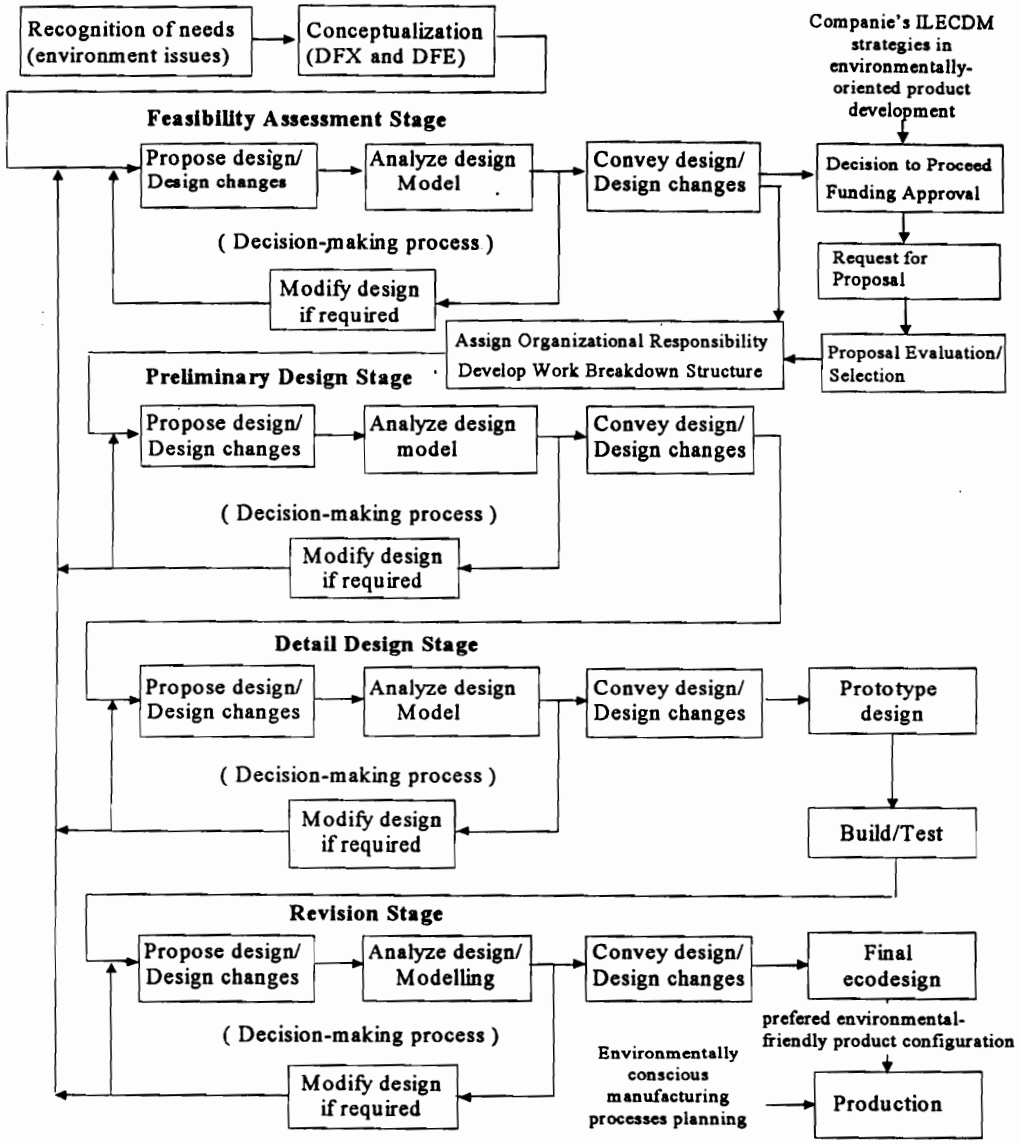


Figure 3.5. The system design cycle

Figure 3.5 illustrates an example of a hierarchical, iterative design procedure of an engineering system. It is suggested that the system be decomposed into smaller subsystems hierarchically. The system design problem using the hierarchical approach is one of sequential design procedure in which the decision maker can focus on the proper functioning of the subsystems to yield a properly functioning system instead of making a judgment from the entire system. During this design process cycle, designers play an important role at each design level.

Engineering system designers are continually making decisions. Design has been defined as an iterative decision-making process. These decisions occur at all stages and all levels of the design process. The designer must decide on the real job or function of the system that includes: deciding the specifications, constraints, and relative importance of the dependent variables; choosing the best alternate system configurations for the overall design; and selecting the best suppliers for major components, etc. The detail designer must make innumerable decisions on the best configuration for details. The designer or test engineer must decide how much testing is necessary to prove out the design. If all of these decisions are the right ones, the design will be optimum or at least near-optimum.

Although the product design process does not have direct impacts on the environment, it must be considered in the IECDM engineering process because of its importance to achieving future goals of maximizing the recyclability of products while minimizing waste, disposal cost, and product liabilities, thus avoiding negative impact on environment. Designers must adopt DFE techniques that promote upgrading for the existing equipment and include the development of standard documents that lead to the reuse of parts and assemblies and reduce waste. By its very nature, traditional design is a combination of an art and science that satisfies specific design criteria required in the system under development. Such criteria could include performance, cost, resources, physical constraints, reliability, availability, maintainability, and testability. Compared to traditional design, the IECDM adds several design criteria to the standard design elements mentioned above, including DFE elements, energy consumption and hazardous wastes, and the effects on landfills as major issues when the product reaches its end-of-life point.

Designers today are being asked new questions about how their design might pollute the environment, cause hazards, or increase "hidden" costs such as hazardous waste disposal. The additional environment-related design requirements have made the designer's task more complex and difficult [Schutsenberger, 1994]. Since most products of industry are the result of a design effort, the designer can make a significant contribution to environmental quality by using the most environmentally conscious design principles and processes in the product design phase. For most products, environmental impacts can and do occur during one or all of the product's life-cycle stages. Stephan *et al.* [1994] pointed out that:

> "*A designer is able to influence the raw materials used, the production process employed, the way in which the product is utilized, its life, its 'reparability,' its recyclability and even the mode of its eventual disposal. Therefore, product design decisions which beneficially influence any of the above potential environmental impacts should be encouraged and acknowledged.*"

When designers use techniques (tools) to minimize the impact of their design and product on the environment, the result could be called *ecodesign*, or green design. This ecodesign approach, as a part of

the IECDM methodology, will generate a design that optimizes the use of recycled materials and ensures that all parts are recyclable at their end-of-life. This approach will reduce the generation of waste [Kirby and Pitts, 1994].

Product designers have been primarily concerned with conventional product attributes, such as the optimization of product performance, the efficiency of manufacturing operations, the safety of product operations, and the containment of costs. Now, they are forced to also be concerned with designing for minimized environmental impacts. However, most system designers do not possess a background or knowledge of IECDM methodology or of how to make a greener product by the *ecodesign* process. The challenge of how to successfully address these new environmental requirements during the ecodesign process is now facing design teams in different major industries, such as electronics and automobiles. This challenge requires an additional engineering course to teach system designers how to be more concerned with environmental issues in an ecodesign procedure.

3.2.2. Qualitative Basis for Green Design Evaluation

It is impossible to create the perfect green product either by traditional design or the IECDM approach; any design effort that requires tradeoffs among cost-effectiveness-environmentability and adjustment to satisfy the customer. In a sense, such tradeoffs effort is a evaluation process. An ecodesign evaluation system is required for quantitative analysis and for selecting a "best" design by tradeoffs between given product criteria and environmental rules.

Design Emphases and Environmental Loading Commitment. Environment-related design is much more than the efforts for disassembling and recycling. The accent on design is important since 80~90% of total product life-cycle costs are committed by the design stage (conceptual and detail designs) before a system is manufactured or a service is initiated. According to Fabrycky and Blanchard [1991], great benefit can be derived from accelerating the accumulation of system-specific knowledge earlier in the life cycle of the product. Fully two-thirds of the commitment to final system characteristics and life-cycle costs is made by the time conceptual/preliminary and detail design are completed, and, in a parallel manner, life-cycle environmental loads. This situation is shown conceptually in Figure 3.6.

Similarly, environmental impacts (e.g., wastes and pollution) resulting from product creation, use, and disposal are largely determined by the original design. Currently, however, disposal options and environmental impact are not common initial design criteria. In conventional manufacturing activities, environmental loads created by the post-processing of manufactured by-products and abandoned products have seldom been taken into consideration during the design phase. Design for environment loading is

critical because evaluating or measuring the manufacturing impact of a product on the environment after it has been designed is too little, too late. Many of the significant product innovations of the twentieth century represent an exponential increase in the level of environmental burdens associated with their life cycles [Rhodes, 1993].

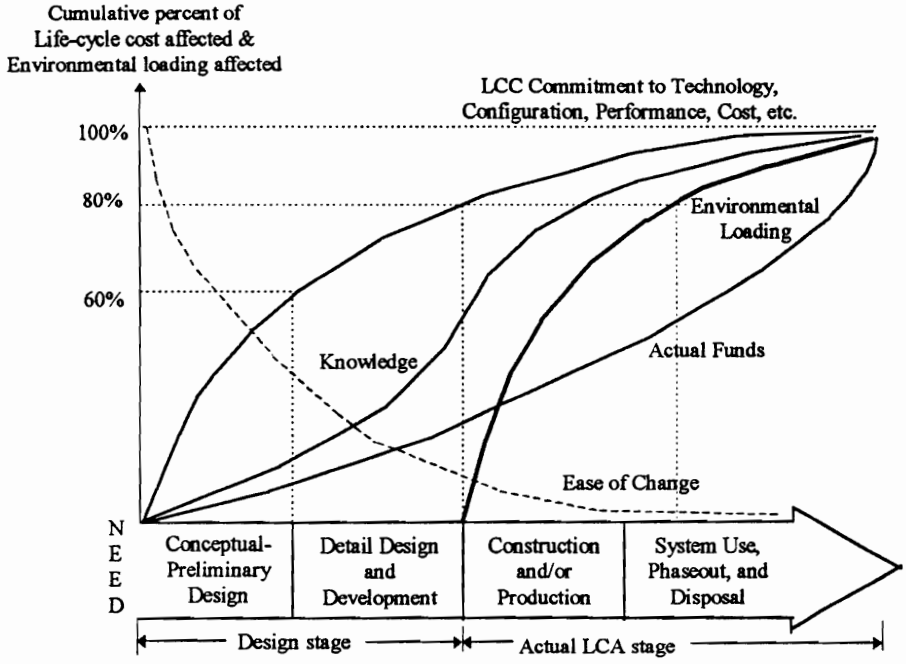


Figure 3.6. LCC commitment and environmental loading impact

In practice, improved design tools and procedures would help firms identify where innovation would provide the greatest environmental benefits and smallest negative environmental impacts. In the life-cycle design approach, at least six elements of product design can help to assure that products are environmentally sound: product definition, product design reviews, platform design, design for reduced material usage, design for reuse, design for recyclability. These approaches allow the product development team to fulfill the environmental requirements specified in the product design tool, such as QFD techniques and other structured design methodologies.

Figure 3.6 also indicates an important fact for the product development process, which is pointed out by Alting and Jørgensen [1993] as:

> "*...decisions determining structure and properties are taken very early in the development process, which may make it difficult to influence/change the environmental loads in the detailing phase. In the early stages knowledge about materials and processes is limited and consequently*

also the knowledge of environmental loads, but the degrees of freedom [of changes] are large.... When the knowledge level increases, the degrees of freedom go down."

This statement implies that uncertainty factors on environmental issues exist in the early stages of design decision-making. They also suggest that those support methods (or tools) for product development should both be able to handle the early development phases where the assessment basis is mainly qualitative and the later phases where the assessment is quantitative.

Further, the development processes must include active feed-back from production, distribution, usage and disposal, where the environmental loads assessment, thus the life-cycle assessment (LCA), will identify areas or opportunities for improvement in product concept, structure and specifications, even requirements. The LCA analysis or evaluation does not in itself provide environmental improvements but it reveals where improvements can be made. The total design method or environmental improvement techniques, such as the IECDM engineering process, for product development must therefore simultaneously include various considerations and databases as well as guidelines for improving environmental performance.

Mapping of Cost-Effectiveness-Environmentability in System Design. Generally, to a large extent of green design, system design can be conceptualized as the mapping from the cost-effectiveness requirements of each candidate system, as expressed by values of certain cost-effectiveness measures, onto suitable values of decision variables, which describe the physical design or the manner of operational control of the system. Figure 3.7 shows this mapping, taking the manufacturing system as an example, i.e., cost-effectiveness-environmentability evaluation.

For practical reasons whole-system design should achieve an overall optimum with respect to the two criteria that matter most: system performance and life-cycle cost, either product or manufacturing process. Figure 3.7 illustrates that system design follows the cost-effective design process. One can identify that each candidate system intensively interacts with the other and the denominator which has to be taken into consideration is that of effectiveness. Of interest in environmental issues, environment-related factors have also been included in this cost-effectiveness evaluation.

Especially from the viewpoint of manufacturing system design or/and processes selection, a manufacturing system should be constructed for enhancing re-production and re-use of the components/parts after consumption, when the products, parts, and materials capable of recyclization are collected. In addition, in recyclization-oriented manufacturing companies the flow contains a by-path called *recycling*, or *demanufacturing*, which definitely reduces the environmental burden (loading) to a reasonable level.

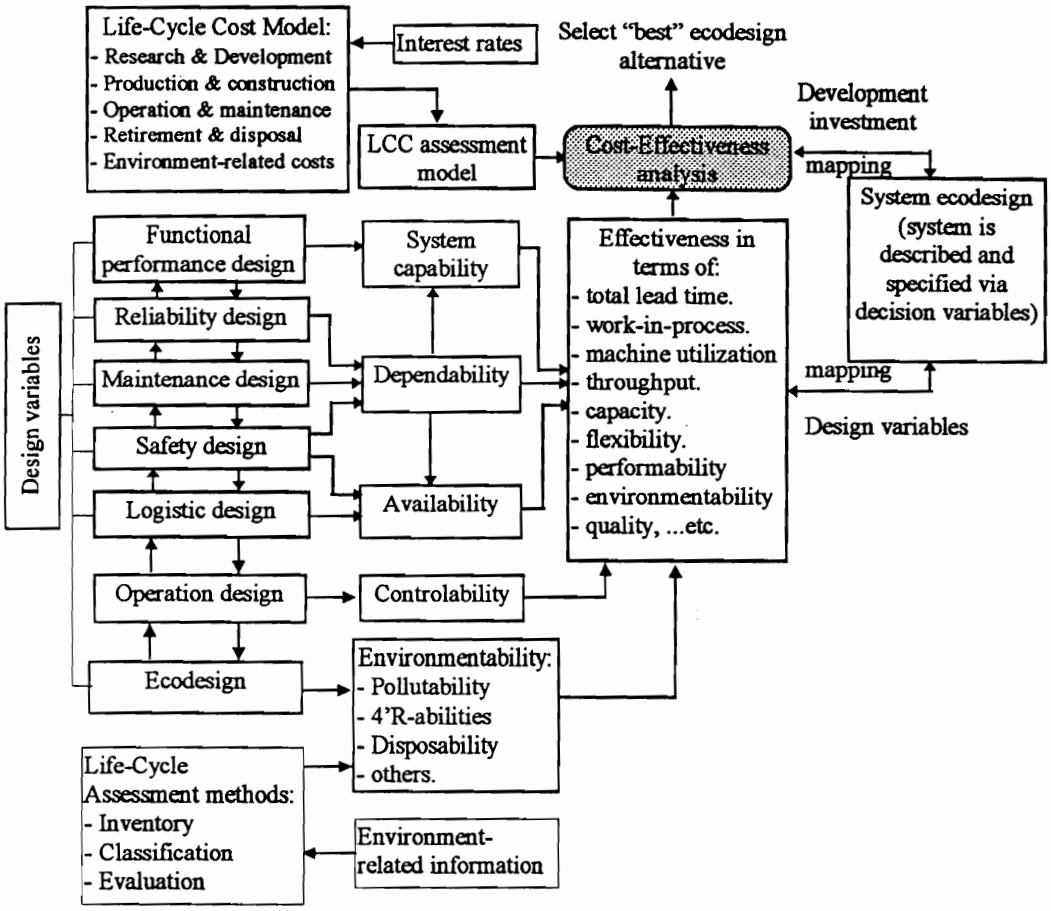


Figure 3.7. Factors for cost-effectiveness mapping in system ecodesign

In constructing the recyclization-oriented production system, analysis of the cost-effectiveness of demanufacturing activities is one of the crucial items considered. It is very important that demanufacturing activities should be sustained economically and ecologically. From this viewpoint a cost-effectiveness analysis is made, such that the expense required for demanufacturing be shared in the industrial ecosystem (society) or covered by reasonable product pricing.

3.2.3. Quantitative Basis for Green Design Evaluation

Ecodesign evaluation in terms of life-cycle cost and effectiveness as well as life cycle assessment criteria can be achieved by adopting the design-dependent parameter approach incorporating a Design Evaluation Function (DEF). This approach can be viewed as an extension of the DEF proposed by Fabrycky [1990], which is a mathematical method to link design actions with operational and

environmental outcomes. It is based on models and indirect experimentation, and implemented in accordance with the processes of the Evaluation System and Database (ESD). Furthermore, system ecodesign evaluation must recognize and incorporate multiple criteria that are displayed by the design evaluation display together with the energy profile and environmental impacts profile.

A Model of Evaluation System and Database . In a Concurrent Engineering (CE) environment, one objective of CE is to evaluate product and process designs simultaneously in order to reduce manufacturing lead time and a product's life-cycle costs. Manufacturing lead time may be reduced by improving communication between design engineers and manufacturing engineers, and eliminating unnecessary queue time at various product development stages. Cost reductions can be achieved by avoiding product and process redesign. Such objectives also hold true when the IECDM approach is embedded into the system engineering process. Nevertheless, a product/process design evaluation system should be organized into several interrelated modules for design evaluation, as illustrated in Figure 3.8 in which QFD module is focus.

Design evaluation involves the derivation, estimation, and prediction of values for all relevant design parameters (dependent and independent) and design variables. The purpose of design is to determine the product's acceptability and the process's feasibility in terms of the initially stated needs, objectives, goals, and specifications, including function, cost, and environmental criteria. In Figure 3.8, QFD plays a critical role in implementing the design evaluation system in which the QFD-process is employed to identify all possible product-related attributes. QFD is employed both as a synthesis tool and analyzer. It is utilized in order to capture the user's needs and to aggregate design characteristics data that entry to the proposed system (product), $\Xi = f[\Xi, A_n, A_p, S(A)]$, where A_n and A_p are identified qualitative and quantitative attributes, respectively, and $S(A)$ represent connections among attributes. It is also used as a set of matrices (in terms of attributes) which associate with customer requirements to the functional requirements by decomposing the green design problem into several sub-problems. The use of QFD-process in IECDM will be discussed in detail in Chapter 4.

DFE can help companies reduce life cycle costs and improve overall product quality. However, an IECDM model for ecodesign verification is needed for effective use of DFE concepts in developing an environmental-friendly product. This IECDM model should be capable of assessing the relative importance of environmental factors and issues associated with all product life-cycle stages. It should explicitly represent uncertainty, and should allow evaluation of economic impacts associated with product strategy decisions related to environment issues. For practical reasons, the IECDM model should be available as part of a CAD/CAE system to enable integrated assessment and optimization of system ecodesign decisions. Moreover, assembly/disassembly design of products is one of most important

subjects in the CAD/CAM systems. Such work can be seen in the proposal by Araw and Iwata [1993] for a CAD software system to execute product assembly/disassembly planning function.

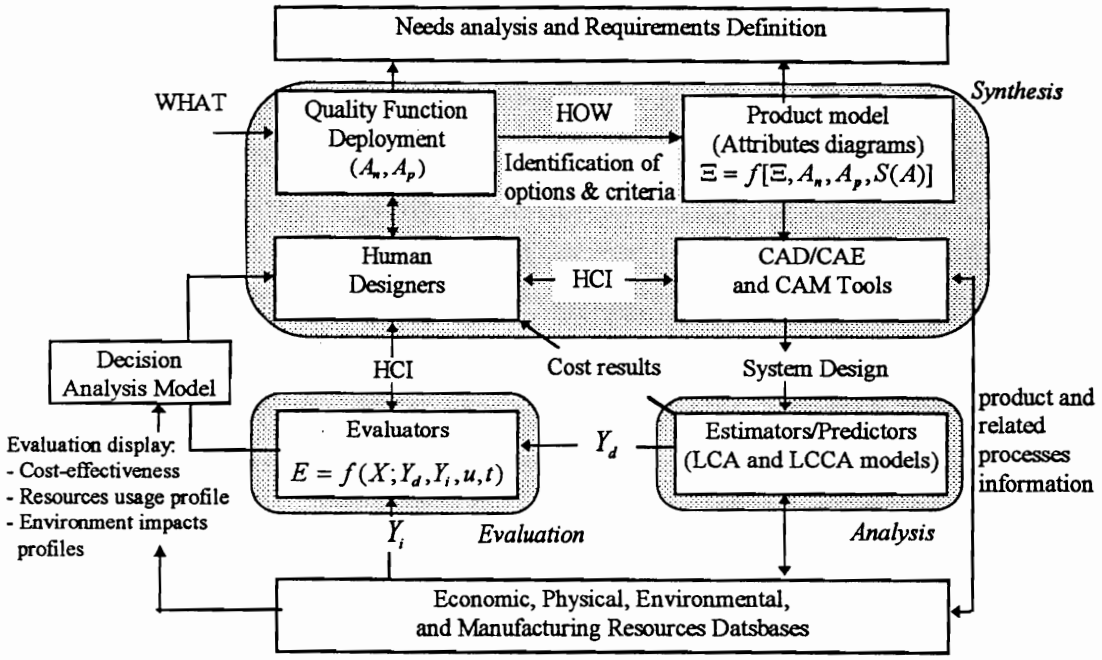


Figure 3.8. Factors to be evaluated in concurrent system ecodesign

Taking advantage of computer technology, an ecodesign evaluation system on the existence of a concurrent product, and process development environment needs to be substantiated by at least a product-modeling system, some CAD/CAE systems, and a database supporting these systems. This database should include economic, physical, and environmental design data related to the designed product and process, as well as manufacturing resource data for production/process planning and scheduling. Such an environmental design database that compares various processes, chemicals, and other materials in terms of environmental effects, cost, and quality will need to be developed for life-cycle assessment and design for environment. This tool would be used by the product and process designers to help them find ways to minimize negative environmental impacts.

In addition, depending on the extent of the evaluation of the intended product designs, the CAM systems may include facility-layout planning, process planning, production scheduling, and other systems as required. An actual design evaluation system should contain the following components evaluators and estimators/predictors. The evaluators, in terms of the design evaluation function (DEF), must be linked to all stages of the system life cycle. This function, with both design-dependent and design-independent

parameters, facilitates the feasibility and optimization of the product/process design. The feasibility means to ensure that the current product design is technically producible, regardless of other manufacturing concerns. The optimization means that the best design is achieved based on a search-based choice. The estimators/predictors determine design-dependent parameter values according to given design factors. They also provide a life-cycle cost estimate for the current design and identify potential manufacturing difficulties as well as possible environmental impacts (or environmental compatibility) of the current product and process. Consequently, estimators/predictors also provide schedule and quality evaluation, which is concerned with production-related issues and the quality of the product design and process plan, respectively. As companies recognize the importance of environmental quality to their long-run viability, DFE systems will become a standard part of CAD/CAE and CAM technology in the form of the IECDM model.

In summary, due to the proliferation of computer applications in the engineering process, the IECDM principles and procedures may also be implemented as computer systems and integrated into a product-modeling system, leading to the integration of CAD/CAE/CAM systems and the implementation of environmental impact evaluation systems. Moreover, solving the IECDM problems is a decision-making procedure. On the other hand, a Decision-Making Support System (DSS) is also required for implementing IECDM principles. The computer-aided IECDM attempts to develop an Integrated Design Decision-Support (IDDS) system that integrates IECDM with CAD/CAE/CAM system and LCA/MCDM applications in the DSS environment. However, this potential research topic is beyond the scope of this work.

Ecodesign Evaluation Mathematics. Given a cost-effectiveness requirement, the system designer must create a suitable system design. This design can be created numerically by specifying the values of an appropriate definition of decision variables (or design variables). In other words, designing systems involves the tasks of mapping cost-effectiveness measures onto decision variables of systems, which are formulated into either the design evaluation function, with selected design parameters, or a cost-effectiveness optimization model as follows.

(1) Design Evaluation Function as a Dynamic System Model: The IECDM engineering considers the immediate and long-term costs of materials extraction, transportation, product lifetime, recycling, and product ultimate disposal. Design constraints include government regulations, technological innovations, consumer preference and costs. Because these constraints change with time, each design must be customized, and a successful outcome is by no means guaranteed. In spite of this complexity and the dynamic features of the design problem, a general mathematical model can be expressed.

Generally, the form of the ecodesign evaluation function can be expressed as the dependent parameters function proposed by Fabrycky [1990]. For handling uncertainties imposed by dynamic changes in environmental regulations superimposed upon the normal uncertainties in product demand forecasting, computational methods need to be developed to generate designs based on anticipated demand and environmental restrictions over the life of the project [Blau 1995]. The dynamic problem that is formally used to determine the design parameters $Y(t)$ should be integrated into the design evaluation function as follows:

$$E = f(X, Y_i, Y_d) = f(X_{e,j}(t), X_{s,k}(t), Y_i(t), Y_d(t), u(t)) \tag{3.6}$$

Subject to $\quad g_l(X_{e,j}(t), X_{s,k}(t), Y_i(t), Y_d(t)) \leq \text{ or } \geq C$

$$h_m(Y_i(t), a(t), u(t)) \leq e(t)$$

Where

- j = 1,2,...,F number of independent design variables
- k = 1,2,...,N number of dependent design variables
- i = 1,2,...,J number of design independent parameters
- d = 1,2,..., D number of design dependent parameters
- l = 1,2,..., N number of constraints equations
- m = 1,2,..., M number of constraints equations

E is the evaluation measure of ecodesign, X the set of ecodesign variables, Y_d the set of design-dependent parameters, and Y_i the set of design-independent parameters. f and g_j define relationships among design variables X. These relationships are typically mathematical functions, where the number of design variables whose numerical value are to be decided (M) is greater than the number of equations relating them (N), $M>N$. There are thus $F = M - N$ degrees of freedom. F of the variables may be selected as independent ecodesign variables X_e ; the remaining dependent or state variables X_s are then fixed. We have to explore on F the dimensional search space for design optimization. Dependency in the above design problem may also be represented by a function dependency matrix (FDM), which will be discussed in Chapter 4. In the context of life cycle ECDM, the terms are defined as follows:

E is a life-cycle complete evaluation measure that could be the equivalent of life-cycle cost and/or environment-related performance measures such as measures of environmental impact, which will enable us to determine an optimum design within the feasible region of the search and design space. The objective function $f(\,)$ may use a simple objective function such as net

present value. However, a more realistic approach is to use a variety of performance criteria and extract an acceptable optimal policy.

$X(t)$ are ecodesign variables. These are factors that define the optimization design space. Once a feasible set has been synthesized, each candidate green product is optimized over the set of ecodesign variables before being compared with other alternatives. In general, the variables may be continuous or discrete, and they may be subject to constraints. Examples of decision variables include material choice, manufacturing-process selection.

$Y_d(t)$ are design-dependent parameters. These are factors (attributes) with values under the control of designers, which are impacted by specialty multi-disciplines brought to bear in the system development process. Moreover, since these parameters represent the ecodesign space, every instance of the design-dependent set represents a distinct and potential candidate system or design alternative. Examples of design-dependent parameters include reliability, design life, predictability, maintainability, pollutability, recycliability, remanufacturability, disposability, etc.

$Y_i(t)$ are design-independent parameters. These are factors beyond the control of the designers, but which impact the overall effectiveness of all candidate systems or design alternatives, and can significantly alter their relative desirability. Examples of design-independent parameters include cost of money, labor rates, materials cost per unit, shortage cost, etc.

$u(t)$ are estimated demand and expected environmental considerations.

$a(t)$ are technical estimates such as kinetic parameters.

$g(\ )$ and $h(\ )$ are problem constraints such as conventional material mass and energy balances from a steady state.

$c(t)$ are expected environment constraints imposed by government regulations or international standards on environmental issues.

C is a set of constraints and/or ecodesign requirements. Examples include limited energy consumption, waste treatment capacity, etc.

t is a discretized time dimension over the life of the production project.

The formulation expressed in the above equation provides a framework for the evaluation of alternative ecodesigns in the IECDM model. The design evaluation function is embedded within the model of computer-aided concurrent engineering morphology, as illustrated in Figure 3.8. The output from this mathematical model is a design-related attributes of product-system. For example, in chemical-process design problem, the attribute-outputs may specify the number, size, and time during the life of a project of engineering systems in which resources are required for green product realization and development. The life of a project is determined by how long the demand forecasting is made; it can be

determined by how long the product/material life cycle is designed while meeting recycling requirements [Blau, 1995]. In the next chapter, we develop a QFD-based IECDM methodology that is used for identification of critical design-related attributes, design-dependent and design-independent parameters, decision variables, and their relationships which, in turn, are integrated into a mathematical-based design function such as equation (3.6).

(2) Cost-Effectiveness Optimization Model: In the context of the IECDM, reducing waste at the source is more cost-effective than end-of-pipe treatment, and can provide substantial added values for both product and process. Therefore, with regard to development of cost-effectiveness models, it has become customary in the field of systems engineering to develop a cost model simultaneously with the effectiveness model, even adding the environmental issues. A few ways of dealing with cost-effectiveness comparisons are indicated in Figure 3.9. In all these models the system designer has to take due account of the available resources and how effectiveness and cost depends upon resources that will result in minimal environmental impacts by the product and its processes.

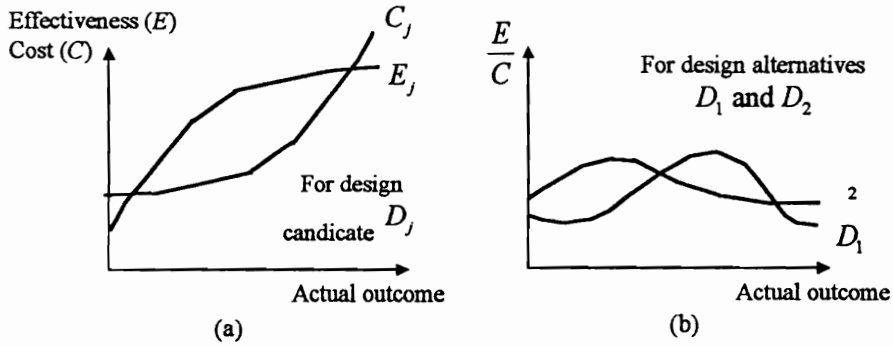


Figure 3.9. Ways for cost-effectiveness comparisons

Assume that a manufacturing system is designed for minimizing the negative environmental impacts, and the system effectiveness is proportional to that effort. Consider k types of resource; in this case, system effectiveness is in the form $e(\mathbf{r}) = e(r_1, r_2, \ldots, r_k)$ and the system life-cycle cost is $c(\mathbf{r}) = c(r_1, r_2, \ldots, r_k)$, where r_i denote the amount of the i-th resource used in the realization of the system, and in turn, the realization of minimization of negative environmental impacts. Three design problems can be formulated as follows:

$$\text{Problem I: Maximize } e(\mathbf{r}) = e(r_1, r_2, \ldots, r_k) \tag{3.7}$$

$$\text{Subject to } \quad c(r_1, r_2, \ldots, r_k) \le C$$

$$0 \le r_i \le R_i \qquad \text{for } 1 \le i \le k.$$

Where R_i is a constraint on each resource of type i and C is an upper cost allowed for the system.

Problem II: Minimize $c(\mathbf{r}) = c(r_1, r_2, \ldots, r_k)$ (3.8)

Subject to $e(r_1, r_2, \ldots, r_k) \ge E,$

$$0 \le r_i \le R_i \qquad \text{for } 1 \le i \le k.$$

Where E is a minimum performance level (requirement) for the system.

Problem III Maximize $\dfrac{e(r_1, r_2, \ldots, r_k)}{c(r_1, r_2, \ldots, r_k)}$ (3.9)

or Maximize $e(r) - c(r)$, if $e(r)$ can be expressed in units of cost

Subject to $0 \le r_i \le R_i \qquad \text{for } 1 \le i \le k.$

As a result of applying one of the optimization processes (problems) given above, an alternative corresponds to an expenditure of resources; thus, the optimal alternative is the k-tuple $(r_1^*, r_2^*, \ldots r_k^*)$ that satisfies the desired criterion formulation.

Of interest in environmental impact issues, it is possible to express the impact evaluation function as a function of system effectiveness and life-cycle cost; thus, the resulting formulation of the impact evaluation functions as one optimization problem. The problem consists of minimizing the negative environmental impact of the system subject to a set of pertinent constraints (e.g., energy limitation, waste treatment capacity) and can be written as

Minimize $EI(\mathbf{r}) = f(\text{system effectiveness, system cost})_{\text{useful life-cycle}}$ (3.10)

subject to Constraints on design for environmentability,

Constraints on system performance.

Where the system effectiveness may include reliability, maintenance, serviceability, availability, disposability, recyclability, environmentalbility, and so on. Other forms of DEF formulations and models are possible that will be discussed in Chapter 4 to show how QFD aids construction of DEF models

(Eco)Design Evaluation Display. Incorporating multiple criteria into system design evaluation allows the decision maker to select a "best" candidate ecosystem, resulting in a preferred environmentally-friendly product. Multi-criteria considerations arise when both economic and non-economic elements

(including environmental factors) are present in the ecodesign evaluation. In these common situations, ecodesign evaluation is facilitated by the use of a set of Design Evaluation Displays (DED) including three common representations: cost-effectiveness display, energy consumption profile, and environmental impacts profile; all DED address evaluation through the system life cycle.

(1) Cost-effectiveness Decision Evaluation Display: The cost-effectiveness display exhibits both cost and effectiveness measures (criteria), as shown in Figure 3.10. Effectiveness is a measure of mission fulfillment for a system (product or process) in terms of a stated need. Mission fulfillment may be expressed by one or more figures of merit, depending on the type of system and the objectives to be achieved. One or more effectiveness measures and the life-cycle costs may be displayed simultaneously as an aid in decision making. Life-cycle cost, shown on the horizontal axis, is an objective measure. This Decision Evaluation Display (DED) is useful to the decision maker in subjectively assessing the degree to which each alternative satisfies effectiveness criteria with a reasonable life-cycle cost. The goal is to select the alternative with the lowest life-cycle cost that satisfies the effectiveness measures to an acceptable degree.

When environmental factors are considered in design evaluation or optimization, the system effectiveness may be a function of environmental factors; then effectiveness measures are more complex than usual. Also cost estimation is more difficult when it includes environmental costs. Therefore, a cost-effectiveness DED is not enough for the selection of design alternatives. Other indicators of measures are required. In other words, the environment-related parameters included in the Design Evaluation Function (DFE) will impact effectiveness measures and life-cycle costs.

A formal trade-off between life-cycle cost and effectiveness measures requires the application of preference functions and utility theory. In practice, it may be also sufficient to have the decision maker or design team decide by visually inspecting a version of the DED. In any event, incorporating environmental effectiveness into the DEF will make the DED more complex, and decision-making for selection of an ecodesign system may require other visible Design Evaluation Displays: an energy profile and an environment impact profile, which might be obtained for the Life-Cycle Assessment (LCA) methods.

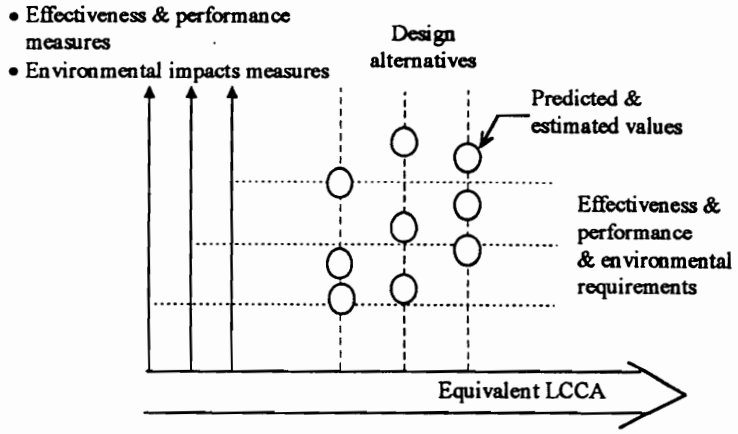


Figure 3.10. Cost-effectiveness evaluation display

(2) Life Cycle Assessment Display-Energy Usage Profile and Environmental Loads Profile: In the design process a development takes place from idea-generation to prototype construction. In this stage, the alternative design results have to be compared in terms of their possible impacts on the environment. One method for characterizing the aggregate environmental impacts for each stage and cumulative impacts for the entire product's life cycle is an *environmental profile*, such as that illustrated in Figure 3.11.

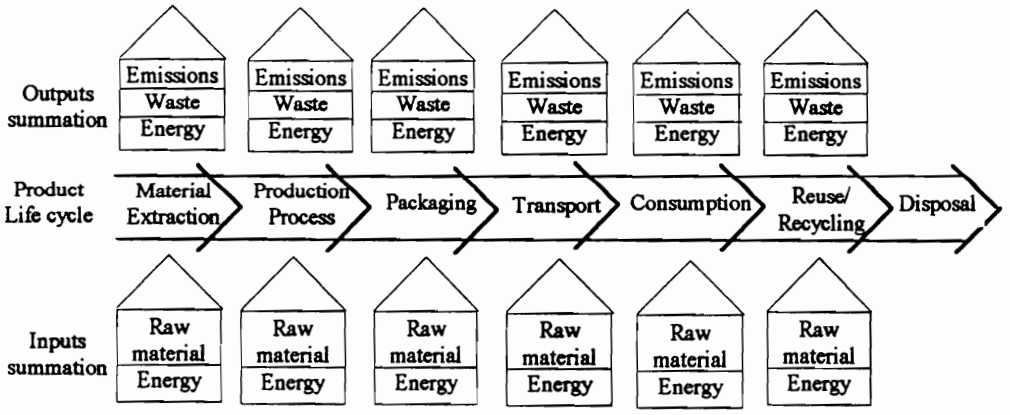


Figure 3.11. Matrix for life-cycle assessment (LCA)

During the first phases it is not possible to give detailed measurements on the environmental effects of a design alternative. The degree of detail of a environmental effects measurement depends on the degree of detail of the design; with an increasing degree of detail, a matrix for LCA has been used to measure and compare the ecological effects (e.g., energy consumption and environmental loads) of

alternative designs, as illustrated in Figure 3.11. However, to our knowledge, no such general matrix exist for dealing with LCA problem systematically (see Appendix B).

In the context of LCA, energy consumption or conservation is one of the critical issues. The energy usage profile of systems also provides an important display that helps the designer decide the "best" system. In addition, the environmental loading profile obtained for LCA is another display for ecodesign evaluation. Conducting LCA methods for alternative systems allows comparison of their overall environmental impacts, i.e., an environmental impact profile.

Operationally, the LCA technique examines every stage of the life-cycle. For each stage, the inputs and outputs are calculated, and these are aggregated over the life cycle to form a useful environmental loading-related information. These inputs and outputs are then converted into their effects on the environment, called the environmental impacts. The accumulation of these environmental impacts represents the overall environmental effect during the life cycle of the product. The profile of environment impacts can represent either between product-categories (e.g., plastic product and steel product) or between product-alternatives in the same categories. The latter representation provides a display for ecodesign evaluation and selection; see Figure 3.12.

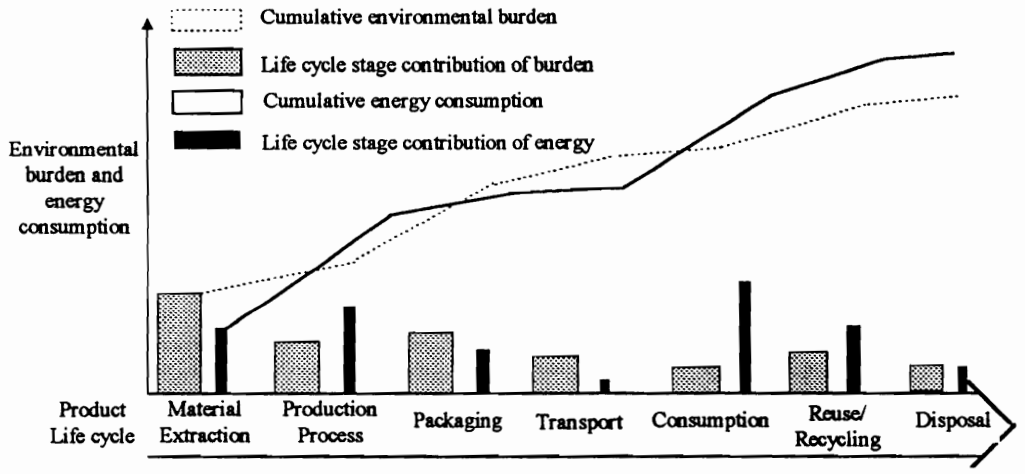


Figure 3.12. Aggregate environmental burden and energy consumption over life cycle of a hypothetical product-system.

Figure 3.12 shows a hypothetical impact profile because at present there is no universal method for precisely characterizing environmental burden [Keoleian and Menerey, 1994]. As illustrated, impacts are generally not uniformly distributed across the life cycle. It is also important to recognize that human communities and ecosystems are also impacted by many other product systems. To recycling point, secondary environmental burden caused by material-reprocessing may generate more environmental

impacts than original processing. Therefore, such secondary impacts should also be considered within recycling decisions.

Further, the profiles provide another important factor for design evaluation and optimization other than cost and system effectiveness. In other words, environmental impact profiles of candidate alternatives will allow trade-offs associated with each factor to be assessed or measured. This assessment provides motivation for integrating environmental, economical, and functional factors together into the IECDM of engineering systems.

3.3. APPLICATION OF THE SYSTEM MODELING TOOL FOR INTEGRATION

The IECDM engineering has to consider both the flow of products/materials and their linkages and relationships among the design and production activities and processes concerned. So far, we have mentioned several tools and design philosophy for the use in IECDM, such as QFD, LCA, LCCA, CE, and LCD. From the integration aspect, we need another tool to integrate these methods into the IECDM engineering process. Herein IDEF modeling technique is applied as such an integrative tool. Use of systems modeling tools, IDEF, will be necessary in order to provide a more complete and accurate picture of the interrelated activities and processes. This section introduces system modeling techniques and their potential application in ecoproduct development.

Template of the System Modeling Model. Systems modeling techniques that have proved helpful in enterprise modeling are the Integrated Computer Aided Manufacturing Definition (IDEF) modeling techniques that were developed by the Air Force's ICAM project in the late 1970s and early 1980s for use in integrated system development[2]. The functional modeling approach of IDEF is defined as IDEF0. A unit of the IDEF0 template is presented in Figure 3.13.

In IDEF0, a box represents a function (or a process or activities) to be performed. The arrows going into the boxes in IDEF0 represent the 'inputs' into the function that will be transformed. The 'outputs' are arrows that come out of the right-hand side of the activity box. Inputs and outputs simply

[2] The original IDEFs were developed for the purpose of enchanting communication among people who needed to decide how their existing systems where to be integrated. IDEF0 was designed to allow a graceful expansion of the description of a systems' functions through the process of function decomposition and categorization of the relations between functions (i.e., in terms of the input, output, control, and mechanism classification). IDEF1 was designed to allow the description of certain information that an organization deems important to manage in order to accomplish its objectives. The third IDEF, IDEF2, was originally intended as a user interfaces modeling method. IDEF3 was designed to the representation of process descriptions, it aims at producing high-level, general-purpose descriptions of processes, i.e., IDEF3 models. IDEF4 was developed to support the design of object-oriented software systems programmed in such languages as C++, Flavors, CLOS, or Small Talk. IDEF5 is a method for capturing domain ontologies.

represent what enters and leaves the function box repetitively. The arrows going into the bottom of the boxes represent 'mechanisms'-- anything that will be able to carry out (perform) the function (activity). The arrows going into the tops of the function boxes are the 'controls/constraints' that represent limitations of the 'function.'

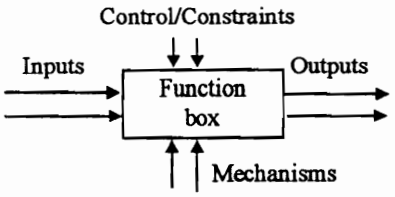


Figure 3.13. The IDEF0 template (ICOMS)

System Modeling of the Product Realization Life-Cycle. The ecoproduct development life-cycle shown in Figure 3.14 represents such IECDM-related approaches as concurrent engineering, Life-Cycle Design (LCD), and Life-Cycle Assessment (LCA), - where the ecoproduct is designed for a number of future life-cycle occurrences (or down-stream activities) such as manufacture, maintenance, recycling, demanufacture, and disposal.

Concurrent engineering is a systematic approach, as mentioned, which is employed in the IECDM model to integrate the simultaneous design of products and related processes, including manufacture and support as well as management, in order to meet design requirements (criteria) including environmental design requirements. Thus, the objective of the IECDM is the simultaneous consideration of the life-cycle impacts during preliminary product system design, along with the immediate consideration of functionality, quality, and costs as shown in the engineering function box. In the context of the IECDM, this objective includes consideration of user requirements and environmental regulations, manufacturing and environmental costs, quality control, production planning and scheduling, marketing and packaging, recycling and remanufacturing, demanufacturing and disassembly, and disposal characteristics. The relations of these characteristics within the ecoproduct development life-cycle are identified in Figure 3.14.

Figure 3.14 represents a general (high level) IDEF0 representation of four processes of the ecoproduct realization life cycle (RLC). The activities are represented in the boxes. These include performance of the IECDM engineering design (including analysis, synthesis, and evaluation), manufacture of the product, the maintenance of the product after it reaches the market, demanufacture of the returned product after its end-of-life, and disposal of the remainders and retreat products.

As shown in Figure 3.14, the customer and environmental requirements should be explicitly considered as constraints (top arrows) when ecoproducts are designed. The accepted product is an output (arrows that come out) of the manufacturing activity, as well as a by-product (waste). For the manufacturing function box, the mechanisms are usually the tools, personnel, and equipment necessary to carry out the transformation (activity). The boxes that perform the IECDM engineering and product design decisions are focuses of the research.

Another feature of the IDEF0 modeling technique is its decomposition relationship among processes and ICOMs at various levels of detail. In implementing IECDM strategies, there is a need for research into the use of IDEF and other integrated, structured methodologies (such as LCA, LCCA, QFD) to help in the evaluation and assessment of the ecoproduct life-cycle, including product retirement and recycling. Development of standard and generic ecoproduct realization life-cycle processes for various products can help a number of organizations develop their own particular models, especially those organization that have limited resources. In addition, we need to determine the role of these structured methodologies in developing practices that will help protect the environment. The IECDM methodology focuses on using these structured methodologies to help in the analysis of products, processes and techniques and of their relationships to each of the strategies, by using system modeling techniques.

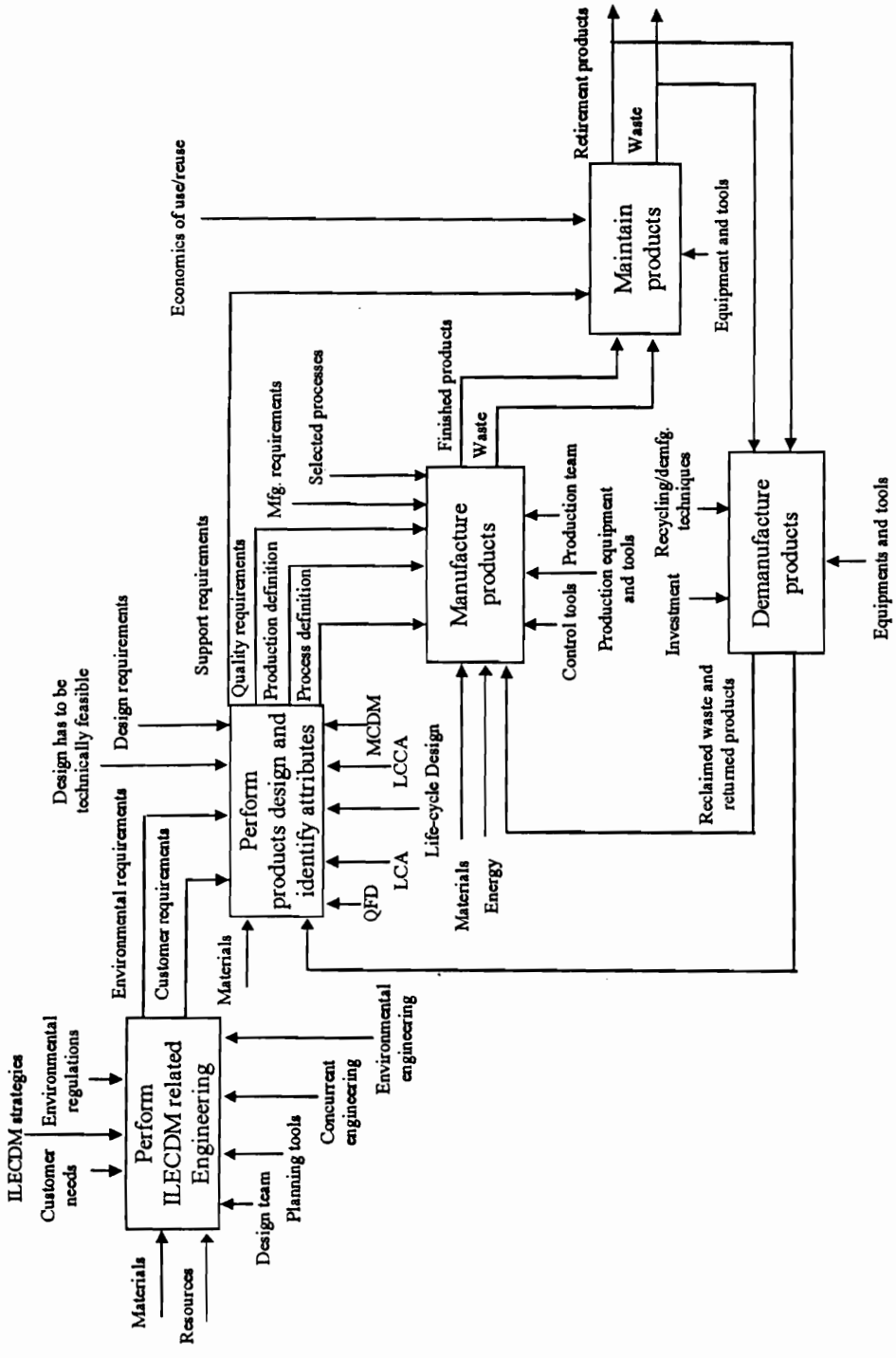


Figure 3.14. IDEF0 representation of life-cycle model for the ecoproduct realization system

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CHAPTER 4

DEVELOPMENT OF A QFD-BASED IECDM METHODOLOGY

4.1. INTEGRATING ENVIRONMENTAL REQUIREMENTS INTO PRODUCT DESIGN
- 4.1.1. The Basic QFD-Process
- 4.1.2. Integrating Environmental Requirements into QFD for Environmental TQM
- 4.1.3. A Template for IECDM Implementation

4.2. PROCESS STEPS FOR QFD-BASED IECDM METHODOLOGY
- 4.2.1. Step 1: Problem Scoping and Identification
- 4.2.2. Step 2: Model Construction Planning and QFD Construction
- 4.2.3. Step 3: Multiple Phases Decision Execution
- 4.2.4. Step 4: Multi-attribute Decision Making and Multi-objective Optimization
- 4.2.5. Step 5: Experimentation
- 4.2.6. Step 6: Evaluation and Selection the Best Design Alternative
- 4.2.7. Step 7: Implementation Based on QFD Information

In previous chapters, we postulated many critical factors that force designers to take a new look at how we can implement an IECDM model so that a firm can successfully develop an acceptable green product; such as environmental issues, consumer needs, legislative concerns, recycling and waste disposal concerns, competitiveness issues, and a changing design world. Consequently, having defined IECDM engineering in Chapter 3, it is necessary to develop a framework and infrastructure for IECDM development. Briefly, the methodology developed in this chapter addresses the achievement of the theoretical discussion in Chapter 3 by exploring QFD methodology application in IECDM.

This chapter aims to develop a general procedure for implementing IECDM strategies in a firm with the help of a well-structured QFD framework. This chapter will explore the idea of planning (eco)product design for the entire product life cycle. It seeks to illustrate how QFD-related methods can be an additional decision-making framework to help designers consider environmental requirements into the product. We conclude that structured design methodologies such as QFD can be adapted for the implementation of IECDM.

4.1. INTEGRATING ENVIRONMENTAL REQUIREMENTS INTO PRODUCT DESIGN

QFD is a key enabling technology for IECDM engineering discussed in Chapter 3. It is used to deploy needs and environmental requirements for product design and manufacturing. QFD emphasizes multi-functional teams and helps to integrate all corporate functions so that they are responsive to the customer's requirements and to environmental impacts. Thus, ecoproduct planning, product ecodesign, processes planning, production planning, and demanufacturing planning can provide a coherent response to customer needs and the company's IECDM strategies. In this section, we discuss the typical QFD process and point out how to address environmental impacts into QFD for TQM. Then a template of the QFD-IECDM approach is proposed.

4.1.1. The Basic QFD-Process

QFD has been used by the automation industry since the 1980s and is being included in the quality programs of many major corporations today. The objective of QFD is to focus on quality issues, naturally including environmental quality, early in the product-system life cycle, by building chart, called Houses of Quality (HoQ) that illustrate the relationships between customer (requirement attributes), engineering design characteristics (design attributes), and the product's manufacturing processes. QFD also provides discipline to the (design) decision-making process, so that all requirements are taken into account, decisions are documented, and all information is brought to bear. Briefly, the most attractive feature of QFD is the focus on integrating customer requirements and environmental impacts into product design.

Before a well-constructed QFD matrix expresses the interrelated information of product, process, and production requirements simultaneously, QFD should be processed four basic phases. QFD has been defined by the American Supplier Institute (ASI) as:

> *"A system for translating consumer requirements into appropriate company requirements at stages from research and product development to engineering and manufacturing to marketing/sales and distribution [ASI, 1987]."*

Through a series of interactive matrices and sequential decision-making, QFD can be employed to address virtually any business situation requiring a decision involving a multitude of criteria, requirements, or demands. QFD is a highly structured technique that contains five phases (as illustrated in Figure 4.1). Each level of the QFD-relationship matrix uses "Hows" selected from the previous level as "Whats." QFD provides a system to address customer environmental needs as part of broader design efforts. To achieve this goal, the four basic phases of QFD must be processed (see also Sullivan [1986]) as follows.

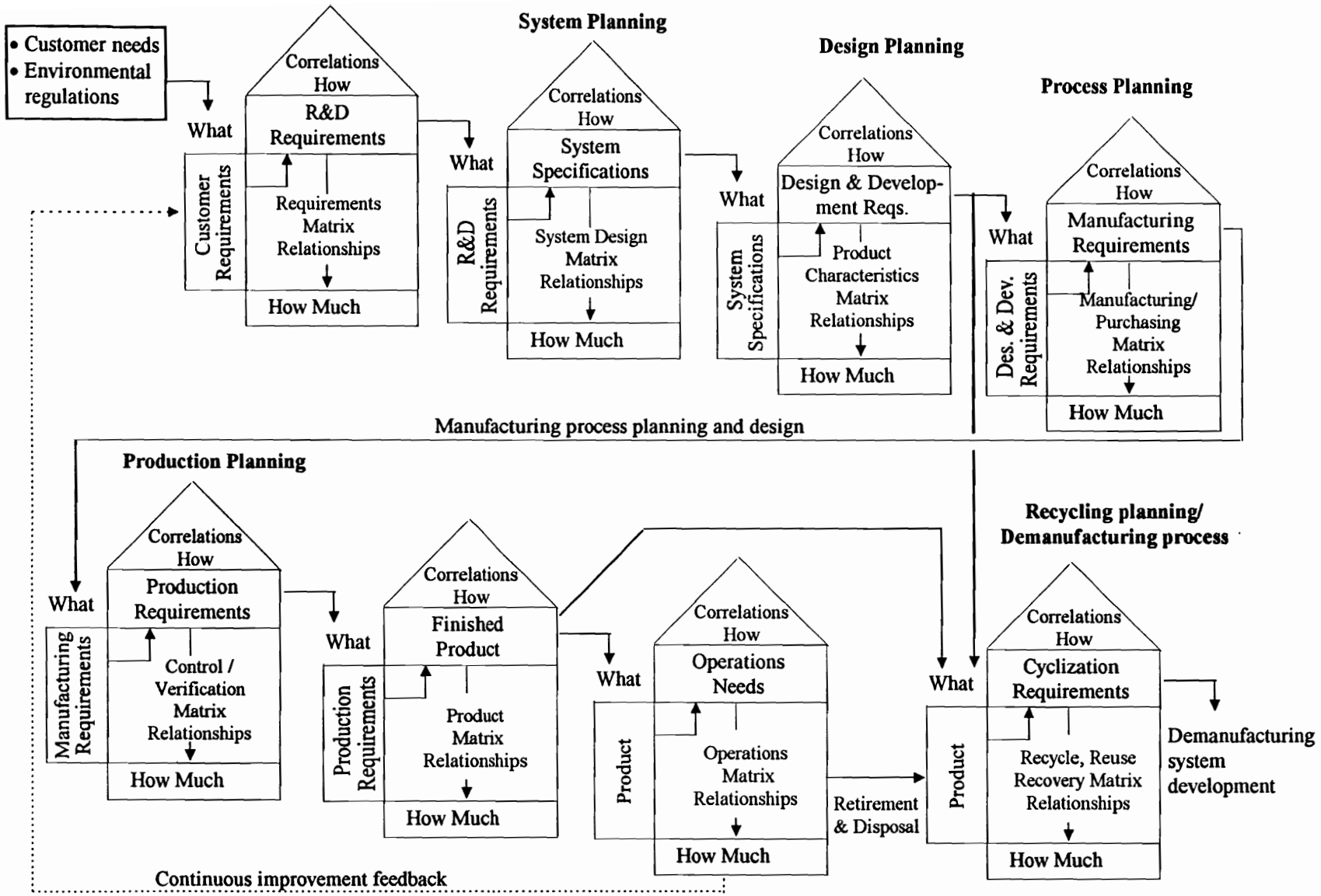


Figure 4.1: A phased application of QFD methodology

Phase 1: QFD-Planning matrix. The QFD team analyzes the voice of the customer and deploys customer demands through the design characteristics of the system. In the product planning phase, customer requirement planning translates the customer's expectations (rows of matrix) or the "voice of the customer" into the desired and specific product characteristics (columns of matrix). The QFD team is concerned with identifying technical requirements such the "Hows" that satisfy customer wants and the "Whats" that may include environmental needs. Marks made within the matrix represent relationships between customer requirements and product characteristics.

Phase 2: Design Function Deployment (DFD)--Deployment matrix. The QFD-team translates system characteristics into requirements of subsystems and components, also the techniques' characteristics, to more detailed analysis. In the design deployment phase, the design deployment matrix lists all customer requirements and product characteristics in greater detail, so that the critical subsystem/component characteristics can be identified. Product specifications convert the customer requirements plan for the finished product into its subsystems and the demand of subsystems' engineering characteristics. Consequently, subsystem specifications are converted into their components and the components' demands of characteristics, and so on. For large systems, such conversions may cover several layers of DFD, depending on actual design requirements. In this phase, the QFD-team identifies the subsystems' characteristics as "Hows" needed to satisfy the product's technical requirements identified in Phase 1 that are now treated as "Whats." In this phase, if the design-team includes environmental-design requirements (criteria) in the product designs in terms of deployed metrics, the resulting products might be more easily disassembled for the recycling purposes.

Phase 3: Manufacture Function Deployment (MFD). The QFD-team plans the operations and processes that will produce the key parts, components, and subsystems. In the process planning phase, production process and quality control plans identify design and process parameters critical to the achievement of the requirement. The process plan chart shows the relationship between manufacturing processes and critical component characteristics, as well as where monitoring points for the process are most needed. The quality control chart includes a schematic of the process flow and describes the necessary control points by location, type, and frequency of use. The QFD-team identifies the process characteristics as "Hows" that lead to the subsystems/components/parts characteristics in Phase 2 that are now treated as "Whats." In this phase, environmental criteria are added into manufacturing-system and operation-process designs, so that the resulting processes might become more environmentally-friendly.

Phase 4: Operation Function Sheet. The QFD-team chooses the control steps that will ensure the predictability and reliability of the operating processes. Operation-process sheets, derived from the process and quality control plans, are the instructions to the operator. This document describes operations which plant personnel must perform to assure that critical product requirements are met. The QFD-team defines the production requirements as "Hows" to achieve the process characteristics identified in Phase 3 - now treated as "Whats." Operating processes may express the recycling processes associated with PROs or MROs in order to explore recycling policies. Also, the operating-press sheet should include all inputs/outputs information (in terms of energy, emissions, and waste) if possible, for environmental impacts assessment.

Used properly, these four phases of the QFD deployment system help the ecodesign team deploy diverse customer requirements, including environmental requirements and regulations. They also help designers prevent conflicts at every major point along the value chain and the end-of-life value of the product. Through linking associated QFD charts, tractability of requirements and environmental effects throughout a product's life cycle can be performed.

4.1.2. Integrating Environmental Requirements in QFD for Environmental TQM

This section discusses how environmental issues are considered into QFD process for green design and Environmental TQM efforts.

Incorporating Environmental Requirements into Design. QFD methodology is used for integrating environmental factors into product design. Building environmental dimensions into the QFD system, design teams can streamline their responses to customer environmental requirements while meeting governmental environmental regulations. Design For the Environment (DFE) takes creativity, hard work and a different mind-set on the part of not only the manufacturer but the customers as well [Kuhre, 1995]. Kuhre proposed a standpoint as:

> "*The customer has got to be willing to accept a product that may not be quite as high in quality. In place of perfect quality the customer would get a product with reused parts or environmentally friendly components.*" [Kuhre, 1995]

This standpoint may not be true for defense-type products such as weapon systems. However, it is increasingly accepted for commercial products and services generally and reflects the fact that customers are becoming more and more environmentally consciousness. In other words, a product may not be able to perform without error in exchange for one that contains recycled parts or can be easily disassembled and recycled. Everyone has to give up a little if design for the environment is going to become a way of life.

Nevertheless, the QFD approach can be used to incorporate with customer's voice in DFE into other performance needs and wants. In such situations environmental factors (or criteria) have a highest priority among all the design considerations.

In addition, owing to the flexibility of the QFD, it is taken as granted to enhance the QFD by considering the environmental effects in each phase. Accordingly, environmental factors are included among the customers' needs, product-design requirements, and manufacturing-process implementation. As mentioned above, DFE may integrate environmental issues into market, demand, and performance issues into a product's engineering characteristics with the help of QFD. Broadly speaking, one can look at DFE within QFD in the following ways:

- to evaluate the relative importance of environmental considerations in the design of a product and its manufacturing process through the product's life-cycle,
- to determine what, when, and how environmental criteria are included in product development through the different QFD-process phases,
- to flesh out the extent to which certain measures of design-for-environment have been implemented and, in turn, the degree to which environmental impact has been evaluated.

The concept of integrating environmental requirements into QFD and the design process can also be found in the works of Hochman and O'Connell [1993], Berglund [1993], and Ovorby [1991]. According to Hochman and O'Connell [1993], QFD can provide a systematic approach to addressing customer environmental needs as part of broader system (product and process) design efforts. However, there is little evidence that even the most quality-oriented companies are accounting for customer environmental demands in the context of the their QFD initiatives. The reasons may be:

- Few companies have made efforts to identify or understand customer environmental demands;
- Customer environmental requirements are often latent and long-term, rather than explicit and immediate;
- Environmental staff tend to have limited or no training in identifying customer requirements and are rarely involved in design projects; and
- Even when customer environmental needs are measured, managers who control the QFD process often disregard significant environmental factors for the sake of short-term expediency.

Nevertheless, forces from outside the company, such as market competition and federal environment-related legislation, enforce designers to reconsider considering the environmental requirements part of the 'voice of customer.'

The environmental issues associated with industry present a unique challenge to the traditional QFD models. According to Hochman and O'Connell [1993], by building environmental dimensions into

the QFD system, design teams can streamline their responses to customer environmental requirements. Quality may be about achieving a maximum level of customer satisfaction with a minimum amount of waste and resource use. Using QFD-process, the customer's needs for environmental quality (for example, can be upgraded, conserves energy, recycled, etc.) can be converted into the product's design characteristics (for example, ease of disassembly, percentage recyclable plastic, percentage recycled plastic, reportable quantities, and power consumption). In turn, the process engineer has to design or modify the manufacturing process to meet the environmental requirements of production planning.

Berglund [1993] proposed a similar concept: that QFD is a critical tool in environment-related decision making during a product's life cycle. Since the overall purpose of QFD is to give proper consideration to the voice of the customer in a generalized sense, specific efforts need to be directed at understanding every interface in which environment issues might affect the proposed product and process. Therefore, the customer's environmental needs should be integrated into QFD matrices in different phases. For example, the customer's environmental needs may include reduction in hazardous properties, pollution prevention potential, recoverable byproducts, reduced liability and safety costs, reduced waste management costs, improved disposition into environment, reduced sudden release potential, etc. These needs can be converted to product-characteristics that include waste characteristics of product, such as recoverable byproducts, waste disposition techniques, waste treatment requirements, etc. Another example, if we were to include environmental 'design criteria' for disposability in our product designs, the resulting products might become easily recyclable as products, or to basic materials [Overby, 1991].

Deploy QFD for Environmental TQM. QFD is a method for achieving product quality. The quality concepts of QFD help the design-team to realize how very important it is to 'get the thing right' at the earliest phases of the green design process, which then shortens the time-to-market. QFD's quality-based 'defect prevention through design' parallels the ecodesign-based 'environmental pollution (impacts) prevention through designs.' With respect to quality, environmental impact prevention also seeks the highest environmental quality with the smallest impacts. 'Quality' concepts should help designers to expand design requirements and criteria to include environmental design requirements for all phases of a product's life cycle. In addition, QFD views 'quality' as the avoidance of loss, not the compilation of benefits, in the same manner as environmental quality is achieved through impact reduction, not through environmental benefits.

Furthermore, TQM is another important reason for using QFD-process. Practitioners of TQM should know that environmental impact and risk reduction through product design are consistent with TQM [Freeman *et al.*, 1992]. The well-known Taguchi method, QFD, is an example of a method for achieving a product's environmental quality. In developing a new product, the relationships among the

customers' quality-related requirements, system design, and manufacturing must be understood. The quality-information from feedback must be maintained at each stage of product planning, trial design, manufacture, assembly, and inspection, [Maduri, 1993]. Hence, a TQM system is required to ensure desired quality in the product at every stage. From this standpoint, the QFD technique aids in the TQM manufacturing environment. QFD-process can be used efficiently throughout the planning stages, including product planning, design deployment, process planning, manufacture/assembly planning, and service planning as well as recovery planning. When environmental quality becomes a part of engineering design criteria, it should be possible to compound these environmental requirements (such as, remanufacturability, disassembality, recyclability, disposability) together with other factors, translating into design requirements at the first stage of the QFD-process.

4.1.3. A Template For IECDM Implementation

For a large extent of green design, our proposed IECDM challenges some of the commonly held views about the nature of ecodesign. Some of these are: (1) ecodesign is a routine process, (2) ecodesign is an innovative process, (3) ecodesign is a problem-solving process, (4) ecodesign is a decision-making process, (5) ecodesign is an evaluation and optimization process, and (6) ecodesign is a team-work effort. Above all, the most challenge is to incorporate environmental concerns into product and process design. Taking advantages of QFD techniques, we will develop a generic QFD-IECDM methodology for solving ecodesign problems in the ECDM domain.

Essential Features in IECDM. The IECDM is implemented in a way that enables environmental requirements to be integrated into the modified QFD process for environmentally oriented product development and environmental TQM. The step-by-step QFD-based IECDM approach (corresponding to design synthesis, analysis, and evolution/optimization activities) involves integrating different design-methodologies and approaches, resulting in a logical process for green product design and development. This chapter will show how designers might use QFD quality approaches to enhance product and process design efforts so as to achieve an integration of environmental quality and functional performance quality.

In an attempt to describe the rapidly growing field of environmentally-oriented product development, three main approaches are often used: product/material-oriented approach, system-oriented approach, and life-cycle approach. A product/material-oriented approach aims at optimizing the environmental attributes of product and material as well as processes within the constraints of the existing supply/production/consumption chain (i.e., the industrial ecology). A system-oriented approach aims to

broaden the scope of optimization, including changes in the supply/production /consumption chain itself, which leads to an ecodesign concept for both products and processes. A life-cycle oriented approach aims to assess or measure the impacts of products, processes, and activities through their life cycle. Some methods include life cycle analysis (LCA), life cycle cost assessment (LCCA), Total Cost Assessment (TCA), among others. Generally, the purpose of these methods is to quantify environmental impacts in terms of unit emissions, resources, waste, dollars, or other matrices. Environmental considerations during product planning, design, and development can help industries minimize the negative environmental impact caused by products and related processes. Changing product design to prevent such impacts, engineers and designers should maintain the quality or function of the product with minimum related cost. Therefore, the IECDM should be implemented in multiple dimensions: economic, environment, quality, performance, and time. These multiple dimensions should be reflected in QFD-based IECDM process.

Applying Structured Design Methodology in IECDM. Structured methodologies are widely associated with successful product development. Structured methodologies such as QFD, Analytic Hierarchy Process (AHP), have contributed to the rapid design of low-cost, high quality, customized products. Among these methodologies, QFD will be selected as the template to implement our proposed IECDM methodology. The QFD-IECDM process proposed in this chapter takes advantage of QFD techniques to help designers in design-evaluation and optimization procedures. It defines requirements and sets competitive benchmarks towards specific functional and esthetic design targets. It is particularly useful in defining society's and environmental compatibility requirements for implementation of IECDM strategies in a firm as well. Briefly, QFD is selected as the basis for implementation of IECDM for following reasons:

- The difficulty of dealing with hybrid multi-attributes (quantitative and qualitative) can be represented in QFD matrices;
- QFD is flexible, and able to integrate different methods in the product development life-cycle from small-scale to large-scale design problems.

Environmentalism, like the quality movement, challenges companies to do what is good for them: perfect their manufacturing processes [Kleiner, 1991]. But the questions that stem from this follow: How can companies implement environmentally conscious design and manufacturing ? How can they reduce waste at the source ? How can they engage design-for-environment successfully? TQM stresses that quality (including environmental quality) must be designed in rather than tested for at the end of the production process. This concept is also suitable in the proposed IECDM model, in which activities begin at the product design level and stress the selection of manufacturing processes that allow both waste reduction at the source and design product's environmental quality.

A particularly problematic aspect of any DFE method is finding techniques to measure and compare the environmental impact of the choice of a product and its manufacturing process design. In other words, how do we measure green design ? How do we measure environmental impact ? Furthermore, there are many complex interactions with the environment in each of the product life-cycle stages. It is necessary to develop design attributes matrix, and this is the only way to help designers measure the environmental impact of ecoproduct and its process simultaneously. Considering the complexity of the industrial ecology system and life-cycle analysis, it would be very convenient if there were a set of design metrics to aid in modeling this process. The QFD process is employed to achieve such quantification efforts.

Quantification of the IECDM decision-making problem is essential. Appropriate IECDM metrics and measurement tools are necessary to understand the baseline environmental quality of existing products and their production processes, and evaluate the development of alternatives. These tools and metrics are then institutionalized as appropriate. Nevertheless, evaluation of environmental impact of a design is based on a LCA of the various processes involved from raw material extraction to product disposal. The notion of LCA is based on system models, that is, product and manufacturing systems.

Without loss of generality, there are two basic evaluations associated with the IECDM problem: system effectiveness and environmental impacts. Basically, system effectiveness (*SE*) is defined as a function of the product design and manufacturing process that is in terms of design decisions and manufacturing system efficiency, respectively. The environmental life-cycle impact (*EI*) is defined as a function of system effectiveness and waste generation during the product life-cycle. These functions are expressed as:

$$SE = [\text{eco - product design, eco - manufacturing process}]_{\text{product useful life}}$$

and

$$EI = [\text{eco - manufacturing system efficiency, waste generation}]_{\text{product useful life}}$$

The model for environmentally-conscious manufacturing is based on case-by-case information for assessing the environment: in very simple terms, the generation of waste. A systematic process is required to integrate environmental and other different conflict factors into a design evaluation function. Among existing tools, QFD is selected as an aid to identify design-related attributes for formulating Design Evaluation Function (DEF) in the environmentally-oriented product development cycle.

The Template of QFD-Based IECDM. Similar to general design concerns in product development, environmental concerns with ecological product development also have technical, economical, and ecological policy dimensions. Technical aspects include the extent and type of pollutant

releases to the environment, their pathways and impacts, and the feasibility and performance of technologies to control them. The economic feasibility of technological solutions to environmental problems has also received considerable attention through LCCA methods. Ecological policy issues (e.g., recycling policy) associated with demanufacturing processes are not independent of technical and economical aspects. The LCA approach for estimating environmental impacts, life-cycle-engineering development with respect to technologies, and economical analysis of cost-benefits affects ecological policy issue with many intangible factors which must be considered in the IECDM approach. Therefore, the IECDM problem is characterized by multiple technical, economical, and ecological dimensions.

Figure 4.2 illustrates the template of the generic QFD-based IECDM methodology which is developed for the use in (eco)design activities of synthesis, analysis, and evaluation as discussed in Chapter 3. As shown at the top, the fundamental goal of IECDM is to promote sustainable development at the global, regional, and local level. Simply, sustainable development seeks to meet concurrent needs without compromising the ability of future generations to satisfy their needs. Essential elements of sustainable development include pollution prevention, resources conservation, environmental quality, human health, and maintenance of ecosystem structure and function [Keoleian, 1995]. Stated succinctly, the IECDM approach seeks to minimize environmental impacts and utilize resources efficiently while meeting basic societal needs. In this case the importance of the environmental issues of customers' preferences and regulatory laws is emphasized. These efforts are all in terms of finding product's TLCV problem as defined in Chapter 1.

For successful implementation of green product design and production, four important efforts (goals) should be considered simultaneously. They are: eco-factory design and layout, product eco-design, production process eco-design, and manufacturing system design. All these goals have their own attributes that are used to determine the design alternatives for the product and its processes. To determine the best design alternative, multi-attribute decision-making techniques and other methods are employed in the design evaluation and optimization procedure. QFD process is applied for identification these design alternatives and related attributes.

As shown in Figure 4.2, first the environmentally-oriented product development (or substantial development) is defined as development of a green system that meets customers' needs and regulatory requirements. The industrial ecosystem is restricted as the global objective which is a multi-disciplinary study of industrial and economic systems and their linkages with fundamental natural systems. These objectives include legal, economic, along with other incentive systems, methodologies, and tools, which also contain data and information by which society provides the necessary and appropriate support for efforts by individuals and firms to implement the principles of Industrial Ecology.

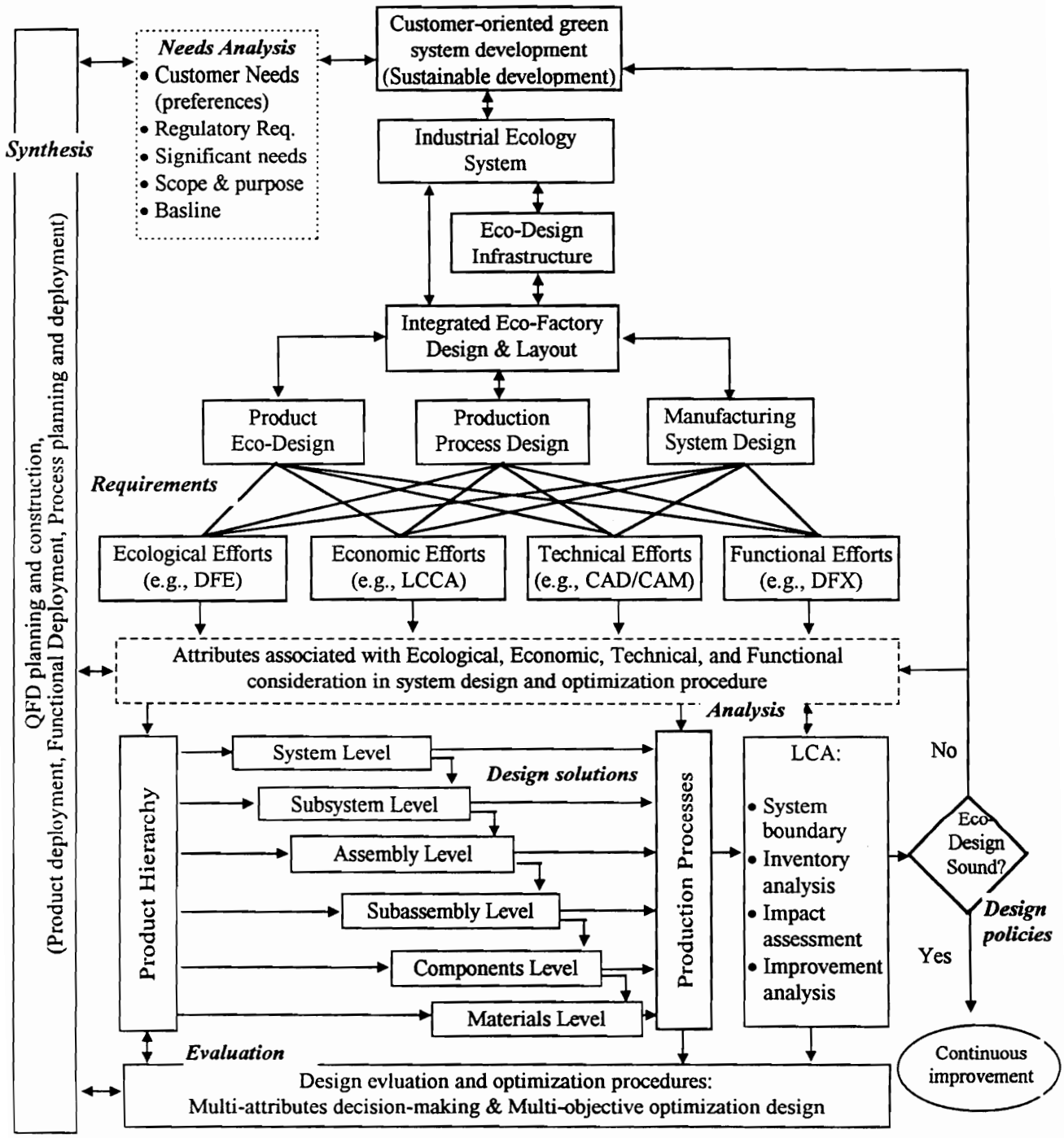


Figure 4.2: A framework of QFD-based IECDM methodology

Generally, green design in Industrial Ecology is concurrent with respect to product and process as well as facility/equipment design, since the product design and the manufacturing process sequence are coupled with the production equipment itself. Hence, a 'green design tool' must be able to provide an 'optimal green design' that has minimal environmental impact with respect to product, process, and production system. The infrastructure is considered for the eco-product, the eco-manufacturing process, and the eco-production system. These are generally characterized by ecological, economic, technical, and functional entities (criteria) that are associated with many different attribute (with single-level or multi-levels). These attributes are employed for tradeoff analysis during the design procedure.

Ecological efforts characterize the environmental effectiveness of QFD-based IECDM process. For example, DFE is the implementation of the principles of industrial ecology, and is achieved by ecodesign efforts. The term 'ecodesign' indicates a design activity aimed at connecting what is 'technically possible' to what is 'ecologically necessary' in order to inspire socially and culturally acceptable new proposals which result in green products. Environmental economic considerations involve green-accounting and life-cycle costing (for example, LCCA methodology), which are integrated into QFD-based IECDM process. The technical considerations can be achieved by adding environmental criteria and extending existing CAD/CAM/CAE systems. Then DFE activities (e.g., design for disassembly and design for recycling) can be completed with the help of CAD/CAM and CAE systems, in which green technology considers waste elimination, waste measurement, etc. Functional effort considers system operational performance, system behavior, and its quality. These functional efforts may require DFX approaches to consider various design activities simultaneously. On the basis of the tradeoffs of design attributes, design alternatives (solution alternatives) of eco-product and the eco-process are determined.

Finally, in order to accurately account for environmental factors, it is necessary to incorporate elements from LCA methodology into the IECDM methodology. For large and complex design problems, decomposition techniques may be required. For example, a product may be decomposed into its hierarchical structure. Designers can formulate IECDM problems by extending the existing methodology while taking function, feasibility, and economics with environmental criteria into account. The eventual design will, as always, be a weighted balance between various requirements and possibilities (see Figure 1.7). On the other hand, analysts involved in LCA development will offer useful data replies to the questions defined in particular IECDM problems. Environmental data and LCA results will have to be made available to designers in the form of databases, structured in a way that allows meaningful use in the QFD-IECDM methodology.

4.2. PROCESS STEPS FOR QFD-BASED IECDM METHODOLOGY

(Eco)design should not merely meet product functional requirements derived from customer's needs and wants; environmental requirements and elegance should be a part of engineering culture and design practice. Selection and design of products and product-related manufacturing processes should incorporate environmental constraints and objectives at the outset, along with functional and economic factors. Unfortunately, most engineering design textbooks do not reflect the necessity of integrating environmental impact considerations with product design, either as part of design constraints or part of objectives. Most existing engineering design texts do not reflect the importance of the life-cycle based system approach together with environmental requirements into the QFD-process that we will focus on below are quite closely related to green design.

The QFD-based IECDM template proposed above (Figure 4.1) provides the template used in this section for integrating major concepts and approaches to incorporate environmental design-requirements in QFD-process throughout a product's life-cycle. The QFD-IECDM methodology is a method of implementing DFE and LCA in an effective and efficient way to produce green product/process. The step by step development of this methodology is as follows.

4.2.1. Step 1: Problem Scoping and Identification

In this step, green design-related problem in the ECDM domain is identified, including system boundary, design goals and objectives. For example, in our study, we define the unique objective on maximization of a product's TLCV (Total Life-Cycle Value), based on LCC assumption, in the boundary of product development cycle. The identification is completed by following activities:

(1) Identify problem: Decide what business the company is in by matrix data analysis, as illustrated in Figure 4.3. Each firm has its own unique environmental problems that needs to define its own problem in the ECDM domain.

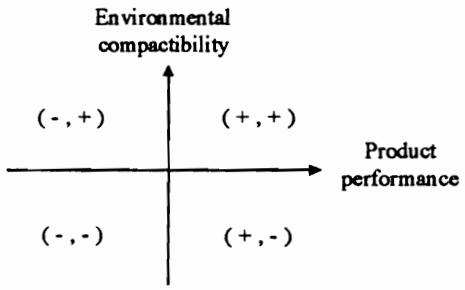


Figure 4.3. Illustration of matrix data analysis (an example).

(2) Define the problem using cause-and-effect analysis: In order to acquire as many parameters related to environmental issues as possible, the problem will be defined as generally as possible. On one hand, the problem is defined by the design department responsible; however, requirements made by the customers can be translated into technical terms by means of the QFD approach. The current outer dimensions can be considered the boundary conditions. Furthermore, brainstorming may be used with regard to all possible influential factors (or parameters) when determining the main influential factors (causes) of the problem associated with an environmental impact. As many as possible of the causes that make a critical contribution to environmental impacts must be pointed out. Figure 4.4 illustrates an example of such an effort.

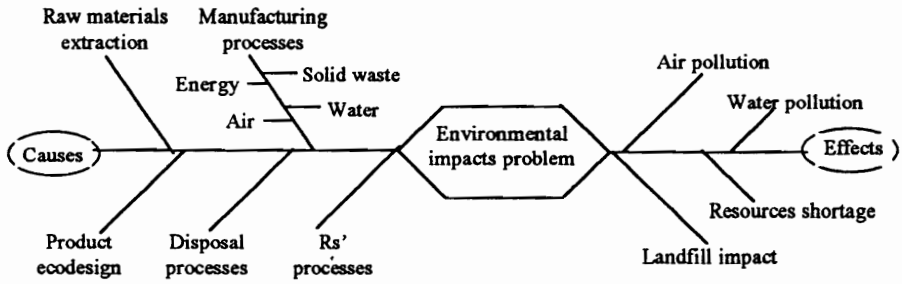


Figure 4.4. A cause-effect diagram for defining environmental impact problems.

(3) Define system boundary (solution space) under review: It is not always easy to define where to find the beginning and end points of the life cycle analysis, but it is necessary to define the system boundary. Two life-cycle analyses of the same product may be carried out, but with different system boundaries, and it is possible that they will produce two different results, each highlighting an area of concern.

(4) Define principal design goal/objectives: Input-output analysis is also used as a technique for helping to define design problems. It provides a framework for guiding our thinking about the design of engineering systems and products. Figure 4.5 shows the general approach of input-output analysis and definition of design objectives.

(5) Need analysis: Determine "voice of customer" from market research arrows (as illustrated in Figure 4.6) and survey results matrix. Figure 4.6 shows the relationship between physically fulfilled conditions and the satisfied feeling of the user. The arrow "available feature" represents the cases where the customers-related wants are given to one, and one gives it to them, and they are satisfied. This arrow comes the closest to specifications. The arrow "required functions" on the bottom represents the items that are expected and must be there to satisfy customers who take these items for granted. Customers are

dissatisfied if these items are missing because the items are expected. The arrow "attractive quality" at the top represents the items the producers or service providers develop themselves. The items can satisfy but not dissatisfy. The customers do not know about the items so they cannot expect them.

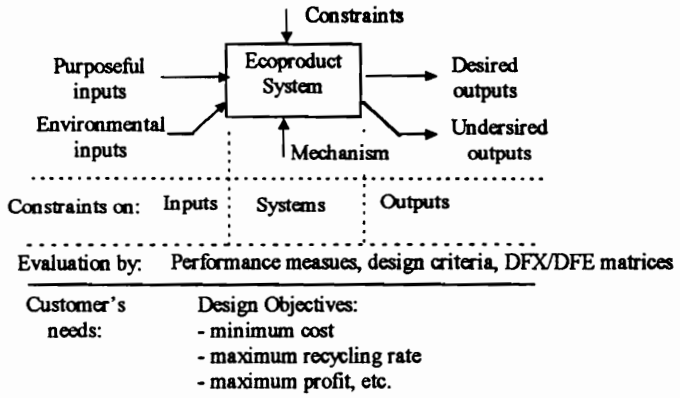


Figure 4.5. Input-output analysis [Lewis and Samuel, 1989, with modification]

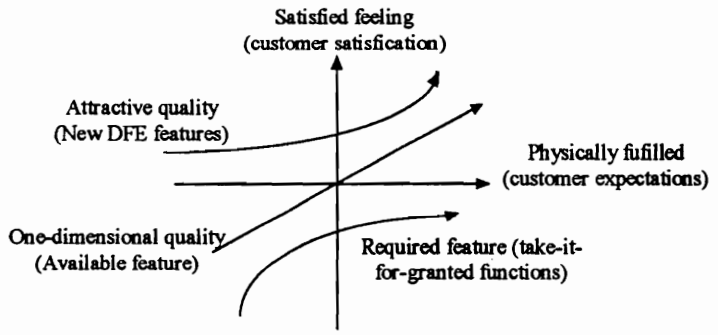


Figure 4.6. Customers' quality perceptions

(6) Organize the customers' needs using the affinity diagram: The customer segments in the affinity diagram will be copied into the customer requirements hierarchy diagram. Customer and regulatory responses to environmental problems are integrated into data collection in the affinity diagram.

(7) Obtain the relationship between objectives and customers' needs: The relationship is obtained by including environmental requirements in the set of customer needs that must be satisfied, system designers will be motivated to focus on development of an environmental-friendly product. Customer's needs correspond to the objectives of the system design. Relationships are represented in QFD matrices.

4.2.2. Step 2: Model Construction Planning and QFD Construction

In this step, we have to plan the green design process by using well-structured QFD methodology for the use in the design management and implementation. The QFD-based IECDM approach encourages asking more interactive questions, and therefore answers more complex questions in the context of green product design and development cycle. It is not easy, but it can be implemented and used effectively and logically to produce answers (e.g., product design alternatives) that solve complex ecodesign questions problems about interactions that are between customer needs (including environment-related needs), between product-related attributes and requirements; and then prioritizing these interactions, interactions between QFD and other methodologies as well. The central feature of this ability is the use of the QFD/HoQ-relationship matrix.

QFD/HoQ-Relationship Matrix. The setting of the overall product/process-related attributes is performed at this point. The customer and/or environmental requirements together with the design engineering requirements and demanufacturing capabilities are translated to a Function Dependence Matrix (FDM) in each QFD phase and/or each product's design level through QFD process. The CE concept and design synthesis are performed at this step, where FDM is set by the simultaneous interaction between design engineering, (de)manufacturing engineering, market research (voice of customer), and environmental considerations. The resulting FDM will be employed for further design analysis and evaluation/optimization.

Matrix methods and QFD are emphasized in the IECDM approach that involves work in the areas of LCA, LCD, ECDM, and multi-attribute design evaluation. Increasingly, system designers realize the need to consider both the effects of design decisions on manufacturing (which occurs very early in the product life-cycle) and on the environment (which occurs at the end of the product life-cycle). Matrix methods have been developed to facilitate input from these diverse interests into the system design process [Pugh, 1990]. The Function Dependence Matrix (FDM) in each QFD phase contains information about the interrelations between performance attributes and decision variables that serve to constrain the feasible choice set. For a complex problem which associated environmental factors, QFD-process can help to define all critical items of these performance attributes and decision variables. QFD house-of-quality methods focus on the "voice of the customer," but manufacturing, marketing, product performance, environmental and other factors can be included as well. When these factors are considered, the design evaluation stage of the design-evaluation-redesign process requires simultaneous consideration of multiple functions and attributes with decision variables [Fallin and Thurston, 1994]. Therefore, it is important to construct the QFD/HoQ-relationship matrix. Although some authors have proposed the modified QFD

matrix depending on the information being aggregated in the matrix, the basic construction of a QFD matrix is followed in the basic procedure.

In each phase of QFD-process, there is a sequence for constructing the QFD matrix. A well-constructed QFD house of quality should provide the product development team with a compact description of three basic and important pieces of information [Ramaswamy and Ulrich, 1993]:

- Customer needs and their relation to objective engineering characteristics (product characteristics and technology requirements).
- Comparisons with competing products (from benchmarking) based on objective engineering numbers (values)
- A summary of the engineering tradeoffs inherent in the system design.

Once the problem is defined, the QFD-team may like to have a plan before the model is actually constructed. The components in modeling plan activities may include: collecting data, designing the model using function dependence matrix related to QFD matrices, verifying the model, formulating incidence matrices or function dependence matrices, and assigning decision variables. Operationally, once the QFD construction is planned, the practical QFD-relationship matrix is constructed according to a certain process as follows.

Planning For QFD Construction Using Management Tools. Berglund [1993], in the "QFD: A critical tool for environmental design making" has suggested that

> "*Quality Function Deployment, QFD, will prove to be a critical tool in environmental decision making in the coming decade -- a tool that when used early in a project's (product's) life-cycle can help make it both economically and environmentally viable.*"

However, to use QFD in IECDM requires inclusion of a range of new evaluation criteria associated with environmental issues, such as hazardous waste generation, waste disposal options, recoverability requirements, etc. Consequently, it requires developing a new matrices to be used for evaluating the life-cycle environmental impacts of a product. One of the basic challenges of a system designer is to deploy the full spectrum of the customer's needs adequately. Especially, these needs have expanded from functional and cost criteria to include a variety of environmental issues.

What is needed is a systematic methodology that effectively deploys the knowledge compiled in the guidelines for solving ECDM problems at the early stages product development cycle. By taking advantage of QFD, IECDM is developed for evaluation of the product design while considering life-cycle environmental impacts. Application of QFD to design-evaluation system allows modification of traditional QFD to incorporate appropriate environmental factors into QFD-based IECDM process. Simple changes of terminology are required, such as using Design Function Deployment (DFD),

Manufacture Function Deployment (MFD), and Recovery Function Deployment (RFD) instead of different QFD phases. When QFD-process has been applied to the change systems, the terms "subsystems" and "components" are added to the "parts" level [Dean, 1995]. Such terminology changes make the typical QFD approach more flexible for large systems associated with environmental issues. Green design together with QFD-process is the basic idea of the QFD-IECDM approach.

To construct QFD matrices successfully, some management tools, skills, and methods are needed. Using QFD, product development team may employ a wide range of tools including affinity and tree diagrams, cause-and-effect diagrams, benchmarking, project management techniques, etc. It is not the objective of this research to explain how to construct QFD in detail; however, a comprehensive understanding is required for a designer using QFD-based IECDM methodology. These tools are described briefly and related to QFD as illustrated in Figure 4.7.

In concurrent engineering, decision-making tools are located with in QFD for a distinct relationship to QFD as illustrated in Figure 4.7 (refer to similar concepts and works in King [1989], Schrage and Gordon [1992], Brassard [1991], and Mazur [1992]). Diagramming aids in the initial investigation of a problem provide a format that encourages the problem solver's first effort to get started. A cause-effects diagram is developed for such an effort. These QFD-related management tools are explained briefly.

(1) System (problem) Black-Box Diagram: A black-box diagram is a familiar model of a system or problem. Inputs are converted to outputs by an undefined transformation that takes place in the black box. The Black-Box diagram is used to focus on input and output so that all information about the transformation process is revealed.

(2) Cause-effects Diagram or Fish-bone Diagram: Causes and Effects (C&E) Diagram is a natural extension of the black-box model. The C&E diagram concentrates attention on the problem to be solved by displaying in detail its causes and the anticipated effects of its solution. [Riggs and Inoue, 1995]

(3) Causes-effects Loop Diagram or Causal Diagram: The Causal diagram is an extension of the C&E diagram, which is used for modeling a dynamic system. It displays cause-and-effect interactions between key variables in developing the model of a dynamic system and its computer simulation model.

These planning tools are very important for construction of QFD-relationship matrix which, in turn, provide relevant information to be used in QFD-based IECDM process. According to King [1989], one of the reasons for the success of the QFD-process in Japan has been the widespread teaching of planning tools throughout the organization. These planning tools support the QFD process well because they are simple. After the problem has been investigated, different data and information from various sources must be categorized. The following tools are used for documentation and planning.

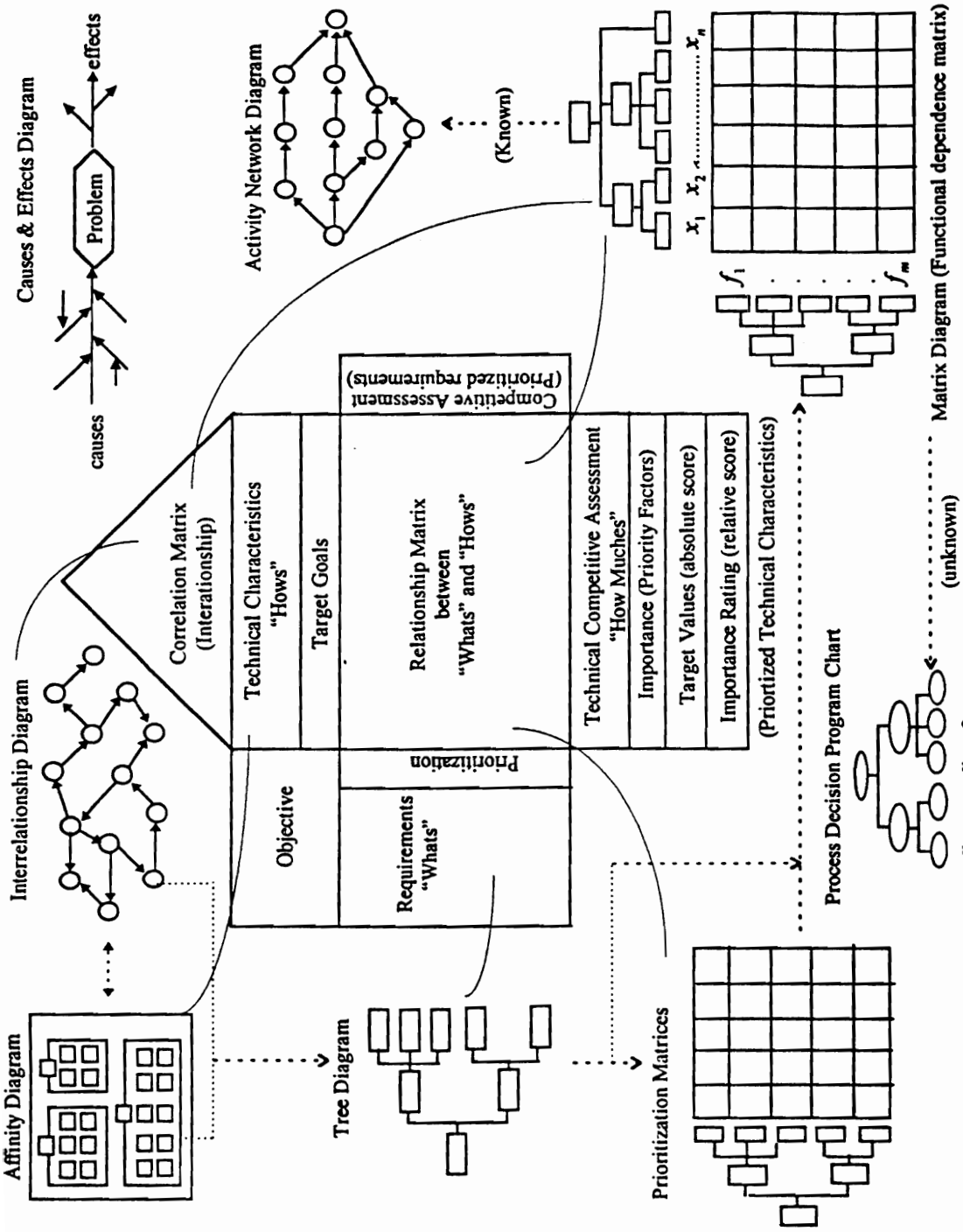


Figure 4.7. Planning for managing QFD construction

(4) Affinity Diagram (KJ method): The Affinity Diagram gathers large amounts of data and organizes it into groupings based on the natural relationship between each item. This tool takes disparate language data and uses cards to rearrange the data into meaningful categories. It is used to organize and integrate language data and statements in a hierarchical fashion. Before QFD is constructed, one may use this tool to effectively rearrange customers' demands that may come from many different sources such as surveys, complaints, warranty problems, reliability problems, etc. The technique is particularly useful for identifying customer needs and wants.

(5) Interrelationship Diagram: The interrelationship diagram explores and displays interrelated factors involved in complex problems. It shows the relationships between factors. Like the affinity diagram, this diagram is used for general planning. It is used when the usual C&E diagram cannot be used because of the complex cause and effect relationships it shows. It asks which idea influences (causes) another idea and draws an arrow in the direction of the influence. It can be read by selecting the idea that has the most arrows coming in or coming out, a sign related to the correlation matrix of QFD that illustrates the degree of complexity of the problem. The most meaningful categories are then identified and given more attention in problem solving. It can be used for developing a promotion and development process for system performance and productivity improvement.

Furthermore, for intermediate planning, three graphical methods are used.

(6) Tree Diagram: The tree diagram systematically maps the full range of tasks/methods needed to achieve a goal. This tool continually identifies information represented in an affinity diagram in detail increasingly. It is a detail map, derived from an interrelation diagram, of the relationship between an overall objective or characteristic and either the sub-objectives required to achieve the overall objective or the sub-characteristics that lead to the overall characteristic. These sub-objectives or sub-characteristics can then be further broken down into a third level of objectives (row in QFD as 'Whats') or characteristics (column in QFD as 'Hows'). This decomposition process can be then repeated to form a tree diagram. Easton [1989] explained the three basic tree-diagrams: the *function tree diagram* specifies the relationship between basic functions and the supporting functions required to achieve them; the *quality tree diagram* specifies and clarifies the relationship between basic qualities required by the customer, and alternative or specific quality characteristics necessary to achieve the customer requirements; the *cause-and-effect tree diagram* is used to clarify the relationships between effects (problems) and their causes.

(7) Matrix Diagram: The matrix diagram displays the relationship between necessary tasks and people or other tasks, often to show responsibility for tasks. This tool is used to document the relationship between multiple inputs and multiple outputs and to help translate priorities between the two. The matrix diagram also helps to prioritize and to specify the most important objectives or characteristics that should be listed. Linking the matrix diagram to the functional dependence matrix (FDM), one can model the

QFD matrix as an optimum problem by a mathematical programming formulation. FDM is a hierarchical structure that might be useful in eliciting and organizing performance objectives and product characteristics. However, it does not necessarily follow that the hierarchical structure should determine the way in which the design process is organized.

(8) Matrix Data Analysis: The matrix data analysis shows the strength of the relationship between variables that have been statistically determined. It is a graphical method that tries to represent high dimensional data in an understandable way. In a sense, the method is just a renaming of the principal components' method from multivariate statistical analysis.

Finally, for detailed planning, the following tools are used.

(9) *Process Decision Program Chart* (PDPC): The PDPC maps out every conceivable event that may occur while moving from a problem statement to the possible solutions. This tool can be used to try to eliminate the potential of a problem in a system (product or process). It is useful in systematically uncovering potential problems in a new system as well as for diagnosing problems in those that have been commercialized.

(10) Arrow Diagram or Activity Network Diagram: The arrow diagram is used to plan the most appropriate schedule for any task and to control it effectively during its progress. This tool collects methods well-known to industrial engineers such as Gantt charts, PERT, CPM and others. It can be modified as schedules and paths change. The primary use is to understand the steps in a design process or plan well enough to consider shortening the time the design process takes, thus, shorten schedules of product development.

Obviously, the three most basic methods used in and most related to QFD are the Tree Diagram, the Affinity Diagram, and the Matrix Diagram. These tools are used to help construct QFD in a systematic manner for improving the process of new system development or existing system promotion. For a detailed discussion of the seven management tools, refer to the works in Golomski [1989] and Easton [1989]. Increasingly, companies are integrating other forms of cross-functional, multi-disciplinary management tools with QFD for maintaining their competition.

Construction of the QFD House of Quality. Several contexts are involved in the construction of a QFD House of Quality (Guinta and Parizles [1993], and King [1989]). A generic QFD-process proposed by Verma *et al.* [1995] is illustrated in Figure 4.8. One of the features is the identification of design-dependent parameters. The dependent parameters define the design space in which feasible solutions (design alternatives) are determined. The design problems can be expressed as the Design Evaluation Function (DEF), the function of design decision variables and these 'design-dependent parameters'. Using DEF-driven analysis, the best design alternative can be chosen.

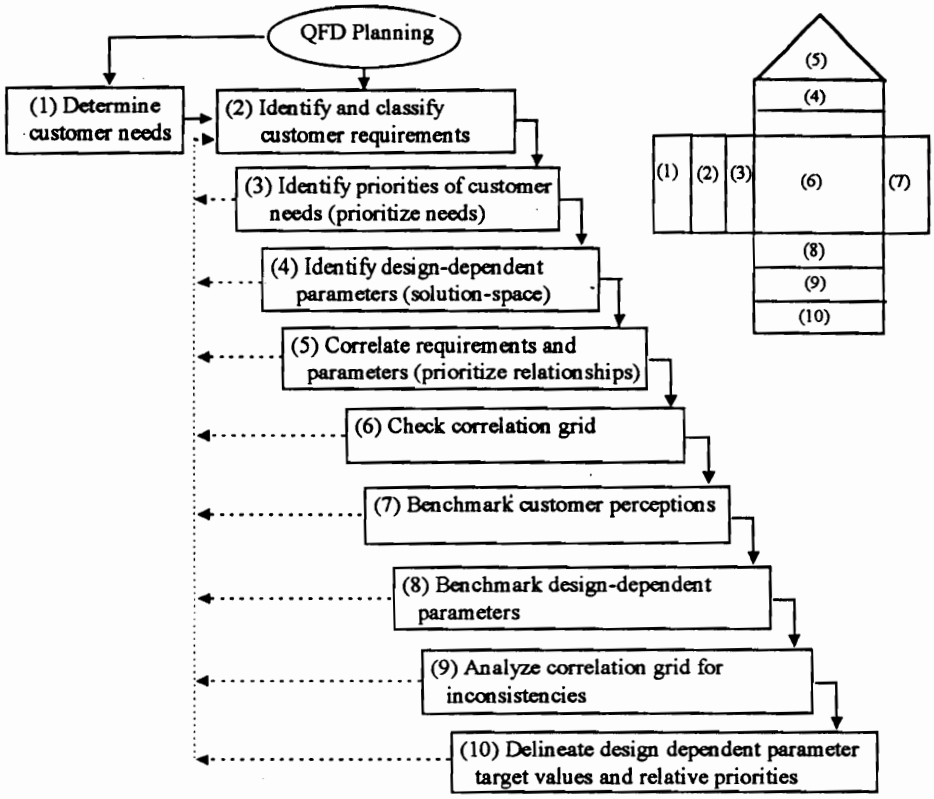


Figure 4.8: Construction of a QFD house of quality

Once the QFD-relationship matrix (or House of Quality, HoQ) is constructed, the information that is attractive is the focus on correlation of attributes (such as engineering characteristics). For example, Lyman's normalized procedure [Lyman, 1990] is extended to accommodate dependencies by Wasserman [1993] to help designers prioritize design requirements during QFD planning. These prioritized design requirements may provide information to help make decisions in design changes in which the designer can redesign the product focus, changing some engineering characteristics that make a critical contribution towards reducing environmental impacts. However, in practice, it is difficult to determine the values of engineering attributes. Basically, determination of these values is a multi-attribute decision-making problem that will be discussed in Step 4.

4.2.3. Step 3: Multiple Phases Decision Execution

After design planning has been completed, the design decisions are made throughout product's development cycle phases. The QFD-relationship matrix (or HoQ) allows the system designer to enter

information concerning customers' preferences, and an HoQ should be constructed for each phase of the system life cycle that corresponds to each phase of the QFD-process. Therefore, when applying HoQ to facilitate QFD-process, implementation of HoQ in this step will yield aggregated information for each phase concerning:

(1) the identification of attributes (customer's attributes and engineering attributes);
(2) attributes weights (using appropriate weighting approaches);
(3) engineering characteristics (measures);
(4) the linkage between engineering measures and customer satisfaction, or between customer preference and engineering design attributes;
(5) key areas for improvement; and
(6) the technical baseline.

Generally, there are some sub-steps associated with each phase in this step for aggregating the information for the product-system design.

Capturing the voice of the customer. Customer voices are diverse and must be considered in problem definition. These diverse voices must be considered, gathered, reconciled and balanced to develop a truly successful product [Crow, 1994]. Once customer needs are gathered, they must then be organized. The mass of interview notes and investigations with customers, requirements' documents, market research, and customer data needs to be treated in statements that express key needs and wants. In QFD planning techniques, "affinity diagramming" is a useful tool to assist with this effort. Brief statements (descriptions) that capture key customer requirements are transcribed onto cards. A data dictionary that describes these statements of need is prepared to avoid any misinterpretation. These cards are organized into logical groups or related needs, to make it easier to identify any redundancy and inconsistency, and as a basis for organizing the customer needs for the first QFD-relationship matrix. Figure 4.9 illustrates a type of affinity diagram [Keoleian *et al.*, 1994] based on the life-cycle process. Bossert [1991] also suggested using an Affinity Diagram to group various requirements that will ultimately be displayed as a Tree Diagram with the actual customer requirements identified at the lowest-level branches.

Once the varieties of customers' voices have been categorized, focusing on environmental issues, companies' green goals should be translated into clear environmental requirements that help identify and constrain factors related to environmental impacts. For example, these environmental requirements may include minimization of raw materials consumption, total energy consumption, waste generation, air emissions and water effluents, health and safety risks, ecological degradation; or the maximization of high

renewable energy, reduction of power used during system operations, long useful system operating life, reduction of toxic or hazardous materials used in production, and reduction of total industrial waste.

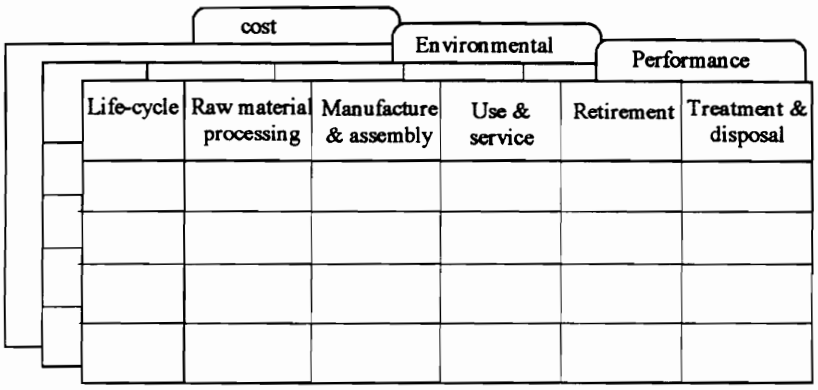


Figure 4.9. A type of affinity diagramming cards

These environmental requirements are then converted into requirements of waste management hierarchies as planning in effect eliminating waste at the source, in-plant recycling, effective treatment, and environmentally safe disposal. Then the product-planning is converted into design characteristics (or engineering requirements), including product (process) requirements, techniques characteristics, system disassembly and recovery time, percent of recycled materials used as input, percent of recyclable materials available at end-of-life, percent of system recovered and reused, purity of recyclable materials recovered, percent of system disposal, and average life cycle cost.

By converting these goals (customers' needs) into clear functions, environmental requirements help identify and constrain the environmental impacts of the product and its process through QFD-process. Table 4.1 shows an example of a QFD approach focusing on environmental requirements. Requirements and their units as well as corresponding objectives are illustrated. The objectives are than converted to the product requirements and techniques' characteristics.

Product Design Deployment Planning. Once customer needs and environmental requirements are identified, the QFD-team can begin to prepare the product planning matrix or the QFD-relationship matrix. Customer needs or requirements are organized as "Whats" on the left side of the matrix. If the number of needs or requirements contain too many items, grouping items becomes necessary; a tree-diagram can help in this effort. The product-planning matrix is decomposed into smaller module or subsystems to reduce the number of requirements (objectives) in a matrix and keep the QFD matrix manageable. A competitive analysis (evaluation) is prepared to develop a strategy for product

development. The strengths and weaknesses of competitor products are reviewed relative to customer needs or requirements to establish objectives for a new product.

Table 4.1. Environmental performance requirements and objectives (an example)

Requirements	Units	Objectives (example)
Reduce or eliminate waste	: kgs of emission over the life cycle	: Reduce life-cycle emissions by 20% annually
	: % of product weight disposed in landfill	: Reduce solid waste disposed to 1 kg per product unit
Develop "green" recyclable products	: % of product weight recovered and recycled	: Achieve 90% recycling
	: solid waste emissions	: Eliminate end-of-life waste disposal
Reduce life-cycle cost of green product	: manufacturing cost	: Reduce total life-cycle cost to ??$ per product unit
	: distribution and support cost	
	: end-of-life cost	: Reduce end-of-life cost (or increase end-of-life value by ? %.
Cost of ownership for customers	: annualized purchase and operating costs	: Must be less than ? ? $ per year
Conserve energy consumption over the life-cycle	: total energy (BTUs) to produce one unit of product	: Reduce to ??? BTUs
	: % by weight of product materials that are processed	: Reduce by ?% annually : Power used less than ?? watts
Conserve natural resources by raising the recycled content	: % by weight of product materials that are recycled	: Achieve ??% or greater total recycled context : Achieve ??% or greater total recyclable context : Achieve ??% recycled plastics

Customer needs or requirements are then translated into product characteristics or technical requirements as "Hows" in columns and the relationship to the customer needs is defined. Importance ratings are calculated to force attention on the most important requirements or characteristics. Consequently, both customers "Whats" and product/technical "Hows" are then prioritized and can be presented by the prioritization matrices.

A technical evaluation is prepared and used to establish preliminary target values for the product characteristics. These values are determined for the IECDM; as in other forms of design, these requirements contain the following (Donald and Weinberg [1989]):

- *Functions* describe what a successful design does. Functions should state what a design does, not how it is accomplished;
- *Attributes* are descriptions of design functions in more detail; and
- *Constraints* are conditions or limits that restrict the design search (or space) to a manageable area.

In addition, a mathematical programming is required to represent the relationship of decision variables (design-decision variables) in functions associated with certain constraints. From environmental aspects,

such requirement objectives include minimization of raw material consumption, energy consumption, waste generation, health and safety risks, ecology degradation, and so forth.

Product, subsystems, and components Design. Once product planning and requirements' formulation are complete, the QFD-team may prepare a more complete specification by using a product tree. The product requirements or/and technical characteristics as well as product specifications serve as the basis for developing the product-realization. The Pugh concept selection matrix can be used to help with the design evaluation process [Pugh, 1991]. The Pugh's matrix uses the product requirements or/and technical characteristics as "Whats" on the left side of the matrix as the basis for evaluating product design across the top of matrix, which correspond to the objectives and decision variables in the Functional Dependency Matrix (FDM), which can be used to help in solving the optimal-design problems. Also, an activity network diagram conducted from the FDM can help schedule and control the product development project through its life-cycle. An activity network diagram conducted from the QFD matrix is used to help schedule and control product design activities (tasks). Regarding environmental requirements, DFE-related rules and principles are considered in design, such as DFR and DFA.

Manufacturing Process Design. The QFD-team continues this translation and planning into the process design phase, and the Pugh concept selection can be used to evaluate different manufacturing process approaches and select the preferred alternative approach. Based on this step, the process planning matrix is prepared. Again, the "Hows" from the higher level matrix (in this case the critical subsystem, assembly or part characteristics) become the "Whats" that are used to plan a process that has minimal negative environmental impacts when fabricating and assembling the product. Important processes and tooling/equipment requirements can be identified to focus efforts to control, improve, and upgrade the defining of specific process and quality control steps in the process/quality control matrix. Also, the QFD matrix conducts the Function Dependence Matrix (FDM) that can be used to optimize the manufacturing-related processes. An activity network diagram conducted from FDM is used to help schedule and control the processes. A process flow chart is created, which includes assembly and disassembly processing and controlling plans.

In the practice of environmental impacts analysis, only when the manufacturing processes are well defined and the related inputs (materials and energy) and outputs (waste and emissions) obtained, can the LCA be performed accurately. Results of the LCA are then used as reference for design evaluation and/or design changes.

Recycling/Demanufacturing Process Planning and Design. In the context of the IECDM, the demanufacturing process design phase involves recycling planning, process design, and selection. Of course, the demanufacturing (or disassembly sequence) is not necessarily the reverse of the manufacturing (or assembly sequence). In fact, demanufacturing is usually different from manufacturing. However, one of the objectives of design for disassembly (DFD) is to make operational demanufacturing process possible, so that recycling costs may be reduced.

So far, the QFD is employed in IECDM methodology for two efforts (see Chapter 3): the synthesis of information to identify (eco)design problem and the decomposition of specified problem into sub-problems. The following steps involve analysis and evaluation activities.

4.2.4. Step 4: Multi-attribute Decision Making and Multi-objective Optimization

This step involves analysis and evaluation of system behavior by using appropriate methods. Due to the fact that various methods might be used, this step is very flexible allowing through the different problems in the ECDM domain. Many research opportunities are involved in this step. Here, we discuss how design evaluation/optimization procedure operates and how QFD-based optimization approach is used to formulate engineering optimal design models. The resulting model (e.g., DEF) can be expressed in various forms.

QFD encourages multi-criteria and multi-attribute decision making. It recognizes that product and process development is a multi-dimensional practice. Many tradeoffs need to be weighed and analyzed for design evaluation. QFD also encourages formulating optimization-based design problems. In this step an interactive product design evaluation and optimization procedure is conducted based on information and data resulted from previous synthesis and decomposition steps, where QFD plays the role as two major efforts: (1) identification of design-related attributes and design alternatives, (2) formulation of (eco)design optimization problems.

Product Design Evaluation and Optimization Procedure Dynamic. Product design development is not only a dynamic procedure, but also one that is continuously being redesigned for improvements in design performance. Continuous improvement is needed by market and customer demands as well as by regulatory requirements that products be developed in less time while maintaining a level of economic, ecological, technical, and functional value. The improvement is mainly effected by continuous, iterative design evaluation and optimization procedure.

In practice, a general design strategy would allow the designers to separate the two interactive design modes: *evaluation* and *optimization* (Figure 4.10), after synthesis and analysis are performed.

During the first phase of the design procedure, the design team would try to find a design space in terms of attributes (parameters). Multi-attributes techniques may be applied to determine the priorities or ranking (restriction) of attributes that construct a feasible solution domain. During the second phase of the search process, the design team would try to find an optimal solution in terms of values of decision variables that construct the search space.

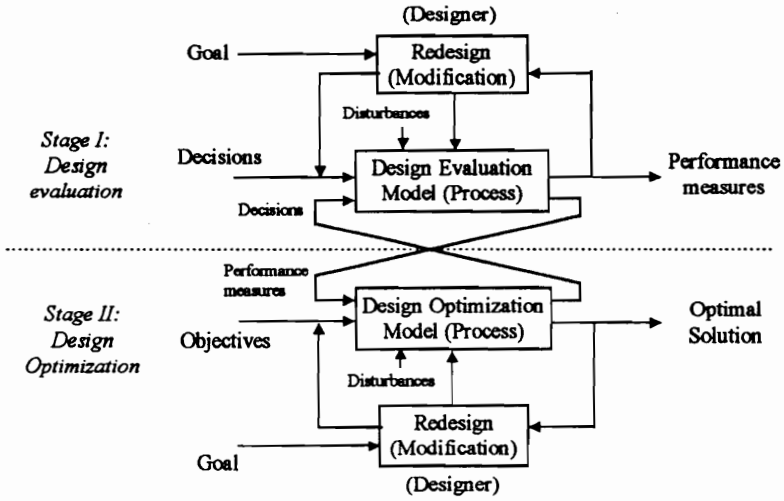


Figure 4.10. Evaluation and optimization procedure

Furthermore, the design procedure is essential to meet an identified need at early design stage. It is recognized that systems (products or processes) are very difficult to optimize once they are produced, operated, and deployed. To a large extent of environmental considerations, the design evaluation and optimization procedure should include functional, technical, and cost (or economic) criteria as well as environmental considerations during the design stages of the product development cycle. If the ultimate disposal of products and materials is to be seriously considered, this should also be done at the earliest stages of original conceptual design. It is widely believed that only 10-20% of recycling costs and benefits depend on recycling process optimization [Kriwet *et al.*, 1995]. The remainder is already determined at the design stage. Hence, it is an industry-wide interest to develop methods and tools for incorporating environmental considerations into product and process designs at early design stage. Figure 4.10 illustrates a general design evaluation and optimization procedure. We explain this design evaluation and optimization procedure briefly as bellows.

Design Evaluation Process: Evaluation and optimization (or generative) processes (models) can be combined by "closing the loop" between them. In other word, one can use feedback from an evaluative

model to modify the decisions taken by the optimization model. This process is shown in Figure 4.10. In this configuration the evaluation process is used to obtain the value of the objective function for a set of inputs. The value of the objective function is then communicated to the optimization process (model) which used this value for the objective function in its search for an optimal solution.

The design procedure is derived from the very beginning by the considering how the design artifact (for example, attributes and parameters) will ultimately be evaluated. Issues of economic, ecological, functional, and technical value of products are each important considerations. A ecodesign is evaluated with respect to its performance in all these areas, and possibly others. The purpose of the design evaluation process is to help designers (decision makers) choose among design alternatives using total quality measures (e.g., cost, performance, environment, time, and quality). These choices are made by estimating how much any one choice may be worth. Operationally, the task of evaluation consists of identifying the potential advantages and disadvantages of any action and comparing them in some specific way. Generally, design evaluation leads to either of two results [de Neufville, 1990]: (1) The identification of worthwhile choices, in which the advantages are greater than the disadvantages. (2) The ranking of choices by some index of merit, which indicates the relative value of each project [design alternative] and thus, within the limits of its precision, also identifies the best choice.

The design processes continually recognizes a rigorously determined Design Evaluation Function (or engineering mode) that accurately reflects the designer's preferences and will progress to make tradeoffs over multiple attributes [Thurston *et al.*, 1991]. The designers (or decision makers) naturally would prefer evaluations that define the best choices clearly. But designers must also have confidence that the rankings are a valid indication of the relative merit of the possible choices. Actually, precision in the evaluation depends on the assumptions made about the design situation (scenario). As a rule, precision is increased by making more simplifying assumptions. Conversely, however, more simplifying assumptions make the evaluation less realistic and the results less acceptable [de Neufville, 1990]. Therefore, the relationship between simplification, precision, and reality is a way to determine when the design evaluation model and/or the optimization model are employed in engineering design problems.

Design Optimization Process: The optimization process and the evaluation process are complementary. The optimization (generative) process provides the designer with an "optimal solution" that satisfies the designer's objective function. The recommended procedure for systems optimum design consists of four main steps [de Neufville, 1990], they are (1) Screening of the feasible solutions to obtain a small set of non-inferior solutions; (2) Sensitivity analysis of these best solutions, to determine their performance in realistic situations; (3) Dynamic analysis to establish the optimal pattern of development

over time; and (4) Presentation, the organization of the final result in a way that makes sense to the client (customers).

Although optimization models have the advantage of providing the designer with an optimal solution, they are generally restrictive in terms of their structured assumptions and less realistic. They are usually only transparent to the model developer. Although evaluation models do not generate an optimal solution for the designer, they usually provide the designer with valuable insights into the engineering design problems being addressed. Several models can be used in design evaluation and optimization procedures (as illustrated in Figure 4.11):

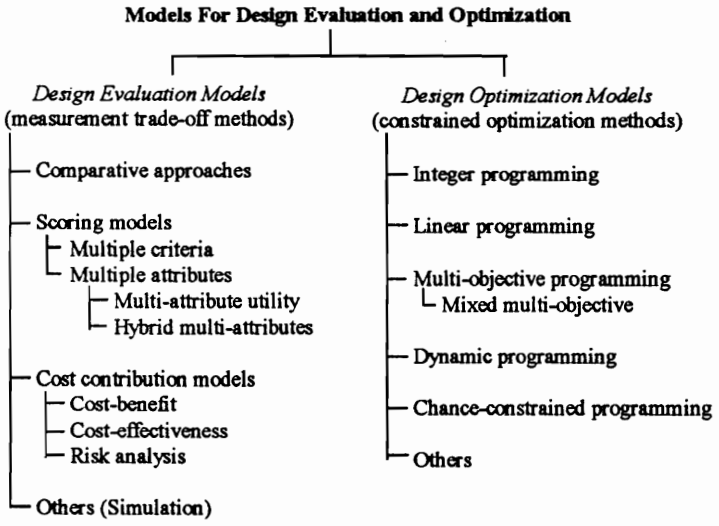


Figure 4.11. Models for evaluation and optimization.

Representation of Design Evaluation and Optimization with QFD Application: In each model for evaluation and optimization, it is necessary to distinguish between attributes, restrictions and constraints, as illustrated in Figure 4.12 [Thurston *et al.* 1991]. An explicit representation of relationships between decisions that designers make and the resulting design performance in each of several attributes determines the optimal design.

The relationships between design decision variables and attributes contribute to restrict the design problem in the design space. The term 'restriction' is the combination of performance attributes that are physically possible. These restricted design functions (engineering modes) are coupled with the evaluation function to guide the iterative design procedure to the optimal feasible design solution in the design space that is constructed by multi-dimensional attributes. Then a optimal-design problem is modeled by these restricted functions as objective function(s) associated with given constraints (or design

requirements) to conduct an optimal solution in search space that is constructed by multi-dimensional design decision variables.

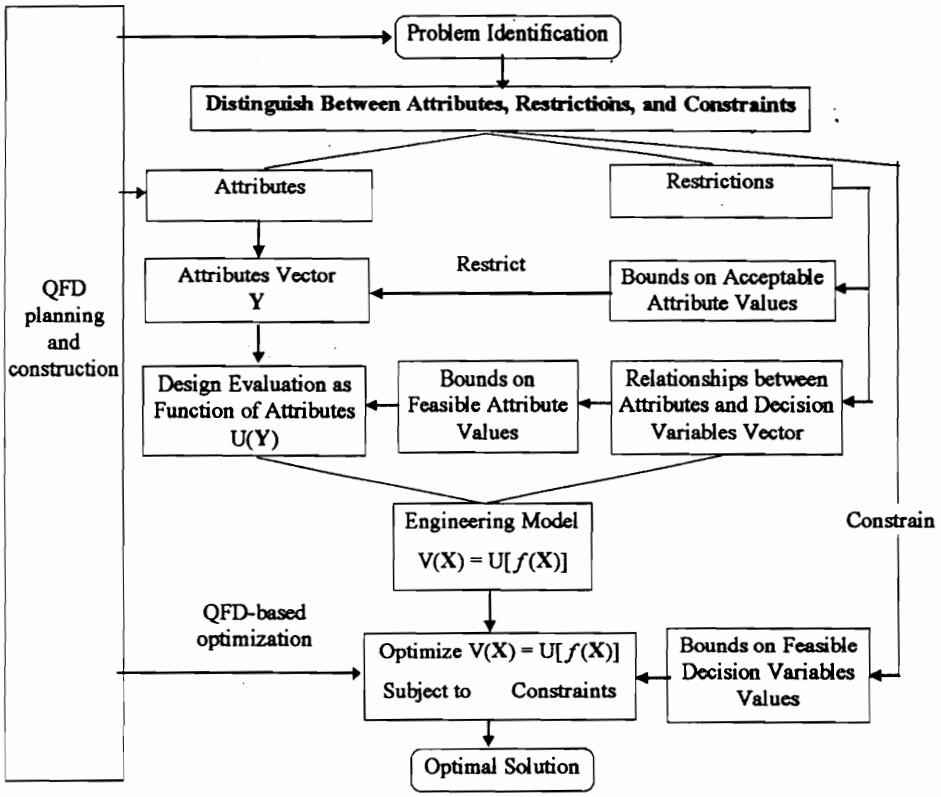


Figure 4.12. QFD-based, evaluation-driven design analysis for evaluation and optimization [Thuraton *et al.*, 1991, with modification].

In a practical design evaluation and optimization procedure, the multi-attributes may be both quantitative and qualitative (for example, hybrid multi-attributes decision-making problems) and may be associated with both dependent and independent parameters; also, the design decision variables may be discrete and continuous (for example, mixed multi-objective optimization problems). Recognizing such complexity in the engineering design procedure, designers require an appropriate tool to help them to construct the relationships between attributes and decision variables. The well-defined QFD matrix can serve to determine the DEF or the engineering model that is restricted by functional relationships between design performance (attribute levels) and design-decision variables. According to Thurston and her coworkers [1991], the QFD can contribute to design procedure in the following way:

> "*QFD could be used as a communications device to elicit information from diverse interests [attributes] within an organization, such as mechanical engineering [engineering design], manufacturing and*

> *marketing. This information would qualitatively determine the relationships between decisions made by design engineers and the resulting effect on design performance relevant to these diverse interests. Evaluation Driven Design Analysis could then be employed to provide a mathematical structure to these relationships which encourage optimization.*"

QFD is used for capturing the information necessary for making decisions on future product upgrades and/or analyzing competitors and their competing products. Furthermore, expressing information relationships is a way in which QFD contributes to concurrent engineering. In the following, the Functional Dependency Matrix (FDM) conducted from QFD is employed to construct the relationships between attributes and decision variables, that is, Design Evaluation Function (DEF). In addition, the QFD has been extended to solve a class of optimization problems. Prasad [1994] has developed a methodology to capture the optimization formulation as part of the QFD process, certainly, this approach has also been used in our IECDM methodology.

Interactive Impact Between Design Evaluation and Design Optimization: As discussed above, the QFD House of Quality approaches represent a major advance in engineering design methodology, by making clear the connections between engineering design decisions and their impact on the customer [Thurston and Locascio, 1993]. To put the information contained in the HoQ matrices to better use, Thurston and Locascio [1993] have proposed two advantages of QFD:

> "*1.) Rather than stopping with a designation of 'positive' or 'negative' to indicate the influence of engineering characteristics on customer attributes, quantify these relationships; and*
>
> *2.) Rather than using a weighted sum to represent imputed importance, use a more rigorously determined multi-attribute evaluation function with strong theoretical functions.*"

These advances permit a more mathematically-based approach for solution of concurrent engineering problems. By these advances, a unique design evaluation/optimization procedure is proposed that employs multi-attribute decision-making and multi-objective optimization methods based on the QFD-process.

The central idea for formulation of QFD-based optimization design problem is that: in each QFD phase, the 'customer attributes' shown along the side of the side 'Whats' of the house comprise the design goals or attributes[1]. The 'engineering characteristics' that are shown along the top 'Hows' of the house represent the design parameters and the decision variables. These parameters may be independent and/or dependent, and decision variables may be continuous or/and discrete. The QFD-relationship matrix that links the voice of the customer to the engineering domain represents the constricted functions. The

[1] Here, the 'customer' has broader meaning that includes the customer outside the company and the inner customer during the product supply chain.

'relative importance' is replaced with a multi-attribute objective function for design optimization. In such a mathematically-based approach, the objective function of any design alternative is represented by an overall multi-attribute function (or Multi-criteria design evaluation function) with either a certainty or an uncertainty issue. The objective function may be represented by a utility function or a monetary or other unified unit. Then the design optimization problem becomes the search domain (optimizing the attributes values) from the design domain (trade-off analysis among the conflicting attributes) for multiple attributes solution.

Formulation by QFD-based Optimization Approach: In summary, this interactive design procedure (methodology) builds on the popular QFD/HoQ symbol that is constructed by using consumer preferences and a transformation of the customer attributes-engineering attributes relationship matrix to form restrictions on the feasible design space and then to form constraints on the feasible search space.

On the other hand, multiple attributes decision making, a decision analysis approach, provides the mathematical basis for model competing design goals (in terms of utility function, total profit, or other unified unit term) simultaneously and to make rational decisions to affect overall (green) design improvement in the design problem. When coupled with the constraints (for example, environmental regulations), this constructed objective function completes a mathematical programming model of the concurrent design optimization problem. In either design evaluation or design optimization problems, the objective function (or engineering model) can be a single-objective (for example, utility function or total profit function) or multi-objective (for example, a cost function and environmental loads function, etc.). To the large extent, these approaches are generally named *QFD-based optimization* in which the 'best' design resulting from the design evaluation problem is defined as the optimum combination of multiple (quality) attributes, while the 'optimum' design resulting from the optimal-design problem is defined as the optimum values of multiple (decision) variables.

In the QFD-based optimization which means formulating optimal design problem by using QFD-matrix information. It is noted that the question we are posing is how QFD can be used in this optimization problem setting and what elements of QFD represent design variables, constraints and objective functions. Recalled that the rows of "WHATs in QFD" form customer (either external or internal customer) wants. It is thus similar to specifying a set of objective functions which design-team must strive to design product to please the customers. They are not all independent. On the other hand, if the columns of "HOWs of QFD" represent system variables, the correlative relationships between HOWs versus HOWs should be posed as constraints in an optimization problem. The correlation situation can be handled through *linking technique* in optimization [Prasad, 1994]. Designers then use the resulting QFD-matrix or its modified form (such as FDM) to formulate engineering design models that generally are

expressed as DEF associated with certain constraints. Based on the structure of design evaluation and optimization procedure, three basic approaches for formulation of QFD-based optimization problem are discussed as follows (see also Appendix C).

Constructing the Function Dependency Matrix. In this step the matrix diagram and method are used. The Matrix diagram is based on the principle that whenever a series of items is placed in a line (horizontal) and another series of items is placed in a row (vertical) there will be intersecting points that indicate a relationship. It also indicates the strength of the relationship between the items that intersect at that point.

King [1989] proposed that the matrix diagram has evolved into a number commonly used matrix forms: L-shaped matrix, T-shaped matrix, Y-shaped matrix, X-shaped matrix, C-shaped matrix, and a combination matrix/tree diagram. It is the combination matrix/tree diagram that is used in the optimal-design problem. For example, the so-called Function Dependence Matrix (FDM) is one of the combination matrix/tree diagrams in which performance objectives and design decision variables are related in an L-shaped matrix diagram. Another example, which would be even more common, would be to create a set of Work Breakdown Structure (WBS) to be accomplished (i.e., vertical axis of matrix) and merge them in an L-shaped matrix with all of the departments/functions (i.e., horizontal axis), namely a *matrix organization*. The degrees of responsibility for each task can then be clearly allocated and indicated.

FDM, one of the matrix methods, is a type of combination matrix/tree diagram conducted from the QFD-process (Figure 4.13), in which two tree diagrams have been merged into a simple L-shaped matrix. In the context of optimal-design problems, these two tree diagrams represent the performance objectives tree and the decision variables tree, respectively. The FDM method can help formulate requirements, in which a well-conceived set of requirements translates objectives into a solution space (design space and search space) of system design. By using FDM, an objective design evaluation function (DEF) must be formulated for each QFD phase (that is, each matrix). Dependency in the critical "Whats" and "Hows" may be represented by the FDM, in which rows are labeled with relation/function names and columns are labeled with variables names. Several methods are available. Different methods may be used at each QFD phase, and should be selected on the basis of their ability to address the degree of difficulty at that phase.

The FDM organizes performance objectives and decision variables in a $n \times m$ matrix, and also indicates their interrelationships by an "x", as shown in Figure 4.13. Objectives are listed along the vertical axis in the hierarchical structure, and decision variables are listed along the horizontal axis. The

entry in the *i*th row and *j*th column is noted by "x" if the *i*th functional objective depends on the *j*th decision variable; otherwise, leave it blank.

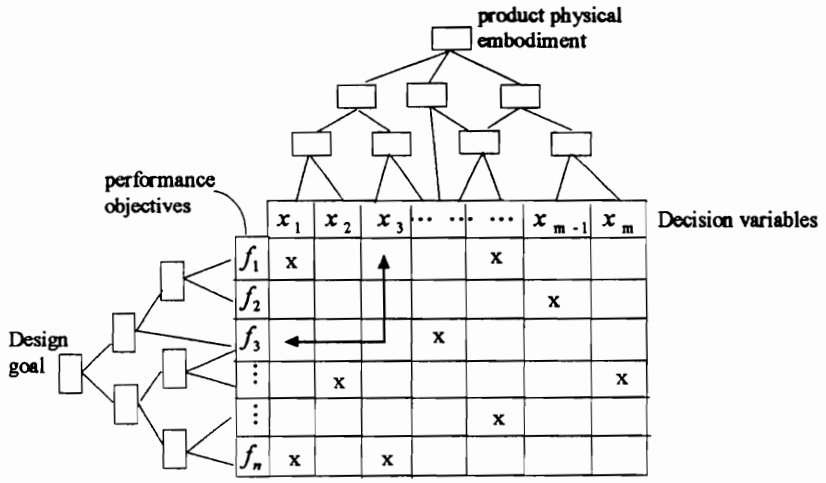


Figure 4.13. An example of a function dependency matrix.

For a large-scale complex problem, this function dependency matrix may also be a large and complex one. Therefore, decomposition techniques are required to decompose the design problem into sub-problems. Such optimal decomposition of design problems can be seen in works by Michelena and Papalambros [1994] and Fallin and Thurston [1994]. Considering FDM, an engineering model (for example, a Design Evaluation Function) is conducted. An engineering model is either a single design evaluation function or a set of functions (equations) that relates the design variables to the performance matrices used to quantify performance of a system.

Modeling an environmental problem by the FDM, which may be derived from QFD matrices, can exclude the need to score every relationship of objective and decision variables individually. A critical problem is that a unified unit set (or called ecounit) is required for different environmental factors and issues for different industrial products. Thus, a set of metrics or measurement tools is needed to help drive product and process improvements and to provide management an easy method to review and measure the program. A QFD team is responsible to develop the methodology and approach. According to Korpalski [1994], such environmental matrices should meet several criteria:

- The approach should be simple (easy to use), pragmatic, timely, flexible, and non-controversial.
- The parameters selected should be based on what the customer/market and/or governmental/ regulatory agencies currently use or are likely to target early on as measures of environmentally responsible products.

- The parameters selected should be factors that product designers have the ability to directly influence and impact versus criteria outside their direct sphere of influence.
- The approach should be a "starting point" to launch improvements. A full life cycle analysis (LCA) of all materials, components, etc., at the product level is not necessary.

Considering these general rules, the QFD team is responsible to select some criteria that must be included in the FDM even if there are many design specifications in the QFD-relationships matrix in order to meet customers' needs.

Another advantage of the FDM approach is that no weightings of the selected parameters are attempted in FDM. Given our current understanding of design for environmental issues, equal weighting is probably the best method to use at the time of parameter selection since improvements in any of the criteria will yield more environmentally responsible products and processes [Korpalski, 1994].

Once the FDM diagram conducted from QFD is constructed, different solution techniques may be proposed, such as by mathematical programming methods or by matrix decomposition techniques, or by multiple objective decision making approaches. The solution approach is selected according to the scale of the matrix, priorities and characteristics of the objectives and decision variables as well as constraints, and features of the parameters.

Multiple Attributes Design Evaluation Function and Decision Making. In a sense, engineering design problems can be seen as either decision-making problems or selection problems in product development. Especially, selection problems in conceptual design arise whenever one out of a number of possible solutions has to be chosen based on multiple criteria or a multi-attributes decision-making process [Basearan, 1991]. QFD serves as an auxiliary technique to aid in the identification of attributes.

Once the FDM is constructed, a multiple-attributes, design-evaluation function may be formulated for solving problem analytically. Before doing so, many QFD approaches require the QFD design team to evaluate the importance of the customers' requirements and assign predetermined weights to each attribute. According to Fallin and Thurston [1994], the simplest method is a *weighted average*, where weighting factors are assigned to reflect the "relative importance" of each objective (that is, the rows of the QFD matrix). This method has been shown to be inadequate as configurations are improved throughout the design process, but might be adequate for preliminary design. In using multi-attributes design evaluation, some essential efforts are usually used as bellows.

Using the Analytic Hierarchical Process (AHP) in QFD process: In the QFD approach, identification and prioritization of the requirements is a nontrivial problem. A related approach, the

Analytic Hierarchical Process (AHP), can calculate a score that reflects how close each alternative comes to achieving the overall goal.

AHP utilizes a hierarchical tree structure and pairwise comparisons to reflect the designers' preferences. The pairwise comparisons can improve the internal consistency of the weighting factors. Generally, the AHP is applied in QFD-process to improve the accuracy of priorities and make QFD-matrix better fit particular projects [Zultner, 1993]. Certainly, Aswad [1989] has found that inconsistency in quantifying expert judgment remains a common weakness using QFD methodologies. A more accurate deployment of priorities can be accomplished by the consistent use of a ratio scale, such as that produced by the AHP, throughout QFD phases. An innovative approach to this inconsistency problem has been suggested by Akao [1990] and Aswad [1989] involving the use of the AHP. Briefly, AHP is employed to develop and prioritize customer requirements in the application of QFD-based methodology.

Using the Fuzzy sets theory in QFD process: When there is imprecision or uncertainty in expected performance, two other methods are used. *Fuzzy set analysis* can be used where there is imprecision in the expected performance criteria or the design specifications/requirements. Probabilistic multi-attribute utility analysis is used as a normative approach for decision making under uncertainty [Thurston and Liu, 1991].

In the context of the QFD method, the phenomenon of *fuzziness* may be common to many of the customer's requirements in the QFD chart for product-system development. In some product-system development cases, only linguistic (vague) statements are used to describe the problem and it may not be possible to state the objective functions and the constraints in precise mathematical form. It may not be possible to express the objectives precisely because the utility functions are not definable precisely or the phenomena of the design problem might only be described in a fuzzy way. For example, the objective of a system design problem may be to produce a design alternative that costs "more green" than a specified amount. In environmental controls, the constraint may be to make the air quality level "considerably close" to the expected air quality. It has been recognized that one's ability to make precise and significant statements concerning a given system diminishes with increasing complexity of the environmental-friendly system.

Fuzzy sets theory will be employed to treat such fuzziness phenomena and to model a fuzzy domain wherein customer requirements are qualitative and have no sharply defined boundaries. Zadeh [1965] first proposed the fuzzy sets theory that is now suggested for converting linguistic terms into their corresponding fuzzy numbers. More recently, Chen and Hwang [1992] proposed conversion scales to convert linguistic terms into their fuzzy number equivalents. The principle of this system is to pick a scale that provides all of the number of customer response categories, and to use the fuzzy number in that

scale to represent the meaning of the verbal terms. Then a fuzzy scoring method is used to convert the fuzzy number into crisp scores, which are then used to derive customer satisfaction ratings for different attributes (customer wants) and for the overall product. Hence, the fuzzy set framework is adopted to transform linguistic data to a crisp score as opposed to direct use of a linear scale of customer responses. Using these crisp scores, Wasserman *et al* [1993] further proposed the use of standard Multi-Attribute Decision Making (MADM) to calculate overall customer preferences, in which a normalized ranking procedure is used to calculate customer indices.

Using the Design Evaluation Function as an engineering design model: As discussed in Chapter 3, the *design evaluation function* (DEF) (or the *ecodesign evaluation function* when design problems consider environmental issues simultaneously) can provide the basis for formulation of an optimal-design problem in mathematical form, either single-objective or multi-objective. The critical ecodesign problem here is to formulate an evaluation function integrating the environmental factors, the performance factors, and the cost factors. The DEF should be factored by the same unit. We will then discuss how DFM is related to DEF.

The DEF can be derived from the FDM. In the context of QFD-based methodology, the target goals (value) of product characteristics and technique requirements are determined by optimization solution techniques, such as decomposition methods. For example, in FDM the two most important defining properties are decision variables and performance functions [Wagner, 1993]. Decision variables are loosely defined as variables that affect optimization problems; similarly, performance functions (usually constraints) are loosely defined as functions that affect optimization problems. The FDM for the example NLP (nonlinear programming) given by following equation is shown in Figure 4.14. Each term in the objective is represented separately in the FDM.

$$\begin{aligned} &\text{Minimize} && f(x) = c_1 x_1 + c_2 x_2 + c_3 x_3^2 \\ &\text{Subjective to} && g_1(x) = c_4 x_1^2 + c_5 x_4 - c_6 x_4^2 - c_7 \le 0 \\ & && g_2(x) = c_8 x_2^2 + c_9 x_4 - c_{10} x_4^2 - c_{11} \le 0 \\ & && g_3(x) = c_{12} x_3^2 + c_{13} x_4 - c_{14} x_4^2 - c_{15} \le 0 \\ & && g_4(x) = c_{16} x_4^2 - c_{17} \le 0 \\ & && g_5(x) = c_{18} x_4^2 - c_{19} \le 0 \end{aligned} \tag{4.1}$$

where c_n, (n=1,2,3,....) are constant coefficients.

	x_1	x_2	x_3	x_4
f_1	1	0	0	0
f_2	0	1	0	0
f_3	0	0	1	0
g_1	1	0	0	1
g_2	0	1	0	1
g_3	0	0	1	1
g_4	0	0	0	1
g_5	0	0	0	1

Figure 4.14. An example of a function dependency matrix

Several solution approaches have been proposed. A comprehensive work that integrates graph representation, matrix method, and decomposition technique for system analysis and design has been done by Steward [1981]. In his book, Steward presents tools to help one plan where assumptions are to be used, how design iterations occur, where design reviews are required, and the duration of the tasks for each iteration. Once these decisions are made, one can lay out the design process as a finite sequence of activities that can be scheduled and controlled by the usual critical path techniques. These tools include graph theory, matrix methods, and decomposition techniques that also help one to plan and schedule the design and fabrication of a system. Such a tools-integration concept for system design and development as well as management is actually the same idea as integrating management tools for QFD construction. More recently, Wanger [1993] proposed a general decomposition methodology for optimal system design. Graph theory and partitioning approach also can be seen in Fallin and Thurston [1994]. However, the decision variables could be quantitative or qualitative, discrete or continuous, in optimum design practices. Therefore, a more generic mathematical model could be used.

Multilevel Multi-objective Optimization with Mixed Decision Variables. Recent advances in system optimization have resulted in the development of techniques for handling problems involving large numbers of design variables and/or constraints that can be expressed in an FDM diagram or QFD-relationship matrix. Usually a scalar-valued objective function, such as DEF formulation discussed in section 3.2.3 and equation 4.1, is optimized over a feasible design space. The result is then used as a guiding device in striving for the best practicable system. However, there often exist several practical system design problems, which involve several, often conflicting, objectives to be considered simultaneously by the designer.

In the integrated design optimization process, both the number of decision-making attributes and the number of decision variables increase greatly. Hence, the design optimization problem is far larger than the usual design optimization problems. Therefore, the multi-objective design approach is increasingly employed in formulation of design optimization problems. Certainly, conflicting relations often also exist among evaluation characteristics for product performance. When relations among the conflicting evaluative factors affect design decision-making, analyses are effective that are based on a multi-objective design optimization problem, in which the multiple evaluative factors (attributes) are selected and combined as objective functions.

The DEF conducted from the QFD-relationship matrix or FDM associated with some given constraints constructs a mathematical model. Model variables, generally, are related to factors that impact the environment through non-linear relationships. Without loss of generality, the (eco)design problem formulation is illustrated conventionally as follows as the constrained multi-objective optimization problem as: Find a vector of design variables, **X**, that minimizes the objective function, $F(\mathbf{X})$, which satisfying the constraint equation, $H_j(\mathbf{X})$ and $G_j(\mathbf{X})$. In mathematical notation:

$$\min_{\mathbf{X}} \text{imize} \quad F(\mathbf{X}) = \min_{X}\left\{f_1(\mathbf{X}),\ldots,f_n(\mathbf{X}),\ldots,f_N(\mathbf{X})\right\} \tag{4.2}$$

Subject to $\quad H_j(\mathbf{X}) = 0, \qquad j = 1,\ldots,k$

$$G_j(\mathbf{X}) \le 0, \qquad j = k+1,\ldots,m.$$

where

$$\mathbf{X} = \left\{x_1,\ldots,x_q,x_{q+1},\ldots,x_Q\right\}^T = \left[\mathbf{X}^c,\mathbf{X}^z,\mathbf{X}^i,\mathbf{X}^d\right]^T$$

$\mathbf{X}^c \in \mathbf{R}^c$: feasible subset of continuous variables; $x_1,\ldots,x_q$ are continuous values.

$\mathbf{X}^d \in \mathbf{R}^d$: feasible subset of discrete variables; $x_{q+1},\ldots,x_Q$ are discrete values.

$\mathbf{X}^z \in \mathbf{R}^z$: feasible subset of zero-one variables.

$\mathbf{X}^i \in \mathbf{R}^i$: feasible subset of integer variables.

$x_i \in (d_{i1},d_{i2},\ldots,d_{iw(i)}), \qquad i = 1,2,\ldots,n.$ $d_{i1},d_{i2},\ldots,d_{iw(i)}$ are constants.

$x_k^L \le x_k \le x_k^U, \qquad k = q+1,\ldots,Q.$

$F(\mathbf{X})$ and $G_j(\mathbf{X})$ are differentiable functions.

In the above formulation, $\mathbf{X} = \left\{x_1,\ldots,x_q,x_{q+1},\ldots,x_Q\right\}^T$ are design variables and F, H_j and G_j are scale objective, equality, and inequality constraints, respectively. x_k^U and x_k^L set the upper and

lower bounds on the design variable x_k. The objective function is a multi-objective function. In many engineering design applications, the design variables can be continuous and/or discrete or integer values. Since zero-one and integer variables are a subset of discrete variables, the term "discrete" variable will be used to refer to integer, zero-one, and discrete variables in this research. In many ecodesign problems, discrete variables are involved together with continuous ones. The fundamental problem is to formulate a definition of $F(\mathbf{X})$, the objective vector, when its components have different units of measure, and thereby, to reduce the problem to a single objective with a unified unit.

Once the optimization problem is set up, several multi-objective programming approaches have been suggested for solving such problems [Goicoechea *et al.*, 1982]. Since no unique solution, which would be optimum for all the individual objective functions, exists for a multi-objective optimization problem, the concept of Pareto optimality or prioritized optimality has been used in all the available methods. In most realistic optimal-design problems, design variables may be continuous and/or discrete; they may lead to multi-objective optimization model with mixed decision variables. In such situations, several solution approaches have been proposed for solving such multilevel optimization problems with multiple objectives and mixed design variables (see Kumar *et al.* [1992]). These methods include: Hierarchical (or linear decomposition) methods; Optimal Sensitivity Analysis; Cumulative Constraint Function; Constraint Relaxation; Non-hierarchical Models for System Optimization; GSE-Based System Optimization Approach; Software Implementation. It is not the objective of this research to discuses and/or compare all these methods. Nevertheless, this is another research topic for solving green design problems that is modeled as a multilevel multi-objective optimization with mixed decision variables, and provides a wide potential for research topics related to environmental impacts problems.

Considering ecodesign in practice, it is recognized that there exists a vast amount of fuzzy information in both the objective and the constraint functions of the optimum problems, such as the disassembly problem and the design for a green product-system. Most practical system-ecodesign problems involve several objectives that are often conflicting, so a multi-objective fuzzy programming method is outlined in the design problem. Theoretically, the fuzzy constraints define a fuzzy feasible domain in the ecodesign space, and each of the fuzzy objective functions defines the optimum solution by a fuzzy set of points.

In modeling practical ecodesign problems (or environmental problems), this multi-objective fuzzy decision support system (DSS) should assume the "total life-cycle impact" of each potential course of action, and identify those which are "non-inferior" (those which are not clearly disadvantageous) with respect to the selection of a cleaning process for a machined part; this impact is measured in terms of expected system performance and expected life-cycle costs that include the internal costs of the firm and

the external costs to society. Therefore, environmental life-cycle cost assessment is another important issue in green product development.

Tradeoffs in Decision Making. In addition, the model for environmentally conscious manufacturing might be based on heuristic information for assuming environmental impact in terms of factored ecounits. Taking the fluid waste minimization problem as an example [Butler, 1994], in very simple terms, the negative contribution or environmental impact (EI) of a manufacturing process might be viewed as a function of the amount of toxic waste produced (W), its toxicity (T), its rate of biological or chemical decomposition (D), its mobility (M), and the method or technology used to dispose of it (Z). This relationship can be expressed more compactly as:

$$EI_{negative} = f(W,T,D,M,Z) \tag{4.3}$$

Note that some of these variables are highly interdependent.

On the other hand, the system efficiency of a manufacturing process can also make a positive contribution or a positive environmental impact. In very simple terms, the environmental impact contributed by system efficiency can be viewed as a function of the material-extracting efficiency (τ), the manufacturing efficiency (η), the recovery efficiency (ρ), and the recycling efficiency (λ). This relationship can be expressed more compactly as:

$$EI_{positive} = f(\tau, \eta, \rho, \lambda) \tag{4.4}$$

Then, the total impacts of the product-system on the environment can be expressed as:

$$EI = f(EI_{negative}, EI_{positive}) \tag{4.5}$$

The ecodesign of the product-system generally involves a tradeoffs type of decision-making within the constraints of technology, as depicted in Figure 4.15. Tradeoffs between environmental issues and other performance issues will be critical in selection of green design alternatives.

A set of unified units is required that contains the impacts of the product (materials) and its manufacturing processes on the environment in a comprehensive manner, and expresses these in quantitative terms. By including these unified units in the general decision model, all related environmental issues can be appropriately incorporated into the product design and manufacturing decision making. This would enable a typical optimization problem to minimize the environmental impact associated with some constraints. Thus, a trade-off exists between the cost of the product and the process choices, including environmental issues pertaining to waste disposal, recyclability, public health and safety, air and water quality, remanufacturability and energy use, among others.

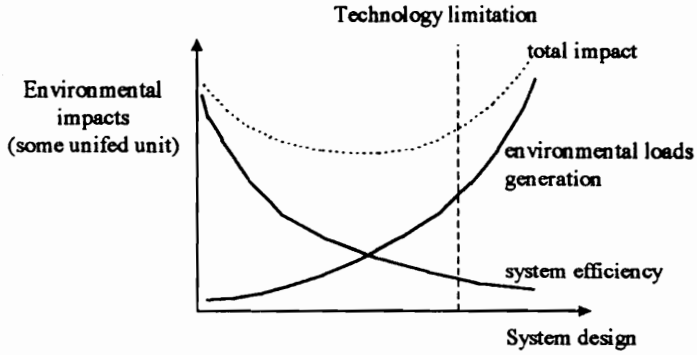


Figure 4.15: Conceptual scheme of total environmental impacts (an example)

A Generic Model Representation. In the context of green design, the system design problem associated with environmental issues involves many factors, and judgments must be made in a coherent way that embody comparisons on a multi-attribute design function for decision making. It is also important that the optimum design problem is modeled mathematically so that a best design alternative can be found. To satisfy these requirements, a QFD-based methodology is developed that is comprised of these essential assessment stages:

- An analysis of the function dependence matrix of each life-cycle QFD phase for each possible design alternative is completed for modeling the multi-attribute design problem.
- Ecounits as indicators of environmental impact measures and evaluation are developed for comparing different design alternatives. (However, the development of the ecounits is beyond the scope of this research).
- An algorithm for solving the multi-attribute optimum problem is developed to find the optimum solution (the best design configuration).
- The Analytical Hierarchical Process (AHP) may be used to provide a structured multi-criterion decision-making scheme for a problem that is impossible modeled as an optimum problem from a mathematical programming aspect.

The ecodesign problem in the product realization life-cycle is actually an optimization problem that can be represented as following expression without loss of generality. The objective of this research is to develop a decision support model that will maximize a company's profit with respect to product-design and process-selection, considering environmental issues in the product development process. In very simple terms, the total profit objective (OBJ) might be viewed as a function of the product configuration design (PCD), the manufacturing process selection (MPS), and the demanufacturing policy determination (DPD). Each PCD, MPS, and DPD is a triple; for example $\mathrm{PCD} = \left(N(\Xi), A, S(A)\right)$.

Moreover, the model will evaluate alternative configuration solutions by selecting the associated manufacturing processes and recycling policies in the manufacturing processes. The many attribute measures are combined into the following general model:

Objective function:

$$\text{Optimize} \qquad OBJ = F(\text{PCD, MPS, DPD})_{\text{product life cycle}} \tag{4.6}$$

or expressed in multi-objective form as

Maximize The company profit:

$$OBJ)_1 = f_1(\text{Revenue, Life - CycleCost})_{\text{Expected product lifetime}}$$

Maximize Product effectiveness as time - varied utility function:

$$OBJ)_2 = f_2(\text{System effectiveness } (A_F))$$

Maximize Green design objective:

$$OBJ)_3 = f_3(\text{Product / Processes ecodesign } (A_G))_{\text{Expected lifetime}}$$

Maximize Recycling rate:

$$OBJ)_4 = f_4(\text{Recycling rate of recycled items})_{\text{Expected life time}}$$

Minimize Environmental impacts:

$$OBJ)_5 = f_5(\text{Processes of produced product } (A_G))$$

Subjective to:

Engineering design constraints,
Production constraints,
Capacity constraints,
Energy constraints,
Environmental regulations constraints, and
Capital constraints, etc.

Note that elements in the objective function are usually interdependent. These variables are highly interdependent, as discussed in the previous section. The advantage of developing such a general model is that it provides a way to determine the optimal product and processes planning in the presence of marketing, environmental, and recycling issues that do not have a common frame of reference. Second,

by manipulating the design attributes of the product/process, the general model can be explored to develop some insights into a system for a specific situation.

Specifically, the product attributes selection is governed by the following general equation in terms of cost function; thus, the objective becomes minimum cost while meeting engineering and environmental requirements.

$$\text{Minimize} \qquad \Phi_{Cost} = f\left(\Xi(F,\ A,\ S(A),\ LCC(MCOST,\ RCOST,\ X(\Xi))\right) \tag{4.7}$$

$$\text{with} \qquad \Xi = f\left(N(\Xi), A_D, A_M, A_F, A_P, A_G, x_{e,l}\right)$$

$$\text{and} \qquad M_{COST} = \left(C_{MP} + C_{IE} + C_{EE}\right) + others$$

$$R_{COST} = \left(C_{DA} + C_{MR} + C_{DP}\right) + others$$

Subject to

$$\Xi(A_F) \geq EDS$$

$$\Xi(A_M) \geq EPS$$

$$ENR \geq EGR$$

$$CAP \geq X(\Xi)$$

where

Φ_{Cost} the total life cycle cost of a product made of the selected attributes.

A_D the geometry parameter of items (for example, subassemblies, components, parts, materials), such as the dimension of material attributes in a product.

A_M the properties of material attributes.

A_F the requirements of functional attributes of the product items.

A_G the greenness attributes of the product items and materials.

$MCOST$ the cost of the product associated with manufacturing and environmental impacts of the processes that produce material attributes.

$RCOST$ the cost of the recycled product associated with demanufacturing of the product disassembly, material recovery, and disposal (dumping).

$X(\Xi)$ the product volume and the demanufacturing volume of product Ξ which is determined by marketing demands; when a product structure is designed, the number of items in the product can also be defined.

CAP the capacity of manufacturing and assembly.

C_{MP} the manufacturing cost including the material cost per mass.

C_{IE}	the internal environmental cost caused by the environmental effects, which reflect the environmental control cost to the manufacturer per items mass.
C_{EE}	the external environmental cost, which reflects social and environmental impact of the material per items mass.
C_{DA}	the disassembly cost of the product including transportation and inventory costs.
C_{MR}	the material recovery cost of the recycling product.
C_{DP}	the dumping (disposal cost including transportation cost and waste treatment cost).
$\Xi(A_M)$	the material properties of the specific product (items).
$\Xi(A_F)$	the functional performance of the product (items).
$EDS(A_F)$	the engineering design constraints (performance specification requirements)
$EPS(A_F, A_G)$	the engineering (processing) constraints a material attribute needs to meet
ENR	the environmental requirements
$EGR(A_G)$	the environmental (green) design requirements

The objective function discussed above now integrates product configuration design, functional requirements, geometric requirements, processing requirements, material properties, and the product cost associated with manufacturing, demanufacturing and the environmental issues.

4.2.5. Step 5: Experimentation

Based on results from previous steps, this step generally performs the following tasks:

(1) Feasibility analysis: Hypotheses are tested on the model to see if they are possible and do not violate any constraints.

(2) Optimality analysis: Decision variables are studied to find a set of values that give the best performance.

(3) Adaptivity analysis: Sensitivity of the proposed solution to changes in the environment.

In practice, this step involves taking a real-case problem in ECDM domain (or a hypothetical problem) to illustrate the applicability of developed methodology and model through previous steps.

4.2.6. Step 6: Evaluation and Selection the Best Design Alternative

If each QFD phase results in the selection of only one configuration for further refinement, the problem-solving process is complete when all the phases of design evaluation are complete. When more then one possible configuration design is selected, one may have to use a decision-making algorithm to determine the optimal solution. After synthesis and analysis are performed, the evaluation is processed.

The systematic design evaluation and optimization procedure portrays the idea that system designers need both synthesis and analysis for system (product and/or process) design evaluation. There may be many alternative solutions, and there is no general rule for choosing among them. From the ecodesign or DFE standpoint, cost comparison, waste elimination, energy consumption, resource conservation, and system effectiveness may be used as criteria for selecting the "best" alternative. When the differences among alternatives are small, high accuracy of data and information is required to identify the true optimization [Malone and Doherty, 1995]. Conversely, larger differences among the design alternatives mean that less accurate models will not lead to bad decisions. In other words, analysis/synthesis models need to be sufficiently accurate to discard poor alternatives and yield a smaller number of candidate designs worthy of further attention.

Formulating requirements (attributes) may well be the most critical phase in green product design, which comes out to be the expected output of system synthesis. In order to meet these requirements, all combinations of the material/product configuration, processes, and other production-related activities are possible. Nevertheless, effective design relies on synthesis of multiple feasible designs (or design policies and principles) for translating design requirements into solutions which may be obtained by appropriate analysis efforts.

Appropriate design solutions need to satisfy the entire set of design requirements, thus promoting integration of environmental requirements into the synthesis design process. Design solutions associated with policies of design for the environment (DFE), for fulfilling environmental design requirements, are critical issues in the IECDM engineering process. These DFE principles become the foundation in the QFD-IECDM process that will be discussed in Chapter 6.

4.2.7. Step 7: Implementation Based on QFD Information

This step involves design management and resources allocation in the product development process. In this step, QFD is employed as an auxiliary tool to construct the network that is used to schedule and control the design activities and tasks. Several models are commonly used to represent design procedures (or activities or tasks), such as the Direct Graphic, the PERT chart (Program Evaluation and Review Technique), and the design structure matrices [Steven *et al.*, 1991]. However, these models have their limitation in problem size. Using the QFD-based IECDM approach, design procedure is based on the method of design-structured matrices in the QFD-process, which can overcome the limitation on problem size and complexity found in PERT-based methods. This process is done as follows.

The matrix conducted from the QFD process embodies a structure of underlying design activities (both product and process designs) by mapping the relations between design tasks in a precise order (not necessarily priority order), which makes interdependence explicit. Such a matrix reflects such relations in a systematic way so that they are easy to understand, regardless of the size to the matrix, and also can easily be transferred to the network diagram as required.

For example, a design process, which has been decomposed into n sub-tasks, would be represented as $n \times n$ square matrix. The design task (or activity) labels are placed down the side of the matrix as row headings and across the top are column headings in the same order. The non-zero element c_{ij} of the matrix indicates that task i provides information to task j ; in other words, task i proceeds to task j. Elements below the diagonal represent information transferred to later tasks (activities), while elements above the diagonal indicate information feedback to earlier tasks. The design matrix is a structured design process for information view. Figure 4.16 illustrates how QFD-process is used to help designers construct an activities network diagram for implementation of the product-design process. In addition, once the design activities are well defined, Activity-Based Costing (ABC) methods might be employed in a more detailed design stage. Project management and scheduling can also be performed, based on the activities network diagram, and provide another possibility for research on QFD-based IECDM mrthodology.

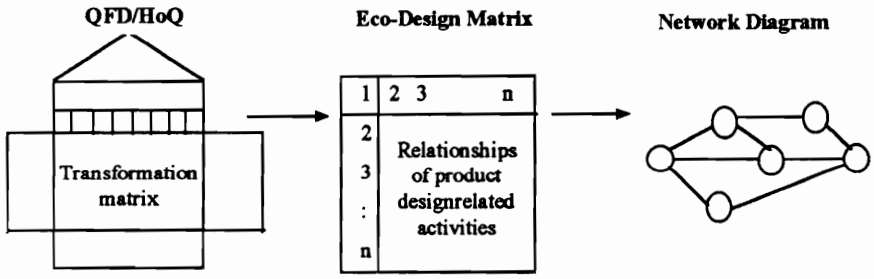


Figure 4.16. QFD, design matrix, and network diagram.

CHAPTER 5

DEVELOPMENT OF A MATHEMATICAL COST-BENEFIT ASSESSMENT MODEL

5.1. BACKGROUND
- 5.1.2. Demanufacturing and Recycling Issues in Production Systems
- 5.1.3. A Complete Cost/Value Economic Flow Diagram

5.2. DEFINITION OF A COST-BENEFIT ASSESSMENT PROBLEM
- 5.2.1. A Hypothetical Product and Process Design Problem
- 5.2.2. A Graphic Representation of the Hypothetical Problem

5.3. MODULES FOR THE COST-BENEFIT FORMULATION
- 5.3.1. Product-Related Attributes and Product-Design Module
- 5.3.2. Manufacturing-Process Selection Module
- 5.3.3. Product Recycling-Options Determination Module
- 5.3.4. Operations Control in a Production System
- 5.3.5. A System's Perspective for Developing a CBA Model

5.4. THE OPTIMIZATION-BASED COST-BENEFIT ASSESSMENT MODEL
- 5.4.1. Assumptions Behind the Model
- 5.4.2. Notations Utilized in Modeling
- 5.4.3. Constraints Considered
- 5.4.4. Formulation of the Model
- 5.4.5. Closure on Formulating CBA Model

The QFD-IECDM discussed in Chapters 3 and 4 is an integrated approach for developing a product and its production-utilization system that is more functionally, environmentally, and economically viable. From this proactive standpoint, the negative environmental impacts of a system can be reduced by addressing the product's entire life-cycle. The QFD-IECDM approach can be viewed as a process for making design decisions, where a mathematical design-evaluation method is used for economic analysis of alternative product-designs. This research especially addresses the links among product-related attributes, manufacturing processes alternatives, and options for production and recycling.

In this chapter, corresponding to the step 4 in section 4.2.4, a mathematical Cost-Benefit Assessment (CBA) model[1] is presented for design evaluation during the QFD-based IECDM process, one which provides a means for making decisions simultaneously throughout the product's life-cycle phases. The CBA is a nonlinear mixed integer programming model. From the optimization point of view, the results of the CBA model are product-related attributes, production plans, and recycling plans that balance revenue and costs related to green product design and realization.

5.1. BACKGROUND

The focus of manufacturers on their customers' requirements has led to improved products, because products are designed with customer satisfaction as an objective. In addition, the growing emphasis on environmental requirements preferred by customers (and environmental regulations imposed by the government) confront manufacturers with yet other challenges. To compete globally, manufacturers must concentrate on customer preferences and environmental concerns during new product development. However, it is difficult to convince manufacturers that they should become environmentally conscious and take actions that are costly in the short term, even though these might be beneficial in the long term. Therefore, analytical methods (such as cost-benefit analysis techniques) are required to convince manufacturers of the opportunities for the competitive advantages inherent in the IECDM approach for product design, manufacturing, and recycling.

Within the IECDM approach, it is also true that the final costs (including environmental costs) of a manufactured product are largely determined at the design stage. This chapter addresses decisions that must be made early in the design procedure, including product design and the selection of suitable processes and materials for the physical attributes of the proposed product. In addition, as Jakobson [1989] concluded:

> "*In good designs, there exists a harmonic relationship between geometric shape, material and the production method used. In order to achieve this harmony, it is necessary to set a procedure which considers the treatment of these elements as an integrated activity.*"

This conclusion suggests that the harmonic relationship will evolve to include the environment as one of the elements of the product's ecodesign, processes/materials selection, and recycling/demanufacturing processes in the analytical model. Integration and unity of approach are emphasized in the development of the CBA model.

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[1] In the context of the QFD-based IECDM process, the CBA formulation plays a role as an evaluation function (to calculate product's total life-cycle value) that helps the design-team make design decisions.

Having realized that integrated approaches are required in modeling a system for product development, this chapter presents an analytical model for ecodesign and process-selection, based on the material in previous chapters. The analytical model integrates various interactive relationships in designing, producing, recycling, and marketing the product. The quantifiable dimensions in this analysis include three major interactive modules: the module of product-attributes selection, the module of manufacturing processes planning and selection, and the module of post-manufacturing (or product-recycling-options selection). The attributes of alternative product designs are determined by marketing issues, while the manufacturing processes are selected on the basis of selected product-attributes. Finally, demanufacturing is planned in accordance with product-recycling options.

The contributions of this chapter are:

(1) An integrated Cost-Benefit Assessment (CBA) model, involving environmental issues, is developed that links together the product design, manufacturing, and demanufacturing/recycling phases of a product's entire life cycle.

(2) Using the system modeling tool (i.e. IDEF0), a mathematical CBA model is formulated in terms of the product's total life-cycle value (TLCV) as an objective function associated with certain constraints.

5.1.1. Demanufacturing and Recycling Issues in a Production System

In a typical product development process, once the product configuration is established, its associated attributes are processed through the manufacturing operations for finished products, and the returned (or recycled) products are processed through demanufacturing operations, also based on the attributes of those products. Recycling and demanufacturing, which are the product's major end-of-life activities, are integrated into the ecoproduct design (for example, material selection) and LCA processes. Ecoproduct design results will affect downstream processes planning for product end-of-life, and processes planning has an effect on the green product design.

When planning manufacturing processes and recycling options for the production system with a demanufacturing capacity (Figure 5.1), the basic structure of the (de-)manufacturing system consists of two major divisions: the production division and the disposal division. In the production division, the manufacturing system purchases raw materials and/or components from outside suppliers, manufactures and produces specified types of products, and sells the products to consumers. The production division plays an essential role in producing the products and selecting the manufacturing processes that have the least impact on the environment. The disposal division's role is to execute the recycling activity and plan the essential demanufacturing processes. The returned products collected from consumers are basically

classified into three groups: (1) recyclable products for producing the same type of products inside the plant, (2) recyclable products for producing different kinds of products inside the plant, and (3) wastes to be dumped. Therefore, a production system with demanufacturing capacity actually contains the closed-loop flow (for group 1) or the open-loop flow (for group 2), or both of them, inside the plant.

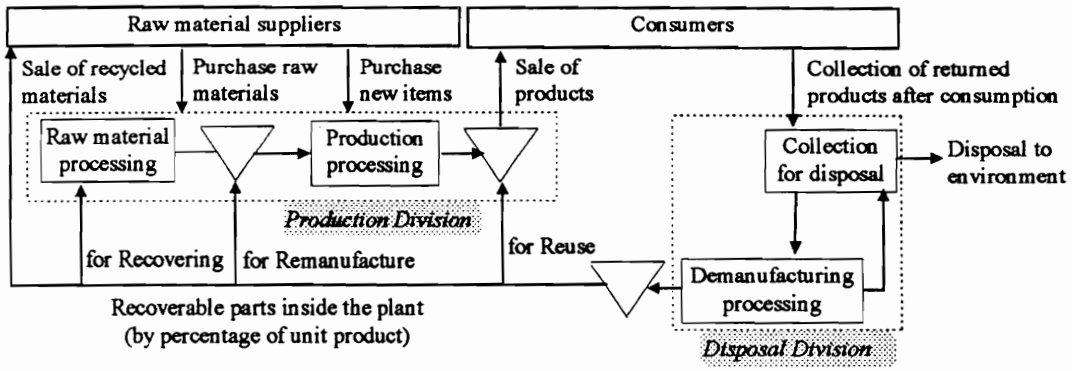


Figure 5.1: Production system with a demanufacturing process

It is recognized that demanufacturing plays an important role in the IECDM approach. Companies respond to social and regulative pressures for environmental issues in several different ways. These responses are directed at decreasing disposal costs by demanufacturing the recycled products received from consumers for reuse, remanufacture, and recycling. Also, these company responses have an impact on the firm's IECDM strategy for ecoproduct development. Moreover, the collection, demanufacture processing, recycling, and disposal of used products recycled from consumers and industry present major engineering problems and environmental threats to the traditional manufacturing system.

Obviously, demanufacturing-operations are essential processes for the purposes of reuse, remanufacturing, refurbishing, recovering, and so forth. Briefly, *reuse* is the highest form of waste reduction and has the potential to increase the product's end-of-life value. Reuse of a product may or may not require total disassembly. Reuse may be easily justified in the case of components with high manufacturing costs, long innovation cycles, and long lifetimes [Jovane *et al.*, 1993].

Remanufacturing, the refurbishing and/or partially rebuilding of a product returned from the market (collection field) at the end of its life in order to give it the functionality of a new product, has been identified by a number of companies as a major source of cost saving and competitive advantage [Berko-Boateng *et al.*, 1993]. Remanufacturing requires disassembly-efforts that contribute to the demanufacturing cost. The recycled components and parts may be used for reproducing either the same or different products, according to the closed-loop or the open-loop recycling system chosen or used.

Recovering of products to obtain raw materials or reuse components is an important means of reducing disposal costs. All these efforts are important ways to reduce the product's life-cycle costs.

However, all these 'R's efforts (or activities) also contribute to demanufacturing costs. As discussed by Ishii *et al.* [1993], Jovane *et al.* [1993], Chen *et al.* [1994], and Clegg and Williams [1995], significant demanufacturing costs for recycling and reuse include costs for retrieval, separation, disassembly, sorting, storage, transportation, identification, testing, reprocessing, and remarking. The value of the recycled or remanufactured product is a function of the intrinsic value of its components/parts and materials as opposed to the cost of recycling and disposal. The cost of recycling is due to the collection and storage of used products from the field until reuse. Furthermore, the availability of returned products and their accumulation over time, together with variations in the quantity and condition of the returned products, can also lead to inventory control problems.

On the other hand, the costs of recycling and disposal can be significantly affected by product design decisions. Design for demanufacturing, design for disassembly, design for serviceability, and design for recycling are thus fundamental to effective demanufacturing and recycling strategies/programs. That is, both manufacturing and demanufacturing processes are affected by design decisions, especially in the consideration of environmental impacts caused by the processes. From such a viewpoint, the product realization problem is complicated by the nature of economic, logistic, and environmental considerations. To explain the relationship between value and cost throughout a product's life-cycle, we present the following cost/value model.

5.1.2. A Cost/Value Economic Flow Diagram

Keeping in mind that integration approaches are required in constructing a cost-benefit analysis model, we show a cost/value economic flow diagram in Figure 5.2. It provides basic concepts of costs and values that vary throughout a product's life cycle. It also depicts a life-cycle, cost/value, economic flow diagram that explains the complexity of economic, logistic, and environmental considerations for the manufacturing system with a demanufacturing/recycling capacity.

Under traditional manufacturing engineering and life-cycle costing, production/ manufacturing cost-benefit analysis is employed in phases I and II as shown. Cost is committed during the manufacturing of the product and other items, including the environmental cost (Phase I). Value is added to the products and items as they are manufactured from raw materials; the extent of the value added is determined by the production/manufacturing costs of capital, purchases, labor, design, engineering processing, etc. During phase II, a benefit is obtained only when the finished products and/or items are sold. The value decreases because the products and items depreciate physically and/or functionally during

their life cycle as a result of use, environmental stress, and competition from newer products and items. For capital products such as vehicles, a net salvage value may be realized. For most small items, the net value is zero or negative to reflect removal or disposal costs [Adams *et al.*, 1989]. This traditional product life cycle and manufacturing cost-benefit analysis does not consider the costs due to environmental effects and the potential revenue from recycling.

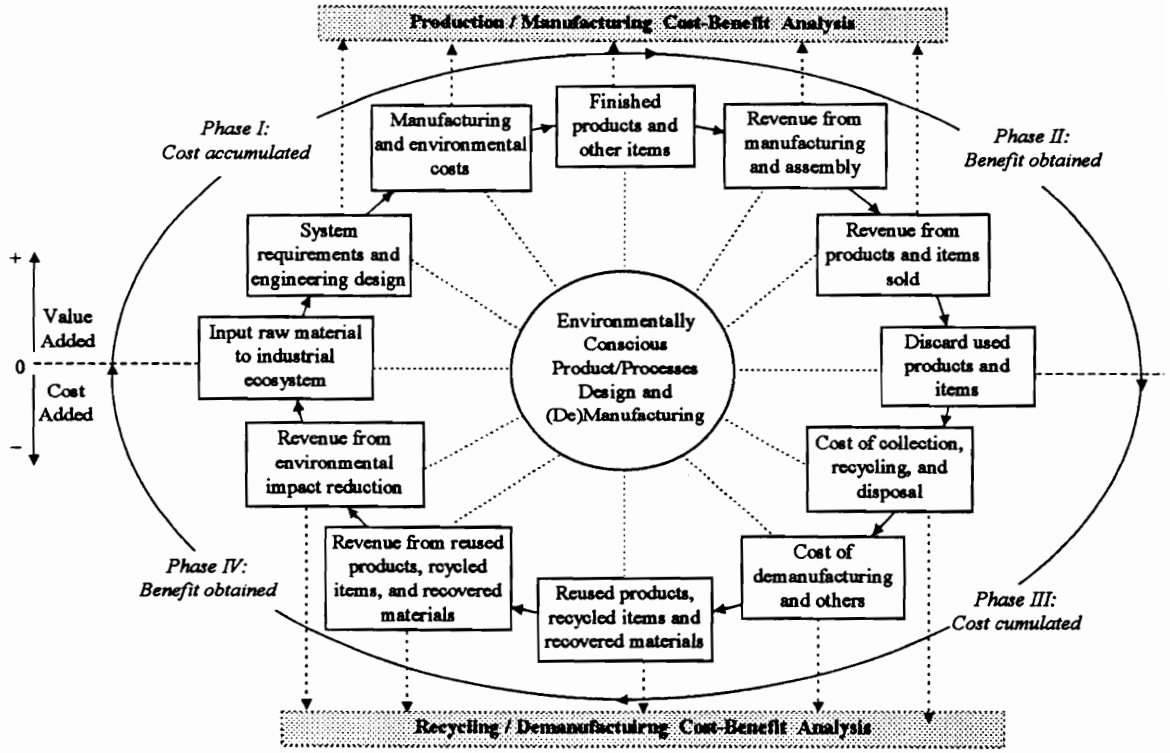


Figure 5.2. Life cycle aspects of a cost/economic flow diagram

A more complete economic cycle would include the lower half of the flow diagram in Figure 5.2. Products and items can be recycled in their salvaged condition. Collection, sorting, disassembly, contaminant removal, and material recovery are often necessary during the recycling and demanufacturing process. These activities add to costs, while extending the actual net value of the product and the items recycled from consumers and industry (Phase III). These additional costs are recovered with market prices permitting in Phase IV when the recycled items and recovered materials are sold to the original or some other product manufacturer. Other savings in the overall four-phase life-cycle result from the reuse of recycled items and recovered materials, as well as the reduction of environmental impact in terms of costs (for example, emission and waste reduction, energy saving).

The environmental costs are actually difficult to specify accurately but show themselves in environmental loading costs, landfill fees and disposal costs, waste handling charges, and environmental liability, etc. Nevertheless, recycling makes good economic sense in many real cases in addition to its environmental benefits. In such a complete economic cycle, the opportunities and feasibility of item recycling and materials recovery should be considered in all product and process designs. All these considerations should be integrated into the cost-benefit analysis model (formulations) that is employed to select design alternatives for the product and process. In our work, an optimization-based approach is used for selecting the 'best' product and process design alternatives. In the following, we will assume a hypothetical problem situation and develop a mathematical CBA model.

5.2. DEFINITION OF A COST-BENEFIT ASSESSMENT PROBLEM

We present a hypothetical optimization problem for a production system with recycling and demanufacturing capacity (Figure 5.1). This optimization-based cost-benefit assessment model has been developed based on the unified approach.

5.2.1. A Hypothetical Product and Process Design Problem

Owing to the increasing regulation of industrial effluents and growing consumer preferences for green products, manufacturers have begun to explore proactive means of reducing both the quantity and the impact of effluents through improved design and planning. These efforts would be aided by comprehensive models that can help in design decision-making and in determining the environmental impacts during manufacturing. The models also aid in determining the influences that design decisions have over the downstream activities in the product's life-cycle. In the context of the IECDM approach, product design determines the product's functionality and environmentability. Also the design of manufacturing systems must be concerned with the needs of productivity and environmentability.

This chapter aims at simultaneous determination of the product's configuration, production processes, and recycling options in the early design stage of product/materials life cycle. A general hypothetical problem can be described as follows.

> *"The XYZ corporation is interested in establishing a periodic operating plan for introducing 'green' products, determining the product's recycling-plan, and conforming to governmental environmental regulations. The XYZ company plans to produce several types of products in which items may be newly purchased, newly manufactured, or remanufactured from recycled products. XYZ operates in an environment characterized by volatile selling prices and changing*

governmental regulations. An analytical model is needed for understanding the impacts of the various interdependent factors in the company's product development process."

Facing such a hypothetical problem, the company does a feasibility study of its production system, to determine:

(1) the configuration of the different types of products and their similarities, such as common items with similar attributes that may be interchanged among products;

(2) products/items-related attributes, such as the percentage of the products/items that are reusable, remanufacturable, or recoverable;

(3) preliminary cost estimates in using or not using recycled items;

(4) all possible items-flow of products inside the plant;

(5) initial goals of Product-Recycling Options (POMs), and so forth.

A general product flow in closed-loop and open-loop systems for three types of product are shown in Figure 5.3. As Figure 5.3 shows, if common items are used in the three product types, any recycled item can be reused in either the original product or in another product type. To deal with this hypothetical problem, we present a unified approach that addresses the complexity of efforts in product-design, manufacturing, and demanufacturing below.

The manufacturing company *XYZ* designs and produces products characterized by various attribute types, with each attribute having different options as factors of that attribute. Given the demand and the selling price, the objective is to determine product-related attributes, manufacturing processes, and recycling options in order to maximize the product's life-cycle value. The design decisions considered in this model involve choosing the optimal product configuration from a set of design alternatives arising from the different options, to satisfy customer preferences and a given set of functional requirements for products during their lifetimes. The sold products are recycled at their end-of-life because of environmental legislation and economic considerations.

Modules for Cost-Benefit Assessment Problem. The proposed optimization model involves a product-design module, a processes selection module, and a recycling options module. The product design module requires determining the product-related attributes to be introduced into the market, that is, selecting the attribute levels of each product, and specifying the production and recycling plans. The selection of processes refers to the determination of manufacturing methods required for production, and the assignment of the chosen attribute (levels) to those processes that have small environmental loads. Recycling options involve determination of the recycling processes from the available options.

A manufacturing 'process' is considered to be a physical entity that can produce an attribute. It can be represented by processing-attributes, for example, a single work-center, or a manufacturing cell or

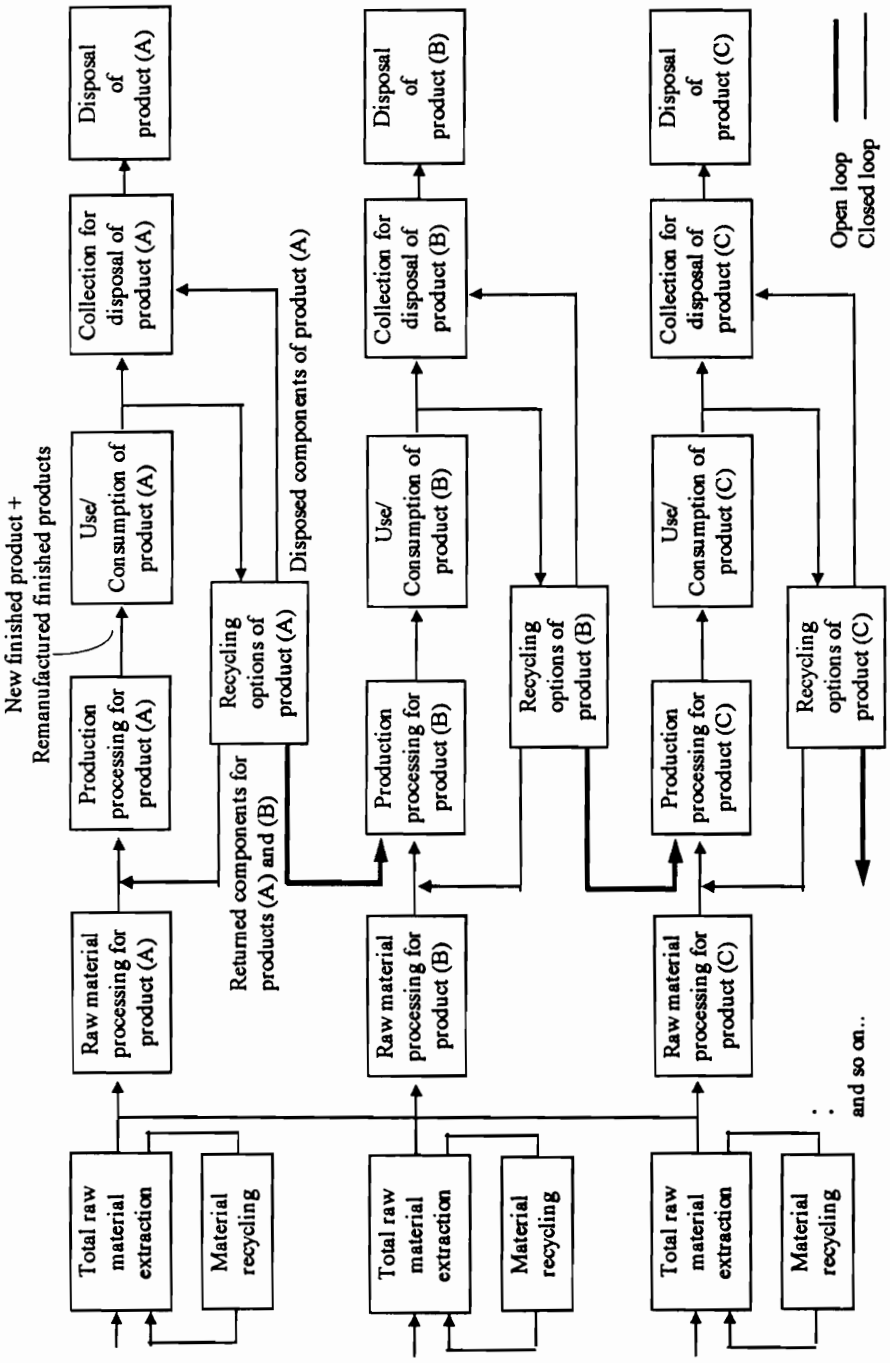


Figure 5.3: A general multiple closed-loop and open-loop recycling system

facility containing a collection of machines, or it can be a supplier. A 'process' can be called 'dedicated' if it produces exactly one attribute element (one level of an attribute), or 'flexible' if it can produce more than one level within an attribute and/or more than one attribute. Each process has an associated fixed cost (setup cost), and a variable cost (production cost) that depends upon the attribute level.

Similarly, a demanufacturing 'process' is also considered to be a physical entity that can disassemble/demanufacture a used product to detail level according to a recycling option that can be any combination of the following recycling activities: disposal, reuse, refurbish, remanufacture, and recover. Each demanufacturing process has an associated fixed cost and a variable cost that depends upon the recycling options. A recycling option, in turn, depends on the material attributes of the product design; that is, it depends on whether the material is renewable or nonrenewable, and on other attributes such as whether it is reusable, non-reusable but remanufacturable, or non-reusable and non-remanufacturable.

Characteristics of the Cost-Benefit Assessment Problem. The proposed CBA model should make the product design and processes/material selection decisions as well as the recycling option decisions simultaneously. The goal of concurrent IECDM methodology is to ensure that the impact of green designs are considered before beginning the production and demanufacturing cycles, and before environmental impacts actually occur. From the integration perspective, this research specifically addresses the links among environmental issues, product design, choice of attributes, production costs, life-cycle assessment, demanufacturing costs, manufacturing system design, process selection, recycling policies, etc. For Company XYZ, the most important aspect is to develop a production resource plan based on long term demand forecasts, while meeting customer preferences and environmental regulations. In addition, the optimization-based CBA formulation can be used to generate several insights. Among others, these include:

- Determination of how traditional manufacturing processes cope with the variation in volume and/or type of products to be produced for the operating period and the demanufacturing/recycling requirements;
- Determination of how changes in production volume affect the optimal choice of attributes of a product;
- Determination of how recycling options and requirements affect the choice of product attributes and materials; and
- Determination of how environmental issues affect the manufacturing system with its demanufacturing capacity.

Within the context of the IECDM approach, construction of a model that is flexible enough to describe all possible decision-making scenarios is a very challenging task, but an attempt is made to

develop such a CBA model in this research. The CBA model will accept as input information on the designed products and the environment-related manufacturing processes and will calculate the company's total profit for the expected lifetime of the designed product. The general CBA model will rely on generic data, and hence will be general in scope, rather than describing a particular scenario of a specific product at each stage of the life-cycle for a particular industry. Because of the generality of its development, the CBA model can be applied to any particular scenario, however.

5.2.2. A Graphic Representation of the Hypothetical Problem

Before we formulate the CBA model, the characteristics of the product and process interactions should be understood. The two basic aspects of a product are its *conception* (engineering design) and its *realization* (production) through manufacturing. Product design is motivated by consumer preferences and presence of opportunities in the marketplace [Chakravarty and Ghose, 1993]. Attribute bundling of the product (determined by design engineers) is an abstraction of such an opportunistic product design. The product manufacturer shapes diverse raw materials and assembles them, thus refining their properties and generating new properties, so as to match the required attribute bundle. Unsatisfactory attribute bundling may cause loss of market share, and unplanned or complex manufacturing processes may increase manufacturing costs to unacceptable levels.

Manufacturing complexity may increase if the options (strength) of the attributes in the bundle are too high or if too many new attributes are incorporated into the bundle too often. Therefore, product characteristics (features) that represent some mapping of the attribute bundle impact manufacturing process plans and cost, while the attribute bundle itself impacts the market share. Recently, it has been recognized that manufacturing process plans are motivated not only by product design for market share but also by environmental regulation imposed by government. For example, the responsibility for product recycling and environmental impact reduction may be assigned to the manufacturer. Since major environmental impacts occur during the materials manufacturing process and product assembly, manufacturers are asked to implement into their production system a recycling capacity that re-collects the returned product for components reuse, product remanufacture, and/or materials recovery. Thus, environmental concerns impact manufacturing complexity and cost; however, recycling activities may provide some potential revenues for the manufacturer. Product design and material selection may also impact the recycling/demanufacturing process, which becomes part of the conventional manufacturing process.

For a competitive product, which should be environmentally conscious today, knowledge of the trade-off between revenues (obtained from market share gain and recycling saving) and costs

(manufacturing and demanufacturing/recycling costs) with respect to attribute bundle and product/material features is a necessity. Two definitions are possible for environmentally conscious products. The first concerns the function of a product during its life cycle; the second concerns the minimization of impacts of the product's life cycle itself. The unified product development method proposed here is not an entirely new design method, but one that integrates customer and environmental aspects into product design and processes planning, as illustrated in Figure 5.4.

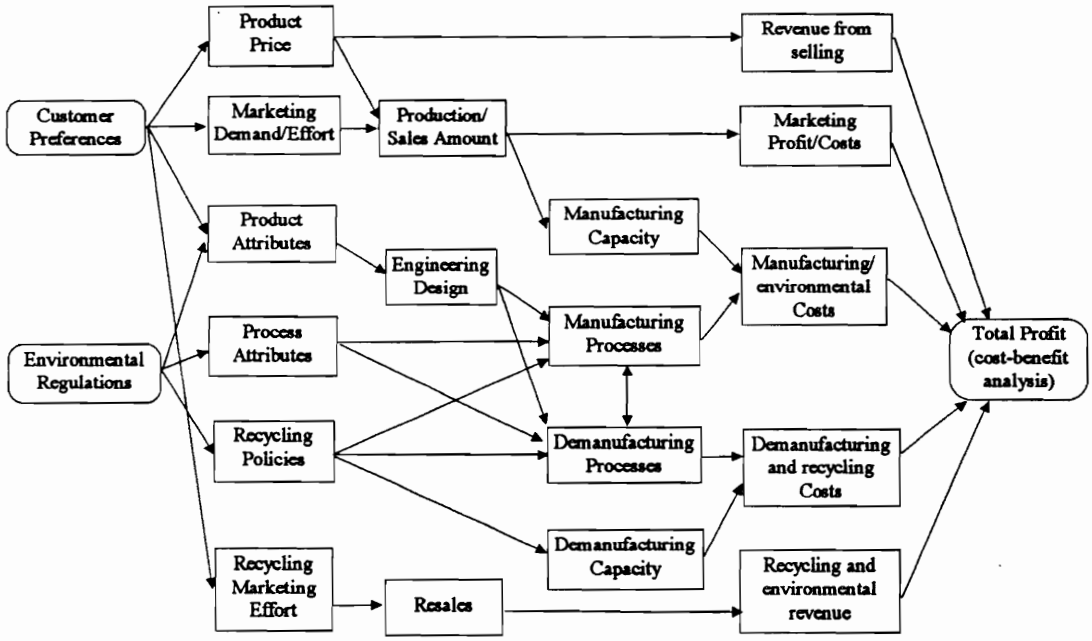


Figure 5.4. Interactions of elements in the modeling approach.

Figure 5.4 illustrates a graphic representation for ecoproduct realization, in which the idea of integration is extended from the graphic model proposed by Chakravaty and Baum [1992]. They consider all the added environmental issues in product/process design and demanufacturing and the recycling capacity in conventional manufacturing systems. The block diagram shows that inter-system interactions play significant roles in such planning. The central issue remains the engineering design of the new product, namely, *green design engineering*. The integrative product/process design procedure considers the interactions between product design, manufacturing goals and requirements, life cycle costing and economic performance, the production system, the demanufacturing and recycling process, etc. It also tries to accommodate these considerations within the constraints of the company to maximize total profit. In the diagram, the engineering designs of the product are conceptualized based on market analysis or customers' preferences and environmental regulations. The design engineers produce product attributes

based primarily on the input from sales and marketing as to what is desired in the market place, with consideration of the available processes or available technology[2].

Products in the market are not purchased only for their functional characteristics, but also because of the quality of the product in all relevant aspects, including environmental characteristics (for example, recyclability and disassemblability of product). The products and processes created by engineering design are in direct response to specific needs defined by management, as a result of strategic marketing or social (environmental) issues. Identifying products to be manufactured and demanufactured is accomplished through marketing studies and cost-benefit analysis. The product characteristics (attributes) are determined by considering changes in customers' preferences (needs), new products competition, technology innovation, environmental regulations, etc.

As illustrated in Figure 5.4, product sales are directly affected by product unit price, the marketing effort in selling the product, and the marketing demand. Customers' preferences have a significant effect on production volume, which has an effect on manufacturing economics and the relative desirability of the product attributes. Moreover, the product attributes preferred by customers affect the engineering design that, in turn, affects the manufacturing and demanufacturing processes to be applied and their costs as well as their impacts on the environment. Equally important to customer preferences, the environmental regulations imposed by government also affect the product attributes that, in turn, affect the processes/material selection and product recyclability. The profit derived from introduction of new products becomes a function of price, production amount, sales, marketing costs, manufacturing costs, and demanufacturing costs. Therefore, attributes selected for a new product cannot be considered in isolation from the production and demanufacturing costs incurred for usage of those attributes. With regard to the QFD-based IECDM approach, this unified approach goes beyond the typical QFD methodology in that the customer's needs, manufacturing's concerns, and demanufacturing considerations are addressed simultaneously.

Once the product goal has been clearly recognized and stated, the next step is to develop specifications (attributes) for the product/process and to define the design goal of the product/process. The overall objective in this step is to identify a combination of product/process and recycling attributes that lead to meeting the customers' needs and environmental regulations. The attributes are then converted into a feasible product-design and an ecological process/material selection. This product design and process/material selection procedure may necessitate tradeoffs in different types and number of attributes with different options of product and process. Moreover, the unified approach must ensure the 'best' match between product design and process/material selection. This match can be obtained while

[2] The term technology includes production technology and required recycling techniques.

satisfying product and process flexibility goals (for example, functional, ecological, and economic goals), to obtain maximum total profit. Therefore, the *goodness* and the *greenness* are measured to indicate the effectiveness of the unified approach associated with the CBA model.

Conceptually, the *goodness* of match is used to indicate how 'good' is the match between product attributes and process attributes. On the other hand, *greenness*[3] is used to indicate how environmental impact is reduced due to the 'best' process/material selection and how much 'recyclability' can be achieved. However, given the variety of attributes available for both product and process, some of which conflict, it is generally difficult to obtain an optimal (perfect) match among the product, material, and process attributes. Generally, economic considerations may be extremely complex in such a unified approach; however, they are important factors in the evaluation or tradeoffs of the attributes. Therefore, cost-benefit analysis is the way our unified approach associates 'goodness' and 'greenness'.

5.3. MODULES FOR THE COST-BENEFIT FORMULATION

Since decision-makers have increasingly focused their attention on the product's total life-cycle value (TLCV), an analytical cost-benefit model is required for striking a balance between revenues and costs for each product-design alternative. The overall CBA model is based on links among the modules of product-design, manufacturing-processes, and recycling options that are used to identify the decision variables. For the purpose of illustration, certain descriptions are needed for each module in the CBA formulation. In this section, we review the decision variables in each module. Then, we present a system aspect for the product realization process and a system modeling tool for formulating the CBA.

5.3.1. Product-Related Attributes and Product Design Model

The design decisions considered in this approach involve choosing the product-related attributes from a set of alternatives, to satisfy a given set of marketing demands. The set of product attributes may include the new purchasing/manufacturing components and sub-assemblies or the recycled components and subassemblies either from the same type of products or from other types of products (see the product-flow diagram in Figure 5.3). So a product is produced and assembled either by all new components or by a mixture of new and recycled components. In the product design module, a product-structure is usually expressed by a set of attributes.

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[3] In the literature, 'greenness' is defined in different ways. Herein, we define 'greenness' in manufacturing processes as a function of environmental factors and process patterns. Environmental factors are defined as inputs/outputs of each process in a particular process pattern (model), such as energy, raw material, waste, emissions, and so forth.

A General Product-Tree: A Design-Structure Approach. In a practical product-design statement, the different types of attributes (in Table 5.1) may be combined in various ways to represent the product features, depending on the characteristics of the specific design problem. However, physical attributes are important for product design. Hence, the product description will focus on the structural relationships (physical attributes) that exist between components in the product-design. Especially in the context of DFA (Design For Assembly) and DFD (Design For Disassembly), product design must be represented by a tree structure.

Table 5.1. Classification of attributes used to represent a product (an example)

Attributes	Examples and description
Physical attributes	Attributes for subassemblies, assemblies, modular, components, parts, materials and their properties, physical dimensions, geometric features, etc.
Connection (operational)attributes	Functional links: functional connections, assembly operations, disassembly operations, system connections, etc. Physical links of mechanical systems: covers, attachments, connections, engagements, supports, etc.
Engineering material attributes	Metals: Ferrous (steels, stainless steels, cast irons, tool and die steels, low carbon steel); Amorphous; Nonferrous (aluminum, copper, titanium, tungsten), etc. Plastics (or Polymers): Thermoplastics (acrylics, ABS, nylons, polyethylenes, PVC); Thermosets (epoxies, phenolics, polyimides); Elastomers (rubbers, silicones, polyurethanes), etc. Ceramics and others: oxides, nitrites, carbides, glasses, glass ceramics, graphite, diamond, etc. Composites: reinforced plastics, metal-matrix, ceramic-matrix, laminates, etc.
Behavior attributes	Top level functionality: reliability, maintainability, availability, supportability, manufacturability, MTBF, MTTR, environmental compatibility, recyclability, etc. Materials manufacturing properties: structure of materials (atomic bonds); mechanical properties (strength, ductility, elasticity, hardness, fatigue, creep, toughness, fracture); physical and chemical properties (density, melting point, specific heat, thermal conductivity, thermal expansion, electrical conductivity, magnetic properties, oxidation, corrosion); property modification (heat treatment, precipitation hardening, annealing, tempering, surface treatment, alloying, reinforcements, composites, laminations, fillers).
Processing/ Assembly attributes	Production processing: assembly and operations sequence, internal joints, external joints, reuse process, remanufacturing, disassembly process (e.g., staging, teardown/stripping, sorting, cleaning, repairing, reassembling, testing), desoliding components, resources requirements, etc. Material processing: Primary processes: extraction, casting, forming and shaping (forging, extrusion and drawing, sheet-metal forming), etc. Secondary and finishing processes: machining and nontraditional machining, joining (adhesive, welded, velcro, bolted, snap), finishing operations, etc. Others: tolerances and surface finish, sequence of operations performed, tools, dies, fixtures, and machinery, production quantity and production rate, energy consumption and waste generation, material recovery/reprocessing, etc.
Greenness attributes (see Appendix B)	Top level: reusability, label, materials variety, material identification, recycled content, chemical usage, waste, disposability, etc. Process level: inputs/outputs of proccess for environmental impact analysis, energy, emissions, solid waste, etc. Material: hazard degree of material, recoverability, etc.

Generally, the product to be assembled or disassembled is graphically illustrated using a product-structure tree as in Figure 5.5. Product-elements may be created in order to describe the processes of

manufacturing, assembly, and disassembly. These product-elements can be distinguished as: product structure (or icon), connections (or links), components, subassembly, and materials, in which greenness attributes (levels) are required for study of the environmental impact of each element during its life cycle. For example, the mechanical design-elements[4] are defined and described briefly as follows:

- *Product structure* (Icon) is a graphical representation of a system (e.g., mechanical product) design element, such as parts, components, subassembly, fastener, or process.
  - *Part* is a design-element which cannot be broken down any further by disassembly without destruction. Parts may exist as fasteners, adhesives, or any single element required in the assembly of a component or product.
  - *Component* is a design-element that cannot be further disassembled without permanent damage to the resulting pieces, or loss of intended function following reassembly of the resulting pieces.
  - *Subassembly* is a design-element that can be disassembled into two or more other elements and performs its intended function following reassembly with the original elements.
  - *Material* is a design-element that can be processed into a part element.
- *Connections* (links) is a graphical representation of a semantic relationship between two design elements. For example, we can define five different relationships for mechanical systems: Covers, Attaches to, Connects to, Engages, Supports. Generally, two operations are used to describe the process of connections:
  - *Assembly operation* is a process involving the combination (linkage) of two or more components or parts.
  - *Disassembly operation* is a process involving the separation of two or more components or parts.

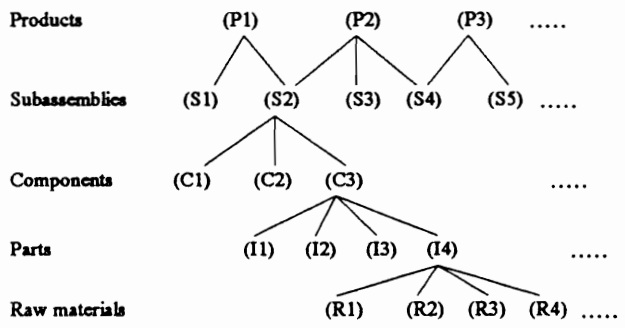


Figure 5.5. An example of multi-product, mixed-model product tree.

[4] For a large-scale system design, more design-elements may be defined as modular, depending on how the design-team constructs the product-structure-tree and defines the product's design elements. Here, the design elements may also be termed the product attributes.

Other representations of the design structure are possible; nevertheless, the design structure is the critical issue in Design For Manufacture (DFM), Design For Assembly (DFA), Design For Disassembly (DFD), and Design For Recycling (DFR). When only the relationships between design elements are known, other indicators can be estimated and calculated -- such as assembly sequence and time or disassembly sequence and time -- which, in turn, are used for the cost estimation of production and recycling. More general and formal representation of design is described below, based on the concepts of attribute statement.

Basic Concepts of Product/Item Attributes in Design Decision-Making. For the purpose of product design, we define two kinds of entities to represent the product structure: attributes and levels (options). A product is generally represented by a set of attributes with levels [Shocker and Srinivasan, 1994]. Any product being designed can be specified by the attributes that it processes. Precisely, each design-element shown in Figure 5.6 is described by a set of attributes. In the QFD-based IECDM approach, the term 'attributes' may correspond to 'requirements' in QFD-process, and 'options' may correspond to different 'factors' or 'criteria' for a particular attribute in the QFD-matrix.

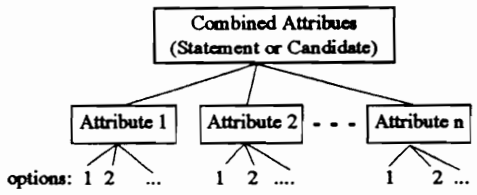


Figure 5.6. Idealistic combination of attributes

Ideally, one would like the attributes used to be aggregated (or combined) by a single aggregation step (Figure 5.6). However, this is not a realistic option, because in most cases the criteria (rules) would be too complex and probably some attributes would not interrelate with other attributes. So, it is useful to build groups of attributes, and combine them, in aggregation (Figure 5.7). From this viewpoint, the aim of ecoproduct development and especially Life-Cycle Assessment (LCA) is often to aggregate several different forms of information into one comprehensive attribute statement. For example, to 'add up' several attributes in one design evaluation and decision, leading to a final aggregated attribute statement, such as:

- --- Yes, this project of ecological product development is decisive in reducing environmental impacts, and the objective of the greening product is achieved; or
- --- No clear statement is possible; further investigation and analysis is needed for more attributes information; or

--- No, this project is not decisive in reducing environmental impacts, the objective of greening system is not achieved.

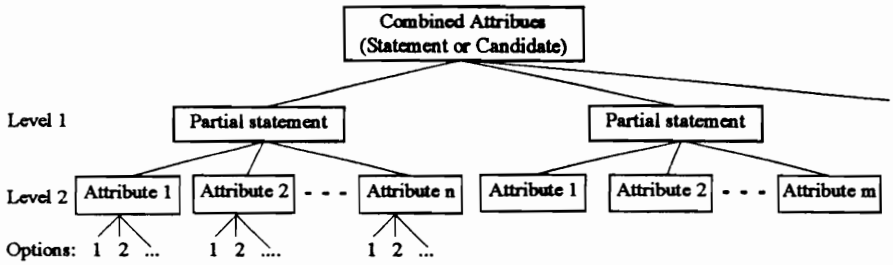


Figure 5.7. Hierarchical combination of attributes with levels.

Once the structured-attributes for a statement (or product-design alternative) are defined, in general, there are sequential aggregation mechanisms on the usage of attributes-information for design evaluation and preference assessment by: (1) the weighting and ranking approach, or (2) by the superposition and aggregation approach.

(1) Comparison of Attributes by Weighting and Ranking Mechanisms: In the review of decision-making mechanisms, weighting approach mechanisms are useful in the evaluation of across-candidate systems. Decision makers will first rank all system decision attributes. After ranking is completed, rating will be assigned to the attributes. Results of the comparison or ranking of attributes may be expressed in a matrix form for each attribute level. Then, the attribute matrices are combined for design evaluation. AHP is a typical example of such an application.

(2) Combining Attributes--Superposition and Aggregation of Attribute Matrices: During evaluation of design alternatives and especially during environmental impacts assessment, traditional but different kinds of attribute data are drawn into different maps (e.g., matrix form), which are then merged into a unified attribute map to get more significant information about the alternatives. If this superposition of maps is done, then decision makers use matrices to describe how the value of two attributes result in a combined attribute in the matrix form. In this way, it is easy to aggregate two attribute maps. For aggregation of more than two attributes maps, other techniques are required; the utility-function approach in Multiple-Criteria Decision Making (MCDM) is a typical example of aggregation of multiple attributes.

Based on the literature review, multiple attributes decision-making (MADM) methods are part of MCDM approaches. In the context of MADM, alternative product designs are generally represented by a number (set) of attributes with many combination-options in each attribute. They are evaluated to

determine if they will meet the needs and the criteria, including the environmental, customer, and design requirements. Based on the results of the needs analysis, the customer will specify the performance goals of the product that must be met by the design. The design-team specifies the new product by indicating the attributes used. Trade-offs between attributes and costs as well as ecological considerations to achieve them are conducted to establish a baseline design.

Such a preference-assessment approach has been adapted in our QFD-based IECDM process. Briefly, if the product-design alternatives are represented by a set of product-related attributes, the 'best' product alternative is selected by preference assessment of alternatives with respect to each attribute. That is, the product design decision-making process is actually a multiple attribute assessment process, either by a ranking mechanism or by combination of attributes approach.

Types of Product-Related Attributes. In our IECDM approach, product-related attributes are defined quite broadly, as shown in Table 5.1. These provide a general consideration of information aggregation for practical design evaluation or design decision-analysis problems. It is best to work with a hierarchical combination of the structured attributes tree with options. This combination of attributes can be a physical characteristic of the product, with the various options being the different realizations of this characteristic; different types of attributes may be combined according to product characteristics and design objective. This combination of attributes may also represent a design subsystem or element of the product; the attribute levels then correspond to the alternative designs possible for each subsystem (element) design (see Figure 5.7).

In practice, the classification of attributes with options can be defined differently from one ecodesign problem to another. All identified attributes may interconnect with each other. In other words, each attribute could be described by other attributes at different hierarchical levels of attributes. The difficulty lies in identifying the attributes required for a product prior to the detailed design of the product and the selection of materials/processes, when the designer can more fully exploit the best cost-benefit product development system. Nevertheless, the number of attributes with options should be adequate to fully describe all product characteristics and detailed enough to evaluate environmental loads in the manufacturing process, carefully selected to minimize overlap. Actually, a major task in the present work is the construction of a general product structure and processes in terms of different kinds of attributes, as illustrated in Figure 5.8. In our QFD-based IECDM, the QFD-process is used as a useful tool for identification of all key attributes for product design alternatives[5].

[5] Again, the "attributes" are used to specify a product within a broad meaning; thus, a product being designed can be specified by the attributes that it possesses. The attributes to specify a product include physical attributes, connecting attributes, material attributes, processing attributes, and so forth. To this point, the product-related attributes contain

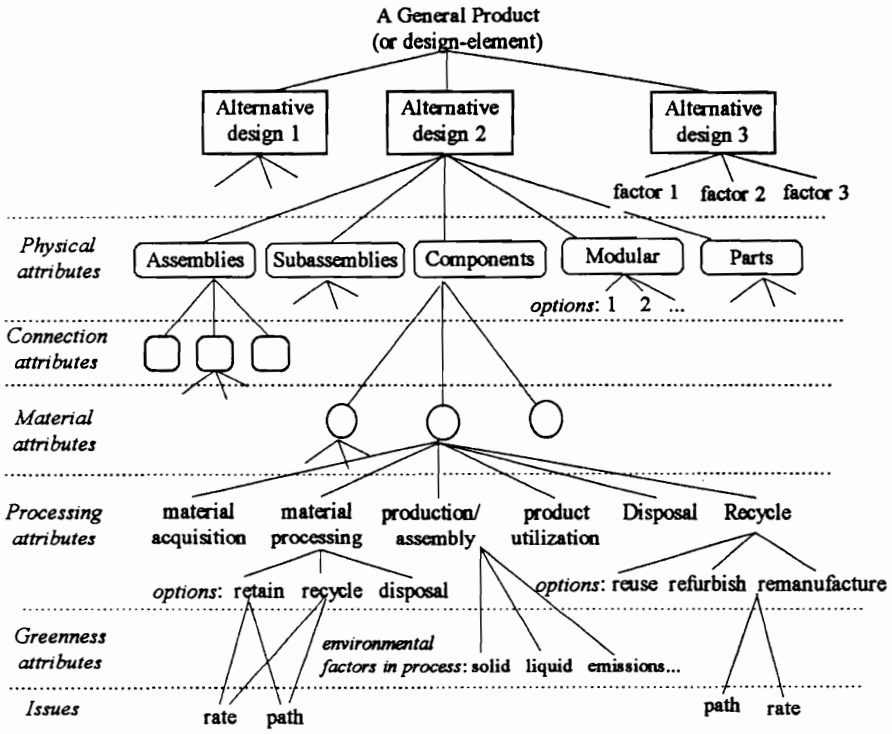


Figure 5.8. A general product-related attributes system with options for product's representation

A General Product-Attribute Graph: A Design-Description Approach. Design is a decision-making process, and most decision processes may be modeled by a design structure with a set of different types of attributes (with or without options). We call such a product representation a *hierarchical structured-attribute graph*, which is used to describe each design element shown in Figure 5.8. The structured-attributes graph not only assures that a product-system is composed of certain attribute elements, but it also describes how the product is composed (e.g., functional iteration) and of what it is made (e.g., material types). Figure 5.8 illustrates a typical product structure, which is to be considered during design; it groups components together to form subassemblies to facilitate the manufacturing process or to perform a specific function within the product.

By using product-related attributes, the product-structure can be represented by a set of attributes connected in different ways at different levels that are subordinate to the overall product-system level. The total product configuration will also be called the assembly. For the purposes of this research, the

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manufacturing processes, demanufacturing processes, recycling issues and other attributes that are used to specify a product more completely and exactly (see section 5.3 in Chapter 5).

products are assumed to be recoverable. Therefore, demanufacturing processes are required to disassemble used products for reuse, remanufacture, and recycling.

For each attribute, a set of decision criteria (factors) is imposed. The decision criteria are those *factors* that will be used to evaluate the candidate designs. These criteria, or goals as they become in the solution process, may be associated with any attribute within the design structure. The decision criteria, together with the design parameters for each alternative design, form the basis of the optimization problem formulation, which in turn allows the bottom level nodes to be compared. Therefore, a product (item) is a function of attribute-element e at product-structure level e' with option l, which is denoted by (e,e',l). In the QFD-based IECDM process, these product attributes, decision variables, design criteria, and design parameters are identified for each product-design alternative through the QFD-process. The information obtained from the QFD-process is the basic input for the design decision-making process.

Furthermore, the relationship between the parent (upper) and child (lower) nodes may be specified as any functional expression (i.e., design evaluation function or utility function) involving design variables and parameters (all are attributes in a sense). The design and parameter values may be specified for any attribute in the design structure, and the lower level nodes may or may not inherit these evaluation functions imposed by the designers.

In addition, each of these physical attributes can be associated with a set of lower configuration levels that includes the level of material attributes which, in turn, is processed by the processing attributes and the level of greenness attributes (Figure 5.8). There may also be different ways to configure alternative designs based on their functional requirements. The set of attribute levels and types to describe the product will be input by the design engineer and the process planner, as will the cost-benefit model. As illustrated in Figure 5.8, the scheme of attributes at one level and then options at the subordinate level alternate until the product is broken down into its individual attribute elements. The final set of levels for environmental-impacts analysis then includes the individual materials processes associated with the processing attributes and with the greenness level with respect to environmental factors.

In the product-design module, the decision variables in product-configuration design are:

$A_{q,j}$ = item q that configures the product j and has a set of attributes expressed by (e,e',l); this set of attributes may be kinds of physical or non-physical attributes associated with either quantitative or qualitative parameters.

Each attribute element $A_{q,j}$ may be a function of attribute elements in subordinate product-structure levels. In an optimal design problem, an appropriate set of attributes $A_{q,j}$ is selected for each optimizing objective function (or design evaluation function). The multi-attribute utility function is a good example that contains all utility contributed by all attributes.

Material Selection in Product Design. In the context of DFE, material-selection is the most important attribute related to environmental impacts. Because most pollution is created during processing of materials, adding environmental considerations into material selection will significantly affect the product-design and manufacturing-process selection which, in turn, will affect the total production cost for product development. The material especially affects environmental costs, including external and internal environmental costs, caused by material processing. It is a major concern for manufacturers trying to minimize the cost (or maximize the profit) while meeting engineering requirements (for satisfying customer preferences) and environmental considerations (for satisfying environmental regulations). The need now exists to identify the lowest-cost method prior to the design of the product, which is broken down to detailed design of each part/material level. The lowest-cost method should allow the designer to fully exploit the most cost-effective material selection based on engineering requirements and environmental considerations in the life cycle(s) of the product and materials.

Formally, material selection can also be expressed as a function of process attributes with level of greenness, thus

$$M = f(\text{name } N(M),\ \text{process attributes } A_P,\ \text{greenness attributes } A_G)$$

Attributes A_P determine the manufacturing process(es) that process a specific material, and attributes A_G are used to measure environmental factors that should be considered in manufacturing processes. In other words, in our cost-benefit model, information for the product configuration design should be broken down to material-level for the purpose of LCI (Life-Cycle Inventory) analysis.

5.3.2. Manufacturing-Process Selection Module

In the context of environmentally-conscious manufacturing, the manufacturing process obviously plays the most important role relevant to reduction of environmental impacts. As Figure 3.6 shows, the environmental burdens actually crest at the beginning to produce products. The manufacturing process is determined depending on the properties of the material selected in the product design stage, which in turn affects manufacturing-related costs.

Manufacturing Processes/Materials Selection. The individual materials selected through product design are processed into parts and/or components by various manufacturing processes. The environmental impacts of these processes are expressed in terms of environmental loads in general. The profile of environmental loads is one of the major attributes for process selection.

A manufacturing model is needed for a company to appropriately select processes and materials in order to minimize environmental impacts. Once the material attributes of the product have been

determined, processes in the manufacturing model are selected to produce the parts needed for the designed product; that is, processes are assigned to produce the physical attributes (that is, components, parts, and material) of the designed product. There are many ways by which any given attribute of an item may be produced; each way contains a series of manufacturing processes[6]. For example, it may be possible to produce a part by machining a solid stock, or by casting, or by machining a recycled part. Whatever processes are selected to produce an attribute of an item, their environmental impacts are the key in this analysis. Thus, Life Cycle Assessment (LCA), especially the Life Cycle Inventory (LCI), is essential to evaluate the environmental burden (e.g., pollution) of each selected manufacturing process (or cell).

In this module, the manufacturing process selection variables are represented by the following list:

$y_{q,j,k}$ = 1, if the production cell (one or more processes) k that serves as the manufacturing site for processing or producing item q with a set of attributes (e,e',l) for product j,

= 0, otherwise.

This variable indicates the assignment of the manufacturing cell that will process or produce each attribute. Processing times for each attribute in the cell, the capacities of the cell, and the environmental loads of each cell will be needed to make the decision regarding where to assign the attribute and which cell meets the environmental requirements. Generally, the 'goodness' is a factor that indicates how 'appropriate' the matching between the component attribute and the processes selected to manufacture the component is. 'Greenness' is another measure for selecting an appropriate process for producing a product with fewer environmental impacts (see Appendix B for the greenness-merit development).

Manufacturing processes can generally be classified into five categories [Chryssolouris, 1992]:

(1) *Forming or primary forming processes*--processes in which an original shape is created from a molten or gaseous state, or from solid particles of an undefined shape.

(2) *Deforming processes*--processes that convert the original shape of a solid to another shape without changing its mass or material composition.

(3) *Removing processes*--processes in which material removal occurs during the process itself.

(4) *Joining processes*--processes that unite individual work-pieces to make subassemblies or final products.

[6] Item, in this model, is used to represent subassemblies, modules, components, parts, and materials, according to the hierarchy of the product (or the levels of attributes that represent the product).

(5) *Material properties modification processes*--processes that purposely change the material properties of a work-piece in order to achieve desirable characteristics without changing its shape.

These categories are applied to a variety of engineering materials, which can be generally classified into metals, ceramics, plastics (polymers), and composites. The selection of materials depends on the product design and involves the environmental considerations. Sustainable and recyclable materials are always considered first in green product design. Consequently, the different processes are applied to different engineering materials (Table 5.2).

Table 5.2: Matching between engineering materials and processes (overview)

Processes / Materials	Forming	Deforming	Removing	Joining	Modifying
Metals	widely used	widely used	widely used	widely used	widely used
Ceramics	widely used	not used	seldom used	not used	not used
Polymers	widely used	seldom used	seldom used	seldom used	not used
Composites	widely used	not used	seldom used	seldom used	not used

The selection of which process to apply to a particular material is influenced by a number of factors (e.g., the lot size of the parts to be made and the physical properties of the materials) which affect process attributes (e.g., cost, production rate, flexibility, part quality), and is especially influenced by the environmental loads caused by manufacturing processes. Selection of an appropriate process often depends on a tradeoff (balance) of all process attributes (or criteria) including the potential environmental impacts (see Table 5.3), based on engineering requirements for making a desirable product in an efficient, ecological, and profitable manner.

Table 5.3: Attribute characteristic of the manufacturing processes (an example)

Processes / Attributes	Forming	Deforming	Removing	Joining	Modifying
Costs	high tooling/ low labor cost	high tooling/ low labor cost	medium tooling/ high labor cost	low capacity/ high labor cost	medium to high capital/ low labor cost
Environmental costs	expert judgment	expert judgment	expert judgment	expert judgment	expert judgment
Production rate	high	high	medium (milling) to low (grinding)	medium (welding) to low (adhesives)	low
Part quality	medium to low	medium to low	medium to high	medium to low	high
Flexibility	low	low	high	high	medium to high
Environmental factors	inputs/outputs	inputs/outputs	inputs/outputs	inputs/outputs	inputs/outputs
Environment-ability	by LCA	by LCA	by LCA	by LCA	by LCA

In Table 5.3, in the context of IECDM, cost-attributes should include environmental costs. "Environmentability" means environmental compatibility, which is viewed as a result of the environmental loads (e.g., pollution, energy consumption, waste generation) caused by each process. LCA methods are applied to estimate the environmental loads that results from the total manufacturing processes that produce a specific part. However, due to lack of realistic or historical data of the environmental loads for each process, LCA is a difficult task. Nevertheless, environmental load is one of the important criteria for selection of process. This also leads to another field of study in product design; that is DFM associated with process/materials selection. In the QFD-based IECDM process, the attributes (or requirements) and design characteristics of the manufacturing process are identified through a QFD-process; the number of attributes and process-steps in Table 5.3 may increase for a particular case, if necessary. When attributes associated with the manufacturing-process are identified, the problem of process-selection may be seen as a multi-attribute decision-making problem.

Assembly-Process Selection. The individual parts and components made by various manufacturing processes are assembled into finished products by various assembly methods. The environmental impacts are contributed by assembly cost and time. Traditionally, assembly has involved much manual work, contributing significantly to a cost that includes handling, gripping, the fitting of individual parts, and so forth. The total assembly operation is usually broken into individual assembly operations, with an operator assigned to carry out each step. Assembly costs are typically 25 to 50 percent of the total cost of manufacturing, with the percentage of workers involved in assembly operations ranging from 20 to 60 percent [Kalpakjian, 1995].

As product costs and quantities of product to be assembled increase, the necessity for automated assembly becomes obvious due to its reduction in the assembly time. However, they also cause some environmental impacts, such as increasing energy consumption and air emissions. Economical and ecological analysis tools are needed for assembly system design using either manual assembly methods or automated assembly methods, or both. This need leads to other research issues in the field of DFE, such as design for assembly (DFA), design for service (DFS), and design for disassembly (DFDA), associated with selection of the appropriate assembly methods/systems.

Considering remanufacturing capacity in our cost-benefit problem, we assume that the manufacturing and remanufacturing operations produce some different attributes and that the list of attributes from recycled products will necessarily add to the load on the existing production cells. That is, remanufacturing is assigned to the manufacturing attributes that the two systems have in common. If the existing production capacity is not sufficient for adding remanufacturing loads, the XYZ company has tradeoffs in recycling and disposal.

5.3.3. Product-Recycling Options Determination Module

The determination of product-recycling options decide the disassembly-depth and demanufacturing processes which, in turn, affect both recycling costs and revenues. The impact of the demanufacturing module (recycling planning) on product design is that it provides the design team with very useful criteria that they can use in the ecodesign process (module), such as:

- use as little material as possible for the product;
- design solid construction with a view to lengthening the life cycle;
- design for disassembly (demanufacturing);
- ensure that valuable parts of the product can be reused;
- use as much recycled material as possible;
- use materials that can be recycled; etc. [van der Horst and Zweers, 1993].

All these considerations can become design criteria to restrict the types of attributes of the product during the design procedure. The design decisions to be made are about the product structure, attributes, and connections between physical attributes. These choices have a direct influence on the possible recycling policies when the product is recycled. The economic feasibility will then determine which policy will be followed.

A model is constructed for the XYZ company with an environment-oriented product development system that involves a demanufacturing system, which introduces new types of products and produces a number of products according to customer preferences (marketing requirements). The company purchases necessary parts from raw-material suppliers, and assembles a new product with the purchased parts together with the recycled parts processed inside the company's plant. Then the company either sells reproducible items to outside raw-material suppliers or uses the reproducible items to remanufacture a new product inside the company. The remaining material (waste) is disposed to the environment.

In the hypothetical problem, the company recycles used products from field collections and has the option of disposing them, reusing (repairing) some components after disassembly, remanufacturing the product, reassembling the product from scratch as a remanufactured finished product (same or different type of product), or recycling the product to obtain raw material. By disposal we mean that items remaining from alternative recycling options are discarded as landfill. Remanufacturing involves a number of old modules, components, and parts that are removed from the recycled product and used to produce 'new' products.

In the demanufacturing stage, recycling options are defined as attributes of the demanufacturing policies, as shown in Table 5.4. Since the ultimate goal of disassembly and demanufacturing is to achieve recycling, this option is of particular concern in the design-for-demanufacturing system. Generally, such

a goal may take on one of the following alternative: (1) reclamation, then disposal; (2) partial disassembly for reuse and disposal; (3) partial disassembly for reuse, remanufacture, and disposal; and (4) total disassembly for reuse, remanufacture, recovery, and disposal. For each situation, a trade-off analysis is performed between revenues and costs related to recycling activities; that is, recycling options obviously affect the disassembly-depth which, in turn, affects disassembly costs. In addition, demanufacturing capacity is determined by the efficient design of disassembly processes and sequences, which affect the demanufacturing time, and consequently affect the demanufacturing cost.

Table 5.4: Definition of recycling options

Demanufacturing capacity	Levels (options)	Product demanufacturing/recycling options	PROs notation
Reclamation	Degree 0	Disposal	$i = 1$
Partial disassembly	Degree 1	Reuse + Disposal	$i = 2$
Partial disassembly	Degree 2	Reuse + Remanufacture + Disposal	$i = 3$
Total disassembly	Degree 3	Reuse + Remanufacture + Recovery + Disposal	$i = 4$

As shown in Table 5.4, there are four types of recycling options for obtaining recycled items for the purpose of reuse, remanufacture, and recovery. The recycled items are described as:

(1) Reusable items: this type of part can be reused inside the plant to produce the same type of product as was returned or to produce another type of product. These items (including the original product itself) are denoted by $ux_{q,j,i}$ associated with recycling-options $i = 2,3,4$.

(2) Not reusable but remanufacturable items: this type of part cannot be reused to remanufacture the same type of product, but can be used to produce a new type of product inside the company or can be resold to an outside company (for example, raw-material suppliers). These recycled items are denoted by $rx_{q,j,i}$ associated with recycling-option $i = 3,4$.

(3) Not remanufacturable/reusable items but recoverable items: this type of item cannot be recycled to reproduce either the same or different types of products, but can be recovered as secondary material for reuse and/or resale. These recovered items (now materials) are denoted by $mx_{q,j,i}$ associated with recycling-options $i = 4$.

(4) Not remanufacturable/reusable items and not recoverable items: this type of parts cannot be recycled to reproduce either the same or different products, nor can they be recovered as secondary materials for reuse. These are disposal items and are denoted by $sx_{q,j,i}$ associated with recycling-option $i = 1,2,3,4$.

For example, if the recycling option $i = 4$, then the returned item contain items used for reuse, remanufacure, recovery, and for disposal. Generally, the stages that can be distinguished in re-use and

remanufacturing of items (that is for options, i = 2,3,4) are: disassembly, cleaning, testing and sorting, upgrading, product reassembly (for original type of product), and product remanufacture (for different type of product). Material recovery (for option, i = 4) can be divided into two recycling policies: 'selective dismantling' and 'shredding and sorting'. These can be seen as separate processes, but all kinds of combinations are possible. The stage of materials recovery can be distinguished as :

For selective dismantling:
- Disassembly
- Upgrading material

For shredding and sorting :
- Shredding
- Sorting
- Upgrading

In practice, the exact processes are selected depending on the product-configuration or product-design. Again, in the QFD-based IECDM process, the attributes (or criteria) and design characteristics of each item-disassembly step and material-recovering step can be identified through the QFD-process.

From the cost-benefit tradeoff point of view, Table 5.5 shows some calculations required for the different recycling policies. The table gives an overview, as an example, of the costs that take place when recycling activities are applied totally. Briefly, only when recycling revenues are greater or equal to costs are recycling activities effective. The greater the recycling activity, the more profitable it is, in general. In the CBA analysis process, the profitable product-recycling options are first determined. In addition, the purposed CBA model considers complete product's life cycle. Therefore, decisions concerning production activities and recycling are made simultaneously.

Table 5.5: Methods for economic feasibility of recycling activities (an example)

Recycling activities	Price of items/materials versus costs in the recycling process
Reuse	Items > return product + disassembly - dumping
Repair (or Refurbish)	Items > return product + disassembly - dumping
Remanufacture (or Recondition, or Rebulid)	Items > return product + disassembly + adapting - dumping
Material recovery (selective dismantling)	Material > return product + disassembly - dumping
Material recovery (shredder and sorting)	Material > return product + shredder + sorting - dumping

5.3.4. Operations Control in a Product Realization System

"Operations control decisions" refer to both production and environmental control decisions. Production control decisions involve determination of production quantities for the manufactured and remanufactured products. Inventory control policies in manufacturing and demanufacturing processes are also considered. In other words, we consider both the inventory of produced products and the inventory of recycled items disassembled from returned products. The inventory also meets the production demands.

5.3.5. A System's Perspective for Developing a CBA Model

After introducing the modules required in a CBA formulation, we present their integrated view. From an optimal design viewpoint, we may design a Product Realization Process/System (PRS) that has minimal environmental impact. Formulating an optimization problem in PRS should be a function of modules of product-design, manufacturing-processes selection, and product-recycling options, among others. From a system perspective, we need to construct a formulation (as a transfer function form) that captures the relationships among these factors to reflect the system behavior of PRS. In the IECDM approach, the CBA model plays this role. Next, a system perspective of PRS is presented. Then, with the help of a system-modeling tool, the relationship between PRS and CBA is identified and is used for constructing the CBA formulation.

General Systems Theory and Approach for a Product Realization System. *General systems theory* provides a useful framework from which a comprehensive understanding of product development projects and processes can be described. The heart of the general systems theory is *system*. A system is a group of related items that operate together for a common purpose in a common environment, such that the interaction or interplay of any of the parts affects the whole.

The *system-oriented approach* provides a frame of reference, a categorizing scheme by which a product planner can explain, predict, and influence complex processes, such as the 'green' product development process. In the system approach, the *model* used to describe a Product Realization System (PRS) is the input-process-output model shown in Figure 5.9. This model, combined with the principles of system theory, provides guidelines for the successful structuring and evaluation of 'green' product projects. For example, from the system model we can clearly see that the inputs (and outputs) of the system are an integral part of the PRS. From the system definition, all components (that is, product design module, manufacturing module, and demanufacturing module) in the PRS have equal importance. A change in any part of the system will have impact(s) on all other parts of the system. Therefore, if the inputs to a PRS process are environmental issues, the influence of inputs will have an impact on all other modules of the PRS. System theory is then useful in explaining the interactive impacts between the green realization system and its environment. It is also useful in explaining the impacts among the modules within the PRS of a green-product design project. The system approach on green product development also includes the following important issues: system problem and dynamic feedback concepts.

System Problem for the Product Realization Process. It has been recognized that interactive impacts exist between the product supply chain and the environmental chain. Figure 5.9 depicts the

information flow among product design stage, manufacturing stage, and demanufacturing as a feedback control system. We assume that the product design stage is dominated by configuration design, the manufacturing stage is dominated by the environmental impact being analyzed, and the demanufacturing stage is dominated by recycling policies. As mentioned in Chapter 3, the three types of system design problems include *system analysis*, *system evaluation*, and *system synthesis*. The problem of product-design and process-selection (PD/PS) for product realization can be described as a system synthesis (or system identification) problem. That is,

> *Given the inputs (IN) and actual outputs (OUT), determine a suitable transfer function (TF) model that is a function of states of the overall product realization system (PRS).*

In other words, a PRS should be configured or identified to determine the *TF* that represents the behavior of the system PRS. The PRS is a combination of various product configurations, manufacturing processes, and demanufacturing policies. We assume that if inputs *IN* and outputs *OUT* can often be obtained from observation of real problems, then the *TF* can be represented as

$$TF = f(IN, OUT, PRS)$$

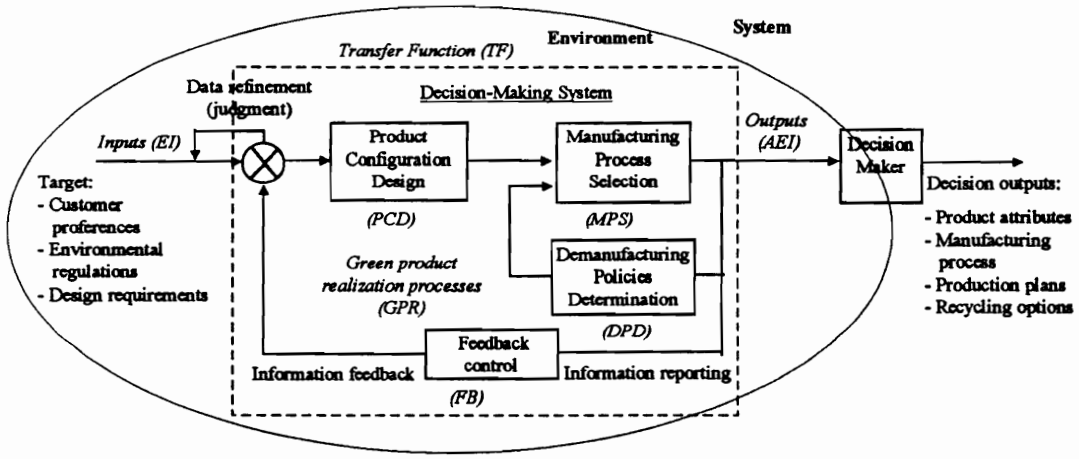


Figure 5.9. System aspects of interactive impacts between system and environment (Figure 1.2).

The key issues in the identification of PRS are twofold:

- Simultaneously determining product configuration, manufacturing process selection, and demanufacturing policies;
- Formulating the transfer function exactly while taking environmental considerations into account in each product realization stage.

In the QFD-based IECDM process, the CBA model is developed as a *TF* in a given PRS. That is, given the inputs (e.g., customer preferences, environment-related data, and alternative product-related

attributes) and outputs (e.g., selected product-related attributes, production and recycling plans) as well as PRS, the CBA model is constructed to calculate the product's life-cycle value, where the PRS consists of the modules discussed in the previous section.

System Modeling Tool – IDEF0 for CBA Formulation. To simplify the problem, we assume that the subject of transforming the product attributes (or customer preferences) to engineering design and of transforming the engineering design to a process plan has been performed by QFD techniques. That is, a set of product and material attributes have been mapped directly into a set of manufacturing and demanufacturing processes (or operations) associated with certain environmental factors in each process. This information is input to the proposed CBA model, and is generated from a function deployment matrix, a design deployment matrix, a process deployment matrix, and a production deployment matrix with the help of the QFD process. This information is also effective for understanding problem dimensions and in tracking product-process interactions. However, system constraints are not incorporated in QFD matrix representations, and a huge number of matrices would be required in a realistic design problem. These activity-relationships of product-design, manufacturing-processes, operation and maintenance, and demanufacturing can be captured by using IDEF0 modeling tool as illustrated in Figure 3.14. Accordingly, a IDEF0 representation for formulating a mathematical CBA model is illustrated in Figure 5.10. We construct the CBA model in next section.

5.4. A MATHEMATICAL COST-BENEFIT ASSESSMENT MODEL

This section develops a mathematical model for the optimal product's TLCV for a hypothetical problem (see section 5.2). Based on the modules discussed in the previous section, we present a mathematical-based CBA as an evaluation function for product design decision-making that is used for maximizing the product's total life-cycle value. The cost-benefit is analyzed throughout a product's total life-cycle (see Figure 5.2). The CBA model is developed for a company that produces multiple products in a production system with recycling capacity (see Figures 5.1 and 5.3). The physical product is structured as a product-tree (see Figure 5.5). Without loss of generality, the product-design is presented by a set of product-related attributes (see Figure 5.8). Based on the concept of a complete cost/value economic flow (see Figure 5.2), the CBA model is developed considering the product's life cycle. The model present values of all costs incurred during the manufacturing and recycling of products, disposal of remainders, as well as environmental impacts caused by products and processes. Economic benefits include revenues coming from selling the products produced as well as those recycled.

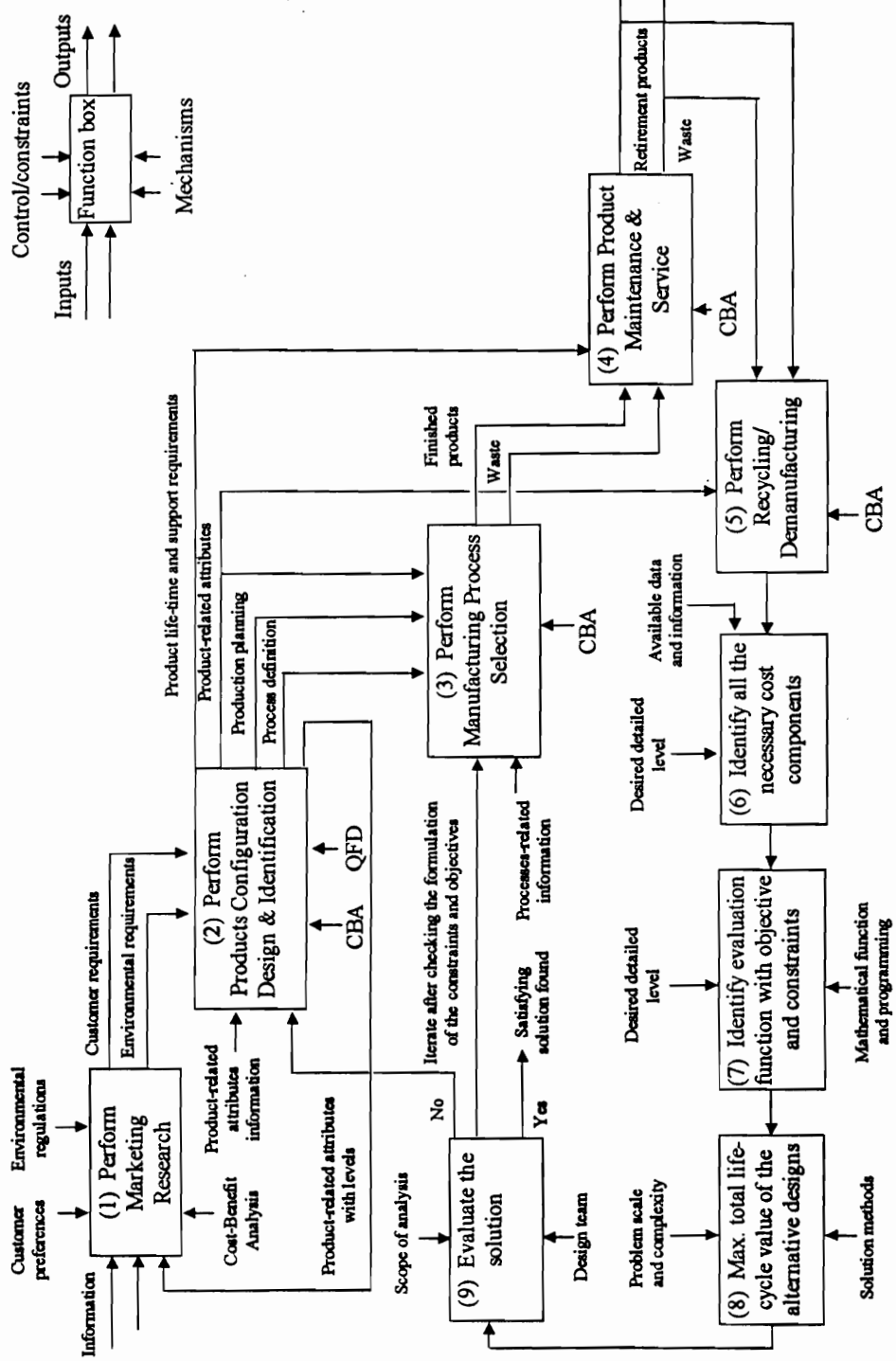


Figure 5.10. The IDEF0 representation of the CBA model and product realization system.

The present work aims at developing a decision support tool for optimal product-design in a product realization system. A mixed integer programming approach is followed in order to specify the optimal product design, as well as the optimal production plans and optimal recycling options (scheme). The optimal product design, represented by a set of attributes, depends on the production plans and recycling options which, in turn, depend on the customer's preferences on the product attributes as designed by engineers. Briefly, optimal design is determined by examining the various possible design strategies (attributes), considering life-cycle costs and revenues, and then deciding production plans and recycling options for maximizing the product's total life-cycle value.

5.4.1. Assumptions Behind the Model

Before we develop the CBA formulation, the following assumptions are made:

(1) We assume that the company produces j types of products of similar properties that consist of several different physical items (subassemblies, components, and parts). The product and its associated items (see Figure 5.5) are expressed by a set of various types of attributes with different options (see Figure 5.8). The production volume of products sent to the market in each period depends on the customers' preferences and marketing alerts. Production quantity in each period depends on the known demand and production capacity for a certain planning horizon.

(2) We assume a product-design process, where a product consists of a number of items (modules, components, parts) described by a set of attributes which may have different options, and which can be replaced with higher grade items if so desired or be used as lower grade product at a lower price. The product flow diagram is expressed by closed-loop and open-loop flows, as illustrated in Figure 5.3. (The model can be extended to cover an item's brand new green design, with the associated manufacturing processes redesigned to reduce environmental loads).

(3) Regarding the manufacturing processes, we assume that the product items selected for configuring the new product are produced by a collection of such processes. Thus, items necessary for product configuration can be produced by alternative cells (processes) in which the environmental loads (and environmental factors) of each individual process are assumed to be known. Given the product items, the manufacturing process selected to process items must meet environmental requirements and be cost-effective.

(4) After the products are consumed, the company collects the used products from the consumers and processes the returned items for recovery. The collection rate and recycled context of products from the consumers is assumed known. (However, it is easy to modify the model with an unknown

collection rate). Each returned product recovered has a different recyclable context, depending on the product's configuration and recycling options.

(5) We assume that recycled items can be reused, remanufactured, and/or recovered, either as the original type of products or as new products through three types of recovering capacity: reusable items, not reusable but remanufacturable items, or not remanufacturable/reusable but recoverable items. A reproduced product has a bill of items and assembly times different from the original product.

(6) We assume that demanufacturing processes (disassembly operations) are manual, as is consistent with most existing disassembly operations, since the variety of products being returned from the market are in unpredictable volumes and conditions.

(7) We assume that both new assembly and remanufacturing are accomplished on the same assembly line (facility) in a production system with demanufacturing capacity (Figure 5.1). As a result, set-up costs for remanufacturing the same products may be neglected. (It is easy to extend the model to cases where remanufactured and completely new products are processed on different lines.)

(8) We assume that all processes (manufacturing and demanufacturing processes) are carried out within a single time period. (The model can be modified to account for different lead times for different processes when demanufacturing/disassembly and remanufacturing/reassembly have been facilitated at different geographic locations). We also take inventory into consideration in the assigned production processes or in the demanufacturing processes.

(9) Costs and revenues are considered throughout the product's life-cycle (see Figure 5.2). The various costs considered include production, pollution, disposal, and demanufacturing costs. We assume that cost data are known for a given planning horizon of T periods. Thus, item costs (i.e., raw material acquisition, purchase, dumping, and recovery with the three types of recyclability attributes mentioned above), and the revenue obtained from selling products and recycled goods are given. Fixed costs for production/disposal operations and variable costs for manufacturing, for demanufacturing, and for disposal activities also assumed known.

(10) We assume that the environmental impact (pollution) occurs only in the processes of machining materials and parts, and in the processes of recovering materials from returned items. There is no environmental load during the assembly and disassembly processes. (It is easy to relax this assumption by considering environmental loads in the assembly and disassembly operations once the environmental impact functions are developed for assembly and disassembly activities).

(11) The decision variables are the set of product-related attributes to be produced, and their quantities as well as the items used in the different product-recycling options (PROs). The company's aim is to maximize the product's total life-cycle value. We also assume that only post-consumer PROs are considered; thus in-process (or pre-consumer) recycling options are not considered in the model. (We

can extend the model to involve pre-consumer recycling options during the production process, if necessary. Also, the basic model can be extended with a single objective function to the multi-objective programming model, for example, that which maximizes the recycling rate, or minimizes the environmental impact).

(12) Quantitative data of the energy and material inputs and outputs, in terms of monetary units, for the entire life-cycle of materials, product and processes are assumed known. System boundaries are well defined which determine the scope of the environmental impact analysis, as well as the cost components being considered.

5.4.2. Notations Utilized in Modeling

Summation sets:

J a set of all products being designed and produced by XYZ company and its competitors; three kinds of products are considered, that are produced in either a closed-loop, or an open-loop systems, or both (see Figure 5.3). $J = J_N \cup J_R$.

J_N a set of new products being produced.

J_R a set of returned products being recycled.

A a set of desired attributes used for describing the product design (see Table 5.1 and Figure 5.8), in which a attribute is denoted by $q \equiv (e,e',l)$; attributes can be different depending on whether they are physical, functional, or greenness related attributes; for example, when environmental issues are considered, the specific attributes are dominated by material and greenness attributes.

Q the number of items with attribute q that are used for a product in production section or disassembled from recycled products under a specified recycling-option in recycling section; the items can be reusable, remanufacturable, recoverable, or disposable. (see section 5.2.3); here, each item in product is characterized by a set of different types of attributes.

L the number of manufacturing processes required for processing a particular selected attribute; we assume that each process exactly produces one selected attribute of a product.

R the number of recycling/demanufacturing processes; more specifically, a set of demanufacturing processes for the recycling options.

I the number of potential recycling options i $(i = 1,2,3,4)$, which are used to express the extent of recycling (or disassembly). Each option may be composed of one or more items which are processed for reuse, remanufacture, recovery, and disposal. Thus, $i = 1$: disposal only without

recycling; $i = 2$: reuse + disposal; $i = 3$: reuse + remanufacture + disposal;
$i = 4$: reuse + remanufacture + recovery + disposal. (see Table 5.4)

H the longest lifetime of a product (or item).

$h_{q,k}$ a specific lifetime of a product (or item) k with attribute q which is utilized by the consumer within its longest lifetime H; thus, the product (item) is recycled beginning from period $h_{q,k}$ after a product has been used.

$h'_{q,k,i}$ time span between the point of time a product (item) k with attribute q that is recycled and it becomes available for reuse. This period depends on recycling options.

T the assumed planning horizon of the model.

t' a previous time period that expressed the time period from a product was produced to the current time period t, thus, $t' = t - h_{q,k} - \sum_{i \in I} \delta_{q,k,i} \cdot h'_{q,k,i}$, $\forall\ q,k,t$

t a time period index in planning horizon T.

Subscriptive indices:

q,j an item with attribute $q \equiv (e,e',l)$ in a product j; $q = 1,2,..., Q$; $j = 1,2,..,J$.

q,j,l process l is selected (assigned) to produce an item with attribute q in product j. The physical (item) attribute (e,e',l) selected for preferred product j may incur environmental impact while it is being manufactured. Therefore, the selection of material should be considered simultaneously with the selection of processes.
$q = 1,2,..., Q$; $j = 1,2,..,J$; $l = 1,2,...,L$.

q,j,i an item with attribute q in a product j that is recycled under recycling-option i; where $i = 1,2,3,4$. Thus, the physical (item) attribute selected for assembling product j in the design phase can be any one of the available attributes. Therefore, the product design affects the recycling policies that have to meet the environmental regulation.

q,j,r,i the demanufacturing process r selected to reprocess the item with attribute q in product j under recycling-option i.

Parameters:

$AT_{q,j}$ unit assembly time (labor hr.) for product j having attribute q, $\forall j \in J, q \in Q$.

$DAT_{j,i}$ unit disassembly time for product j under recycling option i, $\forall j \in J$.

$TDAT(t)$ total time (labor hr.) required to disassemble returned products in period t, which is used as disassembly capacity.

$RMT_{q,j}$ unit time (labor hr.) required to recover material from one unit of returned product j

with attribute q..

$TAT(t)$ total assembly time for producing all the products j in period t.

$TWS(t)$ total amount (limitation) of waste generated by returned products that can be disposed of in period t.

$D_{q,j}(t)$ forecasted demand of product j with attribute q, $\forall j \in J$.

$AN_{q,j}$ number of items (subassemblies, components, parts) required to produce one unit of product j with attribute q. This is determined according to the alternative product-design (see Figure 5.5).

$dx_{q,j}(t)$ the total number of items with attribute q (obtained either from purchasing/ manufacturing or from returned products) required to satisfy the demand of product j in period t; thus, $dx_{q,j}(t) = AN_{q,j} \cdot X_{q,j}(t), \quad \forall q \in Q,\ j \in J.$

$dmx_{q,j}(t)$ the total mass of material with attribute q required to satisfy the demand of product j in period t.

U_j utility of product j, $\forall j \in J$.

$W_{q,j}(t)$ the attribute worth (or utility) of product j with attribute q; it is a dollar measure of the *utility* provided by the specific attribute option in product design; in other words, the selection of a product's attributes depends on the total utility delivered by the attributes.

$w_{q,j}(t)$ a weighted measure of the customer preference for product j with attribute q relative to other attributes; in proposed QFD-based IECDM method, these weighted measures correspond to the normalized importance of design-characteristic attributes.

$PR_j(t)$ a proportion of the market share of product j in period t.

$EF_{q,j,k}$ environmental factors caused by product j with attribute q produced using manufacturing process k.

TEF_j total environmental factors caused by product j; the form and elements of environmental factors depend on the environmental regulation imposed for the different industries.

$\lambda_{q,k,j}(t')$ a ratio of the number of items with attribute q recycled from product k that is produced in t' and then used in product j in current period, i.e., $t' = t$-product life-product recycled time.

$\sigma_{q,j,i}$ a ratio of the number of items with attribute q for actual reuse to the total number of items required.

ϕ a ration of the mass of material to the product (or item).

ϕ' a ration of the mass of material to the dumping item.

Decision variables:

$X_{q,j}(t)$ number of product j with attribute q produced during time period t, $\forall j \in J$.

$x_{q,j_N}(t)$ number of new purchasing/manufacturing items with attribute q produced to satisfy the demand in period t.

$x_{q,k}(t')$ number of items of product k with attribute q produced in time period t' and recycled; $x_{q,k}(t') = AN_{q,k} \cdot X_{q,k}$, $k = 1,2,...,K$.

$PI_{q,j}(t)$ inventory of product j with attribute q in period t.

$MI_{q,j_M}(t)$ inventory of material j_M with attribute q in period t.

$I_{q,j}(t)$ number of on-hand items with attribute q that are available to produce product j under in period t.

$mx_{q,j,l}(t)$ the weight of material being processed by process l to produce the finished item j with attribute q.

$mx_{q,j,r,i}(t)$ weight of material recycled from returned product j with attribute q by process r under recycling option ($i = 4$) in period t.

$sx_{q,j,i}(t)$ number of items obtained from returned product j with attribute q under recycling option ($i = 1,2,3,4$) during period t.

$y_{q,j,l}$ a binary variable (0,1); $y_{q,j,l} = 1$, if the type l manufacturing process is required (selected) for producing an item with attribute q for obtaining product j; otherwise, $y_{q,j,k} = 0$,.

$z_{q,j,r,i}$ a binary variable (0,1); $z_{q,j,r,i} = 1$, if the type r demanufacturing process is required for obtaining an item from product j with attribute q and recycling-option i; otherwise, $z_{q,j,r,i} = 0$,.

ξ_j represents whether product j is produced or not; $\xi_j = 1$, if product j is produced, otherwise, $\xi_j = 0$.

$\delta_{q,k,j}$ a binary variable (0,1); $\delta_{q,k,i} = 1$ if recycling option i is selected for product k with attribute q; otherwise $\delta_{q,k,i} = 0$

Cost Coefficients:

$P_{q,j}(t)$ selling price of product j with attribute q in period t, where $\forall j \in J$.

$U_j^0 - \pi_j^0$ relative value of product j, $\forall j \in J$.

$RP_{q,j}(t)$ selling price of the recycled product j with attribute q in period t.

FC_j fixed cost for manufacturing a product j.

SCA_j set-up cost for assembling a product j.

$CP_{q,j}$ unit cost for purchased (or manufactured) item with attribute q for obtaining product j.

$CM_{q,j,l}$ unit cost of process l that is selected to process item with attribute q for obtaining product j.

$CA_{q,j}$ unit cost of assembling product j with attribute q.

CEE_j unit external environmental related cost of product j, assumed proportional to environmental factors and process.

CIE_j unit internal environmental related cost of product k, assumed proportional to environmental factors and process.

$CR_{q,k,r,i}$ unit cost of recovering item with attribute q obtained from returned product j by type r demanufacturing processes under recycling option i.

$CDA_{q,k,i}$ unit disassembly cost of recycled product k with attribute q under recycling option i.

$CDP_{q,k,i}$ unit dumping cost of recycled product k with attribute q under recycling option i.

$CDM_{q,k,i,r}$ unit demanufacturing cost of recycled product k with attribute q under recycling option i by process r; it can also be expressed as a function of demanufacturing time.

$PCI_{q,j}$ unit inventory cost of new product j with attribute q.

$RCI_{q,j}$ unit inventory cost of returned product j with attribute q.

$ICI_{q,j}$ unit inventory cost of returned item j with attribute q.

$MCI_{q,j}$ unit inventory cost of material j with attribute q.

5.4.3. Constraints Considered

There are three types of constraints: the constraints related to product attributes proposed by the engineering designer and listed from customer preferences, the constraints resulting from the products and processes interrelations, and the constraints resulting from the product-recycling options.

(1) Product attributes-level selection and customer preferences.

The design team provides customers with a number of feasible alternatives in terms of a set of attributes. From this list, the final set of attributes (or product design) is selected based on customer

preferences so as to ensure market share. Customer preferences may be indicated by the product's utility. We may define the utility of any product j as the sum of its attribute's worth. Thus, the multi-attribute utility of product j is

$$U_j(t) = \sum_{q \in Q} W_{q,j}(t) \cdot A_{q,j}(t) \cdot \qquad \forall A_{q,j} \in A,\ j \in J,\ t = 1,2,\ldots,T. \tag{5.1}$$

Where $U_j(t)$ is utility of product j, and $A_{q,j}(t)$ is a binary decision variable. Thus

$$A_{q,j}(t) = \begin{cases} 1 & \text{if attribute } q \text{ is chosen for item with attribute } q \text{ of product } j, \\ 0 & \text{otherwise.} \end{cases}$$

The constraints are developed to represent the fact that product j is accepted in the market only if its marginal profit is at least as large as that of the current product, as well as that of any other product that is introduced. These conditions are stated as:

$$\left\{ \sum_{q \in Q} W_{q,j} A_{q,j}(t) - P_j(t) \right\} - (U_j^0(t) - \pi_j^0(t)) \geq U^* \left(\xi_j(t) - 1 \right) \quad \forall j \in J, t = 1,2,\ldots,T. \tag{5.2}$$

The term $\sum_{q \in Q, j \in J} W_{q,j} A_{q,j}(t) - P_j(t)$ denotes the multi-attribute utility of product j so that the utility contribution due to price is not included in this product utility. Let U_j^0 be the current utility of product j, and $\pi_j^0(t)$ be its current price; then the current marginal profit is $(U_j^0(t) - \pi_j^0(t))$. $\xi_j(t)$ is a binary decision variable that indicates the product's acceptance by the market, which equals 1 if product j is accepted. U^* is a large positive number. In practice, U^* denotes the highest estimated utility of any currently available product in the market. The value of U^* includes the utility contribution due to a product's price.

The total number of products in production is the sum of the number of regular, new, and reproduced products. That is,

$$X(t) = \sum_{q \in Q, j \in J} X_{q,j}(t) \qquad t = 1,2,\ldots,T. \tag{5.3}$$

The volume of products in production should satisfy demand for each type of product in period t, that is,

$$X_{q,j}(t) \geq D_{q,j}(t) \qquad t = 1,2,\ldots,T. \tag{5.4}$$

Considering the relationship between the product attribute with options and the demand variation, the demand for each product j is a function of the attributes possessed by product j. We assume that the marketing share of three types of product is independent. Thus

$$D_{q,j}(t) = PR_{q,j}(t) \times \begin{pmatrix} \text{Market} \\ \text{size } (t) \end{pmatrix} \qquad \forall j \in J,\ t = 1,2,...,T. \qquad (5.5)$$

where the market size of product j is given by market research. PR_j is the proportion of the consumer population which prefers product j, i.e.,

$$PR_{q,j}(t) = A_{q,j}(t) \cdot w_{q,j}(t) \Big/ \sum_{q \in Q, j \in J} w_{q,j}(t) \qquad \forall j \in J,\ t = 1,2,...,T. \qquad (5.6)$$

(2) Constraints related to manufacturing/production.

Once the product is designed, all types of product attributes are then identified. Process planning is then achieved to fit these selected attributes. The constraints related to product-attribute and processes selected are:

Coordination of process-selection and attribute-option:

Once the attributes of a product design are determined, a manufacturing process is assigned to each attribute. Constraints related to the manufacturing processes must ensure that: (1) each attribute selected for the alternative product must be assigned to at least one process, and (2) such assignments can be made only to those processes that limit environmental impacts as specified by environmental regulations imposed by the government. These requirements can be stated as:

$$\sum_{l \in L} y_{q,j,l}(t) = A_{q,j}(t) \qquad \forall q \in Q,\ j \in J,\ t = 1,2,...,T \qquad (5.7)$$

$$A_{q,j}(t) \le \xi_j(t) \qquad \forall q \in Q,\ j \in J, t = 1,2,...,T. \qquad (5.8)$$

Product assembly time constraint:

The assembly time in manufacturing processes leads to another capacity constraint as follows:

$$\sum_{q \in Q, j \in J} AT_{q,j} \cdot \xi_j(t) \cdot A_{q,j}(t) \cdot X_{q,j}(t) \le TAT(t) \qquad \forall q \in Q, t = 1,2,...,T. \qquad (5.9)$$

The assembly time of product j depends on the product's Design For Assembly (DFA), which may provide the 'best' assembly sequence.

(3) Constraints related to the recycling of products and inventory.

Items necessary for production are either purchased (or manufactured) or are obtained through recycling.

Let $dx_{q,j}(t)$ be the total number of items with attribute q required for product j to satisfy the demand in period t. That is,

$$dx_{q,j}(t) = NA_{q,j} \cdot D_{q,j}(t) \qquad \forall\, q \in Q,\ \ j \in J,\ \ \ t = 1,2,\ldots,T. \tag{5.10}$$

where an item with attribute q includes subassemblies, components, or parts in the product j.

Relationship between the amount of an item used for production and its quantity returned from the customers.

Let the recycling rate (or collectable rate) $\lambda_{q,k,j}(t)$ be the proportion of product j collected in period t from the number of product k made in previous period $t' \equiv t - h_{q,k} - \sum_{i \in I} \delta_{q,k,i} \cdot h'_{q,k,i}$ (see Figure 5.11), that is,

$$\lambda_{q,k,j}(t) = \frac{\text{the number of product } j \text{ with attribute } q \text{ returned in period } t}{\text{the number of products } k \text{ with attribute } q \text{ produced in period } t'} \tag{5.11}$$

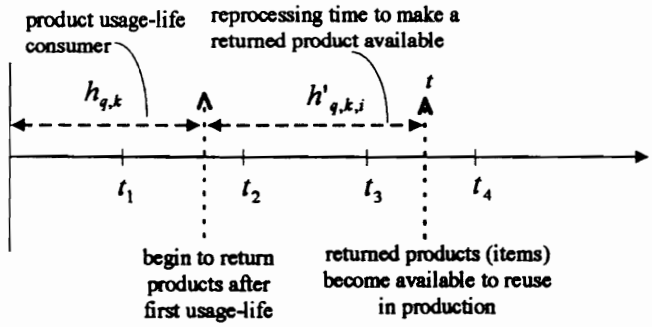


Figure 5.11. Time frame for product/item recycling and production planning

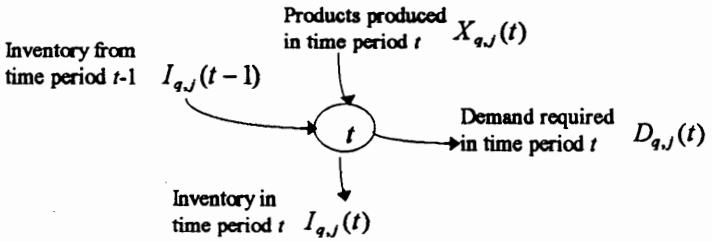
According to the relationships of product's production, recycling, and inventory (Figure 6.12), the quantity of the products collected in the period t is expressed by

$$PI_{q,j}(t-1) + D_{q,j}(t) = X_{q,j}(t) + PI_{q,j}(t) \qquad \forall\, j \in J_N, q \in Q, t = 1,2,\ldots,T. \tag{5.12}$$

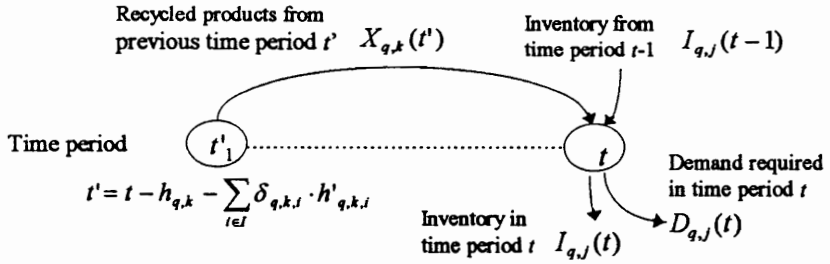
$$PI_{q,J}(t) + D_{q,J}(t) = \sum_{k \in J} \lambda_{q,k,J}(t') \left\{ A_{q,k}(t') \cdot X_{q,J}(t') \right\} + PI_{q,J}(t-1)$$

$$\forall\, q \in Q,\ \ j \in J_R,\ \ t = 1,2,\ldots,T. \quad (5.13)$$

$$\sum_{i \in I} \delta_{q,k,i} = 1 \qquad \forall q \in Q, k \in J. \quad (5.14)$$



(a) The relationships of production and inventory without recycling



(b) The relationships of production and inventory with recycling

Figure 6.12. Realtionships of products production and inventory

Note that the relationships shown in Figure 6.12 are suitable for new and recycled products, as well as material. Therefore, the products collected from the consumers are immediately disassembled into items under different recycling-options i = 1,2,3,4. Each item is classified as reusable, remanufacturable, recoverable, and/or disposable. Then,

$$\sum_{k \in J} \lambda_{q,k,J}(t') \cdot A_{q,k}(t') \cdot x_{q,k}(t') + I_{q,J}(t-1) = I_{q,J}(t) + dx_{q,J}(t) + rx_{q,J}(t) + sx_{q,J}(t)$$

$$\forall\, q \in Q,\ j \in J_R,\ t = 1,2,\ldots,T. \quad (5.15)$$

$$x_{q,J}(t) + I_{q,J}(t-1) = dx_{q,J}(t) + I_{q,J}(t) \qquad \forall q \in Q, j \in J_N, t = 1,2,\ldots,T. \quad (5.16)$$

$$MI_{q,J}(t-1) + \phi \cdot x_{q,j}(t) + mx_{q,j}(t) = dmx_{q,j}(t) + MI_{q,j}(t) + \phi' \cdot sx_{q,j}(t)$$

$$\forall q \in Q, j \in J, t = 1,2,\ldots,T. \quad (5.17)$$

$$x_{q,k}(t) = \sum_{q \in Q, j \in J} AN_{q,j} \cdot X_j(t) \qquad \forall q \in Q, j \in J, t = 1,2,\ldots,T. \qquad (5.18)$$

Disassembly constraints:

Constraints are required for demanufacturing processes since the recycling-options depend on a trade-off between recycling costs and revenues, and the product design which, in turn, is a function of the attributes selected. Therefore, the total disassembly time of product j is constrained by the disassembly capacity $TDAT_j(t)$ in period t. That is, the disassembly capacity is expressed as

$$\sum_{q \in Q, j \in J} \left\{ DAT_{q,j} \cdot X_{q,j}(t) + RMT_{q,j} \cdot mx_{q,j}(t) \right\} \le TDAT(t) \qquad \forall q, t = 1,2,\ldots,T. \qquad (5.19)$$

All recycling options generate waste from disposal that should be limited, due to waste disposal capacity as follows:

$$\sum_{q \in Q, k \in J} sx_{q,k}(t) \le TWS(t) \qquad t = 1,2,\ldots,T. \qquad (5.20)$$

Reusability of items.

Some of the collected items may not be reused because they may have broken-down (failed). Items obtained after disassembly are not always reused. If the reusability rate $\sigma_{q,j,i}$ is defined as the ratio of the number of parts actually reused to the total number of the items recycled, then the reusable (or available) items collected in period t is

$$x_{q,j}(t) \le \sigma_{q,j} \sum_{k \in J} \lambda_{q,k,j}(t') \left\{ A_{q,k}(t') \cdot X_{q,j}(t') \right\} \qquad \forall q \in Q, j \in J_R, t = 1,2,\ldots,T. \qquad (5.21)$$

(4) Constraints related to environmental-factors (pollution).

The total environmental loads constraints (caused by manufacturing and demanufacturing processes) must meet the environmental regulations at time t, $TEF(t)$. Thus,

$$\sum_{q \in Q, j \in J, l \in L} EF_{q,j,l} \cdot y_{q,j,k}(t) + \sum_{q \in Q, j \in J, r \in R, i \in I} EF_{q,j,r} \cdot z_{q,j,r,i}(t) \le TEF_j(t) \qquad t = 1,2,\ldots,T. \qquad (5.22)$$

$$\sum_{r \in R} z_{q,k,r,i}(t) \le \delta_{q,k,i}(t) \qquad \forall k = 1,2,\ldots,K; \forall i \in I; t = 1,2,\ldots,T. \qquad (5.23)$$

where $EF_{q,j,k}$ and $EF_{q,j,r}$ are environmental factors of process k and demanufacturing process r in period t, respectively. A critical issue in the field of ECDM is identification of product's 'greenness' in

terms of ecounit(s). Obviously, greenness is a function of environmental factors and the process selected. A method to measure a product's greenness is proposed in Appendix B. Once the greenness-merit function is defined (see Appendix B), the environmental constraints can be in terms of that measure. In this sense, the environmental costs can be expressed as a function of a product's greenness. However, this approach is beyond the scope of this research.

5.4.4. Formulation of the Objective Function

The overall profit is the difference between the revenue (market revenues and recycled revenues), and the total cost (fixed and variable costs for both manufacturing and demanufacturing processes) plus the disposal costs as discussed bellow.

The objective of the cost-benefit analysis model is to maximize the product's total life-cycle value, that is,

$$Maximize \quad TLCV(t) = \sum_{t=1}^{T} \{SB(t) + RB(t) - MPCOST(t) - OCOST(t) - RCOST(t) - INCOST(t)\}(1+r)^{-t} \tag{5.24}$$

where $SB(t)$, $RB(t)$, $MPCOST(t)$, $OCOST(t)$, $RCOST(t)$, and $INCOST(t)$ are given by the following equations.

Revenues from product sales, $SB(t)$:

The revenue, $SB(t)$, from the sale of three types of products, namely, the regular, new, and reproduced products to customers, is given by

$$SB(t) = \sum_{j \in J} P_j(t) \cdot \xi_j \cdot X_j(t) \qquad t = 1,2,...,T. \tag{5.25}$$

The production quantity decision variables are $X_j(t)$, where $j = 1,\ldots J$. The revenues for a product j in a specific period t are obtained only when that product is purchased for a price of $P_j(t)$.

Revenues from recycling, $RB(t)$:

The company will receive revenues in each period t by recycling products and items that have been in use for a period of time, $h_{q,k}$. Recycling revenues also cover the benefits of environmental impact

reduction (e.g., waste reduction) and emission reduction from energy saving. The revenues due to recycling are given by

$$RB(t) = RB_q(t) + RB_E(t) \qquad t = 1,2,...,T. \qquad (5.26)$$

Revenues from the recycled items q, (e.g., components, parts, and materials) are denoted by $RB_q(t)$. $RB_E(t)$ represents the benefit of reducing environmental loads associated with environmental factors. The revenues from the recycled items, $RB_q(t)$, are expressed as

$$RB_q(t) = \sum_{q \in Q, j \in J_R} \left\{ RP_{q,j}(t') \cdot \lambda_{q,j}(t') \cdot A_{q,j}(t') \cdot X_{q_m j}(t') \right\} \qquad \forall j = 2,...,K, t = 1,2,...,T. \quad (5.27)$$

The total volume and price of item with attributes q from returned product k are denoted by $X_{q,j}$, and $RP_{q,j}(t)$, respectively. The revenues from recycled items are generated only when the items of a product j are sold. This is represented by the binary variable $A_{q,k}(t)$.

Total production/manufacturing costs, $PMCOST(t)$:

The total production and manufacturing costs of a product (associated with different types of attributes) depend on the combination of material property, product structure, manufacturing and assembly, and environmental costs. Thus

$$PMCOST(t) = PC(t) + MC(t) + EECost(t) + IECost(t) \qquad t = 1,2,...,T. \qquad (5.28)$$

These are developed below.

Total purchasing costs of items, $PC(t)$:

Since reusable items are used for producing products, the total number of purchased items required for product j is the difference between the total required items and the recycled items. Then the cost for purchased items is

$$PC(t) = \sum_{q \in Q, j \in J_N} CP_{q,J} \cdot x_{q,J_N}(t) \qquad t = 1,2,...,T. \qquad (5.29)$$

Total manufacturing cost, $MC_j(t)$:

The total manufacturing cost includes the fixed cost of producing product j, FC_j; and the variable cost of production that includes the cost of processing materials for product j, $MCost_j(t)$, the cost of product assembly, $ACost_j(t)$, the internal environmental cost, $ECost_{IE}$, and the external environmental cost, $ECost_{EE}$.

$$MC(t) = \sum_{j \in J} \xi_j(t) \cdot FC_j + \sum_{j \in J} A_{q,j}(t)\{MCost(t) + ACost(t) + EECost + IECost\} \tag{5.30}$$

Manufacturing cost: $MCost(t)$

In order to calculate the cost of manufacturing, manufacturing properties or parameters are quantified for each attribute of product j and are used as cost coefficients in equations for calculation of cost. These coefficients modify the basic cost including overhead, etc., of producing the ideal attribute design (material, parts, components, features, etc.) by a certain production process at a particular quality level. In this way, the manufacturing cost can be determined for any selected attribute of product j, whether it is produced by one or more processes, and can be represented by a series of cost coefficients. The basic equation used to calculate the manufacturing cost of a product is:

$$MCost(t) = \sum_{q \in Q, j \in J, l \in L} CM_{q,j,l} \cdot mx_{q,j,l}(t) \cdot y_{q,j,l}(t) \qquad t = 1,2,...,T. \tag{5.31}$$

Total product assembly costs, $ACost(t)$:

The total assembly cost includes assembly cost of three types of products (i.e., regular, reproduced, and new by introduced products). In general, the fitting process analysis requires the designer to generate an assembly sequence flowchart and the design-of-cost index for the individual process or processes of product assembly. The cost analysis cannot be made unless a proposed sequence for assembling the product is known. A manual assembly system, in which the evaluation procedure influences the cost of assembly, can be explained by considering the simple relationship as:

$$ACost \propto \sum_{j}^{N_I} \left(C_h^A + C_g^A + C_f^A\right) \cdot \xi_j \tag{5.32}$$

where N_I is the number of items (parts and components, in general) in the assembly, C_h^A is the handling cost of an individual item, C_g^A is the gripping cost of an individual item, and C_f^A is the fitting cost of an individual item. In this model, an automated assembling system is considered, the total

assembly cost contains the fixed cost of assembly (usually the set up cost), $SC_{A,j}$, and the variable assembly cost, which can be considered as a linear function of the assembly processing time. Thus,

$$ACost(t) = \sum_{j \in J} \xi_j(t)\, SCA_j + \left\{ \sum_{j \in J} CA_{q,J} \cdot \xi_j(t) \cdot A_{q,J}(t) \cdot X_{q,J}(t) \cdot AT_{q,J} \right\} \quad t = 1,2,...,T \qquad (5.33)$$

Total environmental costs, $IECost + EECost$:

The internal environmental cost, $IECost$, is used to reflect the environmental control cost to the manufacturer per unit mass. It is estimated as a fixed cost or a cost range for each manufacturing process. The external environmental cost, $EECost$, is used to reflect the social environmental impact of the material per unit mass. The social cost of pollution is obtained from environmental effects caused by manufacturing, such as emissions and waste. Then the social cost is the sum of the cost for different environmental factors, that is

$$EECost(t) = \sum_{q \in Q, j \in J, l \in L} CEF_{q,j,l} \cdot f(EF_{q,j,l}, y_{q,j,l}(t)) \qquad t = 1,2..., T. \qquad (5.34)$$

where $CEF_{q,J,k}$ is the external environmental cost coefficient of environmental factors caused by process k for producing item q in product j. $CEF_{q,J,k}$ should be specified to reflect the social cost caused by industrial pollution.

The internal environmental costs can be calculated by

$$IECost(t) = \sum_{q \in Q, j \in J, l \in L} CIF_{q,j,l} \cdot f(EF_{q,j,l}, y_{q,j,l}(t)) \qquad t = 1,2..., T. \qquad (5.35)$$

where $CIF_{q,j,k}$ is the internal environmental cost coefficient for controlling environmental factors caused by process k. C_{IEF} is the cost that the company has to pay for controlling pollution inside the plant. As discussed in Appendix B, the environmental costs can be expressed as a function of the product's greenness in design phase.

The total operating and maintenance costs, $OCOST(t)$:

Products typically have different development costs and useful lives. In addition, the operating and maintenance costs (e.g., inspection, system repair, and worker training costs) can also be different and depend on the product-design. Generally, the operating and maintenance costs can be expressed as a sum of the operating cost, $OPCost$, and the maintenance cost, $MTCost$, that is,

$$OCOST_i(t) = OPCost_j(t) + MTCost_j(t) \quad \forall j \in J. \quad t = 1,2,...,T. \tag{5.36}$$

Where operating cost can be assumed to a fixed cost, and the maintenance cost depends on the maintainability function $M(t)$ for any given distribution which can be expressed as $M(t) = \int_0^t f(t)dt$; where $f(t)$ is the repair time probability density function and t is the allowable repair time. It is impossible to design a system-product (such as equipment) with absolute reliability so that failures do not incur. However, it is important to design a product that is easy to repair and maintain which, in turn, helps to make disassembly easily. Then, the total cost of operating and maintenance for item q can be expressed as:

$$OCOST(t) = \sum_{j \in J} OPCost_j(t) + \sum_{j \in J} MTCost_j(t) \qquad t = 1,2,...,T. \tag{5.37}$$

where the maintenance cost is a function of maintainability that depends on the product design.

The total recycling/demanufacturing costs, $RCOST(t)$:

The total cost for recycling/demanufacturing products collected from consumers contains the disassembly cost, the material recovery cost, and the cost of waste dumping. Thus,

$$RCOST(t) = DACost(t) + DMCost(t) + RECost(t) + DPCost(t) \tag{5.38}$$

Disassembly cost for recycled items q with recycling-options i, $DACost(t)$:

The total demanufacturing cost, $DACost$, is a function of the total volume of the collected product under different recycling options i = 2,3,4. The disassembly cost is assumed proportional to the disassembly time in demanufacturing process r; thus,

$$DACost(t) = \sum_{q \in Q, j \in J, r \in R, i \in I} CDA_{q,j,r} \cdot \xi_j(t) \cdot X_{q,j}(t) \cdot DAT_{q,j,i,r}(t) \quad t = 1,2..., T. \tag{5.39}$$

Demanufacturing cost (including sorting, testing, refurbishing, remanufacturing and so forth) for recycled items q with recycling-options i, $DMCost(t)$:

$$DMCost(t) = \sum_{q \in Q, j \in J} x_{q,j}(t) \cdot \sum_{r \in R, i \in I} CDM_{q,j,r,i} \cdot z_{q,j,r,i}(t) \quad t = 1,2..., T. \tag{5.40}$$

Material recovery cost for recovered items q with recycling-option i, $RECost(t)$:

The material recovery cost is proportional to the weight, $mx_{q,j,i}$, of type q material from returned product j under recycling option $i = 4$, during a period t. Thus

$$RECost(t) = \sum_{q \in Q, j \in J_M} mx_{q,j}(t) \cdot \sum_{r \in R, i \in I} CR_{q,j,r,i} \cdot z_{q,j,r,i}(t) \qquad t = 1,2,...,T. \qquad (5.41)$$

Where $CR_{q,j,r,i}$ is the unit material recovery cost per unit weight of type q material from product j under recycling option $i = 4$ (it may be steel, plastics, etc.).

Dumping cost of item q with recycling-option i: $DPCost(t)$

The dumping cost of a product j during period t (or waste disposal cost of returned products) is proportional to the weight $sx_{q,j,i}$ of dumped items q under recycling option i, to be dumped as waste. Thus

$$PDCost(t) = \sum_{q \in Q, j \in J} \phi \cdot sx_{q,j,i}(t) \cdot \sum_{r \in R, i \in I} CDP_{q,j,r,i} \cdot z_{q,j,r,i}(t) \cdot \qquad t = 1,2,...,T. \qquad (5.42)$$

Where $CDP_{q,j,i}$ is the waste dumping cost per unit weight of item q from product j under recycling option i, where $i = 1,2,3,4$, and ϕ is a proportion of weight per number of disposed items.

Production control (or inventory holding) costs. $INCost(t)$

Total inventory control costs can be devided into two parts: the inventory cost of products and the inventory cost of items. Thus,

$$INCost(t) = IPCost(t) + IRCost(t) \qquad t = 1,2,...,T. \qquad (5.43)$$

The production control (inventory holding) cost of available products for sale (either from purchased/ manufactured or from recycling) for use in production, $IPCost(t)$:

$$IPCost(t) = \sum_{j \in J_M} PCI_j \cdot PI_{q,j}(t) + \sum_{j \in J_R} RCI_j \cdot I_{q,j}(t) \qquad \forall q \in Q, t = 1,2,...,T. \qquad (5.44)$$

The production control (inventory holding) cost of available items and materials, $IRCost(t)$:

$$IRCost(t) = \sum_{j \in J} ICI_{q,j} \cdot I_{q,j}(t) + \sum_{j \in J_M} MCI_{q,i} \cdot MI_{q,j}(t) \qquad \forall q \in Q, t = 1,2,...,T. \qquad (5.45)$$

Substituting equations (5.25), (5.27), (5.29), (5.31), (5.33), (5.35), (5.37), (5.39), (5.40), (5.41), (5.42), (5.43), (5.44), and (5.45) into equation (5.24) give the following objective function

Maximize $TLCV(T)$

$$
\begin{aligned}
&= \sum_{t=1}^{T} \Bigg\{ \sum_{q \in Q, j \in J_N} P_{q,j}(t) \cdot \xi_j \cdot X_{q,j}(t) \\
&+ \sum_{q \in Q, j \in J_R} \left\{ RP_{q,j}(t) \cdot \lambda_{q,j}(t') \cdot A_{q,j}(t') \cdot x_{q,j}(t') \right\} \\
&- \sum_{q \in Q, j \in J_N} CP_{q,j} \cdot x_{q,j}(t) \\
&- \sum_{j \in J_N} \xi_j \cdot FC_j - \sum_{q \in Q, j \in J, l \in L} CM_{q,j,l} \cdot mx_{q,j,l}(t) \cdot y_{q,j,l}(t) \\
&- \sum_{j \in J} \xi_j \cdot SCA_j - \sum_{j \in J} CA_{q,j} \cdot \xi_j(t) \cdot A_{q,j}(t) \cdot X_{q,j}(t) \cdot AT_{q,j}(t) \\
&- \sum_{j \in J, l \in L} CEE_j \cdot f(EF_{q,j,l}, y_{q,j,l}(t)) - \sum_{j \in J, l \in L} CIE_j \cdot f(EF_{q,j,l}, y_{q,j,l}(t)) \\
&- \sum_{j \in J} OPCost_j(t) - \sum_{j \in J} MTCost_j(t) \\
&- \sum_{q \in Q, j \in J, j \in I} CDA_{q,j,j} \cdot \xi_j(t) \cdot A_{q,j}(t) \cdot X_{q,j}(t) \cdot DAT_{q,j,j}(t) \\
&- \sum_{q \in Q, j \in J} x_{q,j}(t) \cdot \sum_{r \in R, j \in I} CDM_{q,j,j,r} \cdot z_{q,j,j,r}(t) \\
&- \sum_{q \in Q, j \in J} mx_{q,j}(t) \cdot \sum_{r \in R, j \in I} CR_{q,j,r,j} \cdot z_{q,j,r,j}(t) \\
&- \sum_{q \in Q, j \in J} \phi \cdot sx_{q,j,j}(t) \cdot \sum_{r \in R, j \in I} CDP_{q,j,r,j} \cdot z_{q,j,r,j}(t) \\
&- \sum_{j \in J_N} PCI_{q,j} \cdot PI_{q,j}(t) + \sum_{j \in J_R} RCI_{q,j} \cdot I_{q,j}(t) \\
&- \sum_{j \in J} ICI_{q,j} \cdot I_{q,j}(t) + \sum_{j \in J_M} MCI_{q,j} \cdot MI_{q,j}(t) \Bigg\} \cdot (1+r)^{-t}
\end{aligned}
\tag{5.46}
$$

The formulation and constraints of the optimization-based CBA model for the hypothetical problem is now complete. Table 5.6 shows the final formulation and constraints. The CBA model is used as one possible evaluation function[1] for use in the QFD-based IECDM methodology. The potential applications of CBA model and design decision-analysis are discussed below.

5.4.5. Closure On Formulating CBA model

In this chapter, we demonstrated how a ecoproduct design problem is defined and how integrated approach (i.e., integration of modules of design, manufacturing, demanufactring, and recycling) is applied to formulate a generic mathematical CBA model based on the LCC assumption. We are not attempting to solve the CBA model to obtain a optimal solution by optimization techniques. Instead, we illustrated that an ecodesign design problem is very complicated because we are considering different modules simultaneously for ecoproduct design and realization through the integrated approach. Before we close the chapter, some discussions are given below.

Potential Usage of the General CBA Model in QFD-based IECDM Methodology. In addition to giving insight into a product development system, the basic CBA model can be used:

(1) To integrate product design, production issues, environmental considerations (in terms of internal and external environmental impact costs), and recycling options (with respect to cost-benefit analysis) into a product-development system.

(2) To demonstrate the cost and benefit inter-actions that occur during a product's entire life. As it attempts to model the entire product realization system, a life-cycle model will show how different stages of the system are inter-connected and will aid in understanding the system's behavior as well as its contribution to the environment.

(3) To clarify the objective of green design. The objective of the CBA is to minimize the environmental impacts at an acceptable cost, since the model contains the components of both product-related costs and environmental costs. The CBA model will not itself decide this, but will provide the data for a process of continuous improvement of environment performance.

(4) To allow for "What if...?" considerations and calculations. The use of the CBA model in terms of monetary units provides an index for doing "What if...?" analysis.

(5) To be used in QFD-based IECDM methodology. Equation (5.22) or (5.45) is developed as an evaluation function for use in the QFD-based IECDM approach. The formulation may also be

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[1] It is recognized that CBA formulation is only one of several possible formulations that could be offered as an evaluation function for use in the proposed QFD-based IECDM process. Depending on characteristics and scale of the design problem, the evaluation function may vary from situation to situation, however, the proposed QFD-based IECDM process is still practical in green engineering.

applied as a measure (or indicator) of legislative and economic policies between different countries. For example, environmental regulation imposed by Germany forces manufacturers to recycle post-consumer products and to reduce environmental impacts caused by the production process. Therefore, the environmental costs and disposal costs (including pollution tax) would be sufficiently high to make recycling products attractive to manufacturers, resulting in a greater total product's TLCV for recycling in long run plans.

A Suggested Design-Decisions Approach with the CBA Model Application. When we were confronted with this mathematical CBA formulation, there was no existing algorithm that could reasonably be expected to solve the model as specified. Since it is a large, complex problem, the natural tendency is to segregate the problem into three major components, creating one module for product configuration design decisions, a module for manufacturing processes selection, and a module for recycling options in demanufacturing processes (see section 5.3). However, an additional and more powerful design strategy was required to make this type of decomposition effective. We categorize modules (in terms of the attribute measures) in a feedback control scheme of three modules to illustrate the integration of operations required to deal with the overall optimal design problem (Figures 5.9 and 5.10). For the CBA model, different scenarios may be specified in which the most important design decision variables can be derived. To obtain optimum solution of the mathematical-based CBA model is beyond the scope of this research. However, from a practical green design point of view, a feasible solution could be obtained through a QFD-based IECDM process.

Generally, to solve any complex problem, taking the proposed CBA model as an example, first we have to identify its cost components and the relations among them. Then, we should decompose the problem into simple structures for analysis, and finally synthesize it. This is the fundamental process for solving any complex problem. Based on this idea, the CBA model is applied within QFD-IECDM approach in a flexible way: (1) CBA is applied in product design evaluation, in aggregation level, to select the best product alternative with highest product's TLCV, or (2) CBA is used in item design evaluation, hierarchically, to select the best item alternative with highest item's TLCV. However, an optimal solution is very difficult to obtain in realistic problem situation. Therefore, in the following chapter we will suggest a decision-based solution procedure to obtain a feasible solution. Our ultimate purpose is to develop a design decision-making approach, drawing from the classic MCDM process in order to use the CBA formulation to help improve product design. As a result, an integrated Design Decision-Making Support (IDDS) that integrates QFD, LCA, MCDM, and CBA will be constructed for an example illustrated in Chapter 6.

Table 5.6. The final Cost-Benefit Assessment model for use in IECDM methodology

Formulation		
Objective term	Mathematical form	Description
Sale revenues:	$\sum_{q\in Q, j\in J_N} P_{q,j}(t)\cdot \xi_j \cdot X_{q,j}(t)$	(revenue from sales of 'new' finished products)
Recycling revenues:	$+\sum_{q\in Q, j\in J_R}\left\{RP_{q,j}\cdot \lambda_{q,j}(t')\cdot A_{q,j}(t')\cdot x_{q,j}(t')\right\}$	(revenue from recycled items)
Purchasing costs:	$-\sum_{q\in Q, j\in J_N} CP_{q,j}\cdot x_{q,j}(t)$	(purchasing cost of new items)
Manufacturing costs:	$-\sum_{j\in J_N}\xi_j\cdot FC_j-\sum_{q'\in Q, j\in J, l\in L} CM_{q,j,l}\cdot mx_{q,j,l}(t)\cdot y_{q,j,l}(t)$	(manufacturing fixed and various costs for processing materials)
Assembly costs:	$-\sum_{j\in J}\xi_j SCA_j-\sum_{j\in J} CA_{q,j}\cdot\xi_j(t)\cdot A_{q,j}(t)\cdot X_{q,j}(t)\cdot AT_{q,j}(t)$	(set-up and assembly costs for assembling 'new' finished products)
External environmental costs:	$-\sum_{j\in J, l\in L} CEE_j\cdot f(EF_{q,j,l}, y_{q,j,l}(t))$	(social costs committed by industrial pollution)
Internal environmental costs:	$-\sum_{j\in J, l\in L} CIE_j\cdot f(EF_{q,j,l}, y_{q,j,l}(t))$	(costs for controlling environmental pollution)
Operation/maintenance costs:	$-\sum_{j\in J}\xi_j\cdot OPCost_j(t)-\sum_{j\in J}\xi_j\cdot MTCost_j(t)$	(operating and maintenance costs during in utilization)
Disassembly costs:	$-\sum_{q\in Q, j\in J, i\in I} CDA_{q,j,i}\cdot\xi_j\cdot A_{q,j}(t)\cdot X_{q,j}\cdot DAT_{q,j,i}(t)$	(disassembly costs of products)
Demanufacturing costs:	$-\sum_{q\in Q, j\in J} x_{q,j}(t)\cdot\sum_{r\in R, i\in I} CDM_{q,j,i,r}\cdot z_{q,j,i,r}(t)$	(recycling costs for returned items)
Recovery costs:	$-\sum_{q\in Q, j\in J} mx_{q,j}(t)\cdot\sum_{r\in R, i\in I} CR_{q,j,r,i}\cdot z_{q,j,r,i}(t)$	(recovering costs of materials from returned items)
Dumping costs:	$-\sum_{q\in Q, j\in J}\phi\cdot sx_{q,j,i}(t)\cdot\sum_{r\in R, i\in I} CDP_{q,j,r,i}\cdot z_{q,j,r,i}(t)$	(waste disposal costs in terms of material weight)
Products inventory-holding costs:	$-\sum_{j\in J_N} PCI_{q,j}\cdot PI_{q,j}(t)-\sum_{j\in J_R} RCI_{q,j}\cdot I_{q,j}(t)$	(IHC for both finished 'new' products and returned products)
Items inventory-holding costs:	$-\sum_{j\in J} ICI_{q,j}\cdot I_{q,j}(t)-\sum_{j\in J_M} MCI_{q,j}\cdot MI_{q,j}(t)$	(IHC for newly purchased/manufactured items and recycled items)

Table 5.6. The final Cost-Benefit Assessment model for use in IECDM methodology (continuous)

Constraints		
Description	Equation	Description
Product attributes-related constraints:	$\left\{\sum_{q\in Q} W_{q,j}A_{q,j}(t) - P_j(t)\right\} - (U_j^0(t) - \pi_j^0(t)) \geq U^*\left(\xi_j(t) - 1\right)$	(product is possibly produced only when its newly value is greater than current value in marketing)
	$X(t) = \sum_{q\in Q, j\in J} X_{q,j}(t)\,;\; X_{q,j}(t) \geq D_{q,j}(t)$	(finished 'new' products meet demands)
	$D_{q,j}(t) = \left(A_{q,j}(t)\cdot w_{q,j}(t) \Big/ \sum_{q\in Q, j\in J} w_{q,j}(t)\right) \times \begin{pmatrix}\text{Market}\\ \text{size}\ (t)\end{pmatrix}$	(market share of the finished 'new' products w.r.t. attributes)
Constraints related to production:	$\sum_{l\in L} y_{q,j,l}(t) = A_{q,j}(t)\,;\quad A_{q,j}(t) \leq \xi_j(t)\,;\; dx_{q,j} = NA_j \cdot D_j(t)$	(manufacturing capacity)
	$\sum_{q\in Q, j\in J} AT_{q,j}\cdot \xi_j(t)\cdot A_{q,j}(t)\cdot X_j(t) \leq TAT(t)$	(assembly capacity)
	$PI_{q,j}(t-1) + D_{q,j}(t) = X_{q,j}(t) + PI_{q,j}(t)$	(balance of production and inventory)
Constraints related to products recycling:	$PI_{q,j}(t) + D_{q,j}(t) = \sum_{k\in J} \lambda_{q,k,j}(t')\left\{A_{q,k}(t')\cdot X_{q,j}(t')\right\} + PI_{q,j}(t-1)$	(balance of recycled products and inventory)
	$\sum_{k\in K} \lambda_{q,k,j}(t')\cdot A_{q,k}(t')\cdot x_{q,k}(t') + I_{q,j}(t-1) = I_{q,j}(t) + dx_{q,j}(t) + rx_{q,j}(t) + sx_{q,j}(t)$	(balance of returned and inventory)
	$x_{q,j}(t) + I_{q,j}(t-1) = dx_{q,j}(t) + I_{q,j}(t)$	(balance of new produced items and inventory)
	$I_{q,J_M}(t) + \phi\cdot x_{q,J_M} + mx_q(t) = dmx_q(t) + I_{q,J_M} + \phi\cdot mx_q(t)$	(materials balance equation)
	$x_{q,k}(t) = \sum_{q\in Q, j\in J} AN_{q,j}\cdot X_j(t)$	(relationships between product and items)
	$\sum_{q\in Q, j\in J} \left\{DAT_j\cdot X_j(t) + RMT_j\cdot mx_{q,j}(t)\right\} \leq TDAT(t)$	(disassembly capacity)
	$\sum_{q\in Q, k\in J} sx_{q,k}(t) \leq TWS(t)$	(waste disposal capacity)
	$x_{q,j}(t) \leq \sigma_{q,j}\sum_{k\in J} \lambda_{q,k,j}(t')\left\{A_{q,k}(t')\cdot X_{q,j}(t')\right\}$	(items reusability)
Constraints related environmental-factors:	$\sum_{q\in Q, l\in L} EF_{q,j,l}\cdot y_{q,j,l}(t) + \sum_{q\in Q, r\in R, l\in l} EF_{q,j,r}\cdot z_{q,j,r,l}(t) \leq TEF_j(t)$	(environmental regulation)
	$\sum_{r\in R} z_{q,k,r,j}(t) \leq \delta_{q,k,j}(t)$	(reprocessing capacity)

CHAPTER 6

DECISION-ANALYSIS WITH QFD-IECDM APPLICATION: A HYPOTHETICAL EXAMPLE, RESULTS, AND DISCUSSIONS

6.1. DESIGN SELECTION AND CHANGES BY QFD-BASED IECDM METHODOLOGY
- 6.1.1. Optimal-Design in the IECDM Approach with a Decision-Support Application
- 6.1.2. Methodological Approach on Design Analysis Problems
- 6.1.3. Product Selection and Design by Decision-Making Approach
- 6.1.4. A Flow Chart of Design Selection and Design Changes

6.2. AN EXAMPLE TO ILLUSTRATE THE QFD-BASED IECDM PROCESS
- 6.2.1. An Example of the 'Car Horn' Selection Problem with Ranking Process Application
- 6.2.2. Product Design and Process Selection with CBA Model Application
- 6.2.3. Discussion

Chapter 4 introduced the concept of QFD and how it fits into the IECDM system, discussed in detail the elements of the QFD matrix, and presented an integrated approach for QFD-based IECDM methodology. A planning procedure was also proposed as a guideline for performing a QFD-based approach to environment-oriented product realization problems. Chapter 5 developed an optimization-based CBA model as a Design Evaluation Function that reflects the interrelationships among product-related attributes design, manufacturing processes, and demanufacturing policies according to customers' preferences.

However, the most difficult task is not understanding the planning of QFD-based IECDM methodology, or how the QFD-matrix fits into other individual methodologies and mathematical-based approaches (Chapter 4), or even how to formulate optimization-based CBA models (Chapter 5); but how to actually perform ecodesign through a QFD-based IECDM methodology and a procedure of evaluation/optimization with a team--that is, its implementation. Implementation of the IECDM methodology focuses on the decision process steps needed to develop a green product. Therefore, the purpose of this chapter is to recommend decision-analysis for making decisions during design-selection and design changes through a concrete, QFD-based IECDM process. Contemporary techniques related to environmental impacts' analysis, engineering design, and decision-making are utilized in the QFD-based IECDM process to meet the goal of environmentally oriented product design. The techniques, viewed

singularly, are no different from the techniques used in other design-related methodologies. However, their specific use for green product development provides a novel context for application.

In this Chapter, the IECDM with decision-making support application is discussed. Then, the QFD-IECDM is demonstrated through the example of an automobile's 'Car horn design' problem. Finally, conclusions are drawn about the applicability of the QFD-IECDM approach for incorporating environmental issues in green product design and realization.

6.1. DESIGN SELECTION AND CHANGES BY QFD-BASED IECDM METHODOLOGY

The thesis of this section is the development of a temporary decision-based integrated design system, called the *Integrative Design Decision-Support* (IDDS) framework, which provides a platform for the adoption of the IECDM to ecoproduct development including design selection and design change (see section 1.1.2). The main idea is that engineering design problems can often be considered as decision-making problems; that is, design through decision-making requires a methodological approach to help the design team select the best candidate alternative. The classic methodological approach for decision analysis is first introduced. Then a temporary IDDS framework, which integrates QFD, LCA, MCDM, and CBA, is developed. Operationally, the IDDS system is used as a template to develop the *design flow chart* as a design procedure for ecodesign and for determination of the 'best' candidate alternatives and environmental improvements. However, the computer-based IDDS system is beyond the scope of this research.

The general concept of optimal-design by the model is proposed in section 6.1.1, where we discuss how decision models and optimal-design are related in the proposed QFD-based IECDM process. The methodology is presented in section 6.12 through 6.1.4. The most general model for decision-making in section 6.1.2 is addressed as the temporary IDDS system in 6.1.3. In 6.1.4 a design flow chart is presented in more detail than in the IDDS. Considering the design flow chart, a formal example is presented in section 6.2 to illustrate the working of the QFD-based IECDM methodology and the CBA model.

6.1.1. Optimal-Design in the IECDM Approach with a Decision-Support Application

Considering the literature review in the area of ECDM, the Design For Environment (DFE) in the IECDM approach actually contains three fields (see Figure 4.2):

- design of product for the environment, such as ease of disassembly and ease of recycling,
- design of eco-manufacturing processes and disassembly procedures,

- design and implementation of green production and disassembly systems.

In the IECDM approach, we focus on product-design and process-selection (including manufacturing and demanufacturing processes). Activities in product design for the environment can be classified into:

- formulation of ecodesign criteria, to be applied by designers during conceptual and detailed design.
- development of evaluation methods for economic analysis of alternative designs.

Activities in process selection, with emphasis on design for disassembly, can be classified into:

- optimizing manufacturing and disassembly sequences.
- optimizing disassembly depth with respect to economic concerns.

In the IECDM approach, design decisions throughout the life-cycle phases are decided simultaneously. We present the QFD-based IECDM process for design decision-analysis problems, in which we develop the optimization-based CBA model for selection of product-related attributes while attaining the product's optimal total life-cycle value.

The Concept of Optimal-Design on the basis of the CBA Model. As mentioned, design can be seen as a decision-making process. Based on this QFD-based IECDM process, the optimal design problem can be defined as:

> *"For a given design (product-related attributes), find a production and recycling plan that balances the amount of revenues and costs. In this way, both production and recycling plans are leveraged processes."*

From the concurrent design point of view, the above optimal design problem considers both product-design and processes-selection simultaneously. Through the QFD-based IECDM process, it is possible to make both DFE and recycling issues more attractive by striking a favorable balance between costs and revenues, where the CBA model reflects the interrelationships among product-related attributes (including attributes of manufacturing and of disassembly processes). The mathematical-based CBA model plays such a role. However, the most difficult task is not understanding the CBA model, but how the revenue- and cost- functions should be identified for a particular design problem and how to find the optimal solution.

The optimal solution problem can be visualized in a graphical model. Figure 6.1 illustrates a hypothetical model of costs- and revenues- curves (not to scale). During the early design phase, the design-team can use this information to modify the product-design, and shift the solution in the direction that increases the product's total life-cycle value. The optimal-design results in a set of product-related attributes (including processes) and production/disassembly plans.

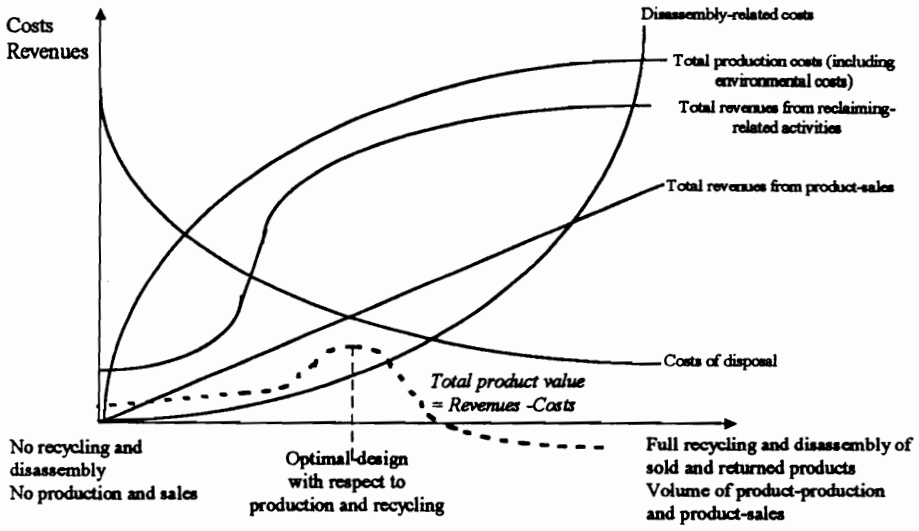


Figure 6.1. A hypothetical cost-benefit model for optimal design (an example).

The Concepts of Models for the Proposed QFD-based IECDM Process. The overall purpose of IECDM (with DFE as the core) is to give proper consideration to environmental impacts in product-design. In a generalized sense, the model developed in this research can be classified as a decision-process model, that is, a QFD-based IECDM approach, with integration (or coordination) features (see Figure 6.2). Multiple criteria scoring, cost-benefit analysis, and mixed integer programming methods are also utilized to aid the IECDM approach and the DFE decisions.

The model described in this section, the QFD-based IECDM process model, utilizes an Integrated Design Decision-Support (IDDS) framework to reach different design-levels and design phases in the IECDM approach, in order to integrate environmental considerations and design-selection decisions into a company-wide, QFD-based decision process. The QFD-based IECDM process model accepts the fact that product-design alternatives are selected by the design team and recognizes the value of the product-design decision process throughout its life-cycle rather than just focusing on decisions that are made at a particular phase at a particular point in time.

The model, through the QFD-process, identifies criteria (as obtained from the customer), design characteristics (as obtained from the design team), and design alternatives (as obtained from relationships between the criteria and the design characteristics) for the DFE problems. Therefore, design-selection decisions are viewed as multiple-phase processes (regarding a design flow chart) among interrelated design activities that are performed toward a goal: the environmentally conscious product, using mechanisms of QFD, LCA, MCDM, and CBA. The QFD-relationships matrix is considered and modeled

to include environmental requirements through a four-phase process. Each QFD-matrix consists of multi-attributes (such as cost, environmental factors and performance), often conflicting, for design decision-analysis problems.

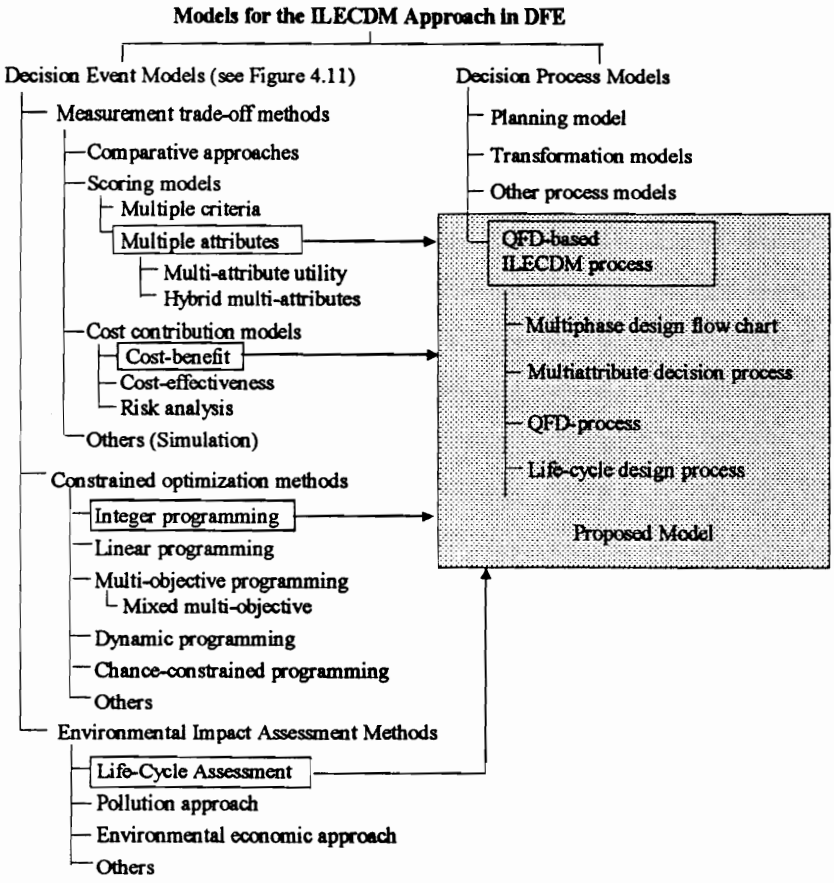


Figure 6.2. Models applied in the proposed QFD-based IECDM process

6.1.2. Methodological Approach to Decision Analysis Problems

According to Fiksel [1996], in order for DFE to be integrated effectively into a new-product development process, the following elements are required:

- Eco-efficiency metrics, derived by fundamental customer needs or corporate goals, to support an environmental performance measurement.
- Eco-efficiency design practices, based on in-depth understanding of relevant technologies and supported by engineering guidelines.

- Eco-efficiency analysis methods to assess proposed designs with respect to the above metrices and to analyze cost and quality trade-offs.

These general guidelines of DFE are employed in our design decision-making process. Based on these principles, we present a conceptual Integrated Design Decision-Support (IDDS) model for green design.

First of all, we introduce an efficient approach for decision-analysis problems -- a classic methodological approach. To be successful in green product design and development, the design team has to consider many interactive design factors and ideas, and in doing so, create design decision-making problems that increase in size with the number and variety of ideas considered. In dealing with such complicated design-decision problems, a methodological approach is required in order to establish a decision-support system for green system design. Such an approach is introduced as a five-step procedure.

The implementation approach, drawing from multi-criteria decision-making (MCDM) analysis, has been developed to support the design evaluation (or selection of candidate alternative) and improvement (optimization) procedure in the IECDM engineering process (Chapters 3 and 4). The steps are as follows: (1) Determination of alternatives, (2) Determination of attribute consequences, (3) Preference assessment, (4) Determination of the 'best' alternative(s) [Briassoulis and Papazoglou, 1994], and (5) continuous improvement. The last step is added to emphasis redesign in a practical design problem. These steps are discussed briefly next.

(1) Determination of alternatives. In design decision analysis, the solutions (alternatives) are limited, and they should be feasible. The set of alternatives, from which the 'best' is to be selected, is determined first. For each alternative, the parameters and factors under the control of the decision maker (designer) are respectively called design-dependent parameters and decision-variables; and the range of their possible values constitutes the design space and search space (or decision space) of the problem (see Chapter 4).

(2) Determination of attribute consequences (or system attribute structure). Each alternative action, if adopted, will result in a number (a set) of consequences (usually expressed by attribute elements), related to the objectives of the decision maker, which constitute the evaluation criteria. This step is known as *attributes generation* or *alternatives identification*. The outcomes or attribute (consequence) variables quantify the performance of each alternative with respect to the criteria, and the range of their values defines the attribute (consequence) space of the problem. Each alternative is associated with an attribute (consequence) vector $\overline{A}$. If the attribute consequences of the alternatives cannot be precisely determined a priori, the consequence assessment also includes the uncertainty assessment.

(3) Preference Assessment. The decision makers' (engineers and customers) preferences are quantified by an established MCDM form. Two ways are often used to assess the preference: (i) by value-function form $V(\overline{A})$ in the multi-attribute utility-function approach, and (ii) by ranking score form $R(w, \overline{A})$ in the general multi-attribute approach (e.g., the AHP method); these are called the value-method and the rank-method, respectively. These MCDM-forms express the value (or weighting-rank) tradeoffs among different levels of the attribute structures (attribute consequences) and among different types of consequences, as well as among candidate alternatives. An alternative resulting in attribute consequence $\overline{A_1}$ is preferable to an alternative resulting in attribute consequence $\overline{A_2}$ if and only if $V(\overline{A_1}) \geq V(\overline{A_2})$ by the value-method, or $R(w, \overline{A_1}) > R(w, \overline{A_2})$ by the rank-method.

In the value-function approach, an alternative *j* dominates an alternative *k* if alternative *j* is better or equivalent to *k* in all attribute consequences and strictly better in at least one attribute consequence. An alternative *j* is called non-dominated if there is no other alternative in the space of possible (feasible) alternatives that dominate it. Assessing the preferences of the decision maker in the form of a value-function or a utility-function (or other MADM methods) yields the determination of the optimization solution by tradeoffs among the values of all attributes. Although such value tradeoffs are unavoidable, it is often desirable to postpone their assessment until the very last stage of the decision process and to carry the assessment out interactively by examining the feasible alternatives and their attribute consequences [Briassoulis and Papazoglou, 1994]. The AHP method is a good example of the latter approach (ranking-method) at determining the best alternative at the lowest alternative level of the hierarchy, by comparing the final normalized ranking scores. A general multi-level evaluation process for hybrid MADM with uncertainty, proposed by Yang and Sen [1994] is another good example of such an approach.

(4) Determination of the Optimization Solution(s) or the 'best' alternative(s). This step in classic decision analysis is to determine the optimum alternative. If there are only a few alternatives (i.e., a limited number of alternatives), the one with the larger (if maximization) or smaller (if minimization) values function (or largest ranking score by the AHP method) is found and chosen by comparison (i.e., multiple-attributes decision making, MADM). If there is a large (e.g., infinite) number of alternatives, then mathematical programming and optimization techniques can be utilized to optimize the expected value of the value function to find the optimum alternative (e.g., by multiple objective decision-making, MODM).

(5) Continuous Improvement. In addition to the determination of the 'best' alternative, solution improvement is also important in practice. For example, once the product-system alternative has been selected, an effective decision-support system for detailed design is required for the purposes of both environmental and economic improvement. Environmental improvement must reduce as much as possible the environmental impacts of the product-system and its manufacturing processes, including energy consumption, pollution caused by production operations, etc. Economic improvement implies operating a cost acceptable to the community in the industrial ecosystem, which includes manufacturer, business, individual consumer, government, etc. The cost of operating an effective, environmentally sound industrial system depends on existing environmental and recycling related costs, etc. Through clever continuous-improvement (redesign), it is possible to make green design and recycling more attractive by striking a favorable balance between economics and environment-burden distress. An appropriate model (e.g., a cost-benefit assessment model) needs to be constructed to reduce the overall environmental impacts of the industrial ecosystem (or system product) as far as possible, within an acceptable level of cost (or system product value). This need is the reason why we have developed the CBA model as a selection function that calculates the product's total life-cycle value, which, in turn, is a quantitative measure for an optimal design problem. The optimal design is the combination of product-related attributes that contribute the largest total life-cycle value.

In summary, the classic approach for decision-analysis problems requires tradeoffs of values (e.g., the value function method) or ranking of scores (e.g., the AHP method) among the attribute consequences and candidate alternatives. The general process is summarized in Table 6.1. Note that the process expressed in Table 6.1 is based on the ranking-score approach for preference assessment. Also, different methods can be used during each process-step, depending on the features of the decision-analysis problem. Furthermore, in the development of design decision analysis, it has been realized that critical issues are the creation of scales for attribute rating and the generation of weights to represent the relative importance of different kinds of attributes. Saaty [1980] originally presented the Reciprocal Matrix Comparison (RMC) method for the generation of relative importance of attributes. Recently, these issues on prioritization of attributes have increasingly been given more attention, especially in the application of the QFD technology. Since the QFD-process can be employed to help decision makers generate and identify attributes, the resulting attributes must be prioritized for selection of candidate alternatives. In the next section, we present a new approach, namely the QFD-based IECDM approach or process, that incorporates the QFD-process into decision-analysis problems while considering environmental issues at the same time.

Table 6.1. A classical approach for decision-analysis problems

Given	a set of feasible candidate alternatives.
Identify	the types of principal attributes influencing the determination, and the multi-level hierarchical attributes structure 1. of each alternative individually (in the utility function method), or 2. among alternatives interactively (in the AHP method) or 3. the QFD-process.
Weight	the relative importance of product-related attributes by 1. AHP methods, or 2. Normalized importance procedure
Rate	the alternatives with respect to their attributes 1. in analytical function form (e.g., value function or utility function) 2. in matrix form (e.g., weighted scores matrices in AHP).
Rank	the alternatives in order of preference, based on the computed function values or weighted scores attributes and alternatives by 1. AHP methods, or 2. the multi-level evaluation process, or 3. merit-function methods.
Determine	The 'best' alternative by comparing the rankings of attributes and alternatives
Improve	the selected design alternative in environmental or/and economic performance through prioritized design changes by 1. Ranking score, or 2. the Cost-Benefit Assessment model, or 3. another mathematical-based optimal design model.
Perform	implementation of the alternative selected and resource allocation.

6.1.3. Product Selection and Design By the Decision-Support Approach

The classical approach to decision-analysis problems provides the motivation to establish a design decision-support system for ecoproduct design. In the following two sub-sections, we develop an Integrative Design Decision-Support (IDDS) and the design flow chart for implementation of the IECDM approach for practice. In this subsection the purpose of IDDS is to provide a well-structured template to help decision makers implement the IECDM that fits their own firm's circumstances. In the next subsection a *design flow chart* is implemented for design-selection and design-changes. The design flow chart is a process that facilitates IDDS by incorporating more details in it (such as QFD's four phases process and DFE principles). Finally, the QFD-based IECDM process is presented as a mechanism that performs the design flow chart.

A Preliminary Integrated Design Decision-Support Framework. In the practical QFD-based IECDM, we present a temporary Integrative Design Decision-Support (IDDS) framework as a seven-step model that integrates the state-of-the-art techniques of QFD, LCA, MCDM, and CBA, as shown in Figure 6.3. The steps are:

Step 1: Determine the IECDM Strategies in the Company: In this step, the goal of green product development is specified by the company. Implementation of the IECDM approach for environmentally oriented product development should be company-wide, because it integrates all aspects of product design and realization through the entire product's life cycle (from design to recycling/disposal). The design team for green product development includes the product designer, process planner, manufacturer, salesperson, environmental engineer, and so forth. A QFD-based approach proposed in Chapter 4 provides guidelines for establishment of a green product development environment in a firm, and provides a proven technique to generate product-related attributes and to identify product alternatives. In the QFD-based IECDM methodology, in order to accurately account for environmental factors (identified by the QFD-process) in an IECDM process, it is necessary to incorporate elements from LCA methodology in the green design methodology. A well-structured database is also required, which is also the objective of implementing IECDM methodology, in order to make LCA results that are available to designers for use in the IECDM process.

Step 2: Product-Related Metrics Construction: In the IDDS study, the QFD is used as an auxiliary synthesis technique to aid in the identification of attributes based on customer preferences and engineering techniques, and in the determination of a set of candidate alternatives (feasible design solutions) through the benchmarking process. The QFD process is used in translating customers' needs into specific actions in the system's product development. In other words, QFD also helps the design team to construct an efficient metrics that is driven by customer needs or corporate goals, including environmental design requirements, to support and integrate the product's related performance measurements; for example, the performance measurements of environment, functionality, quality, and economics. With respect to environmental performance in practice, a variety of eco-efficient metrices (performance measurements) should be constructed and used in various industries, reflecting industry-specific environmental issues.

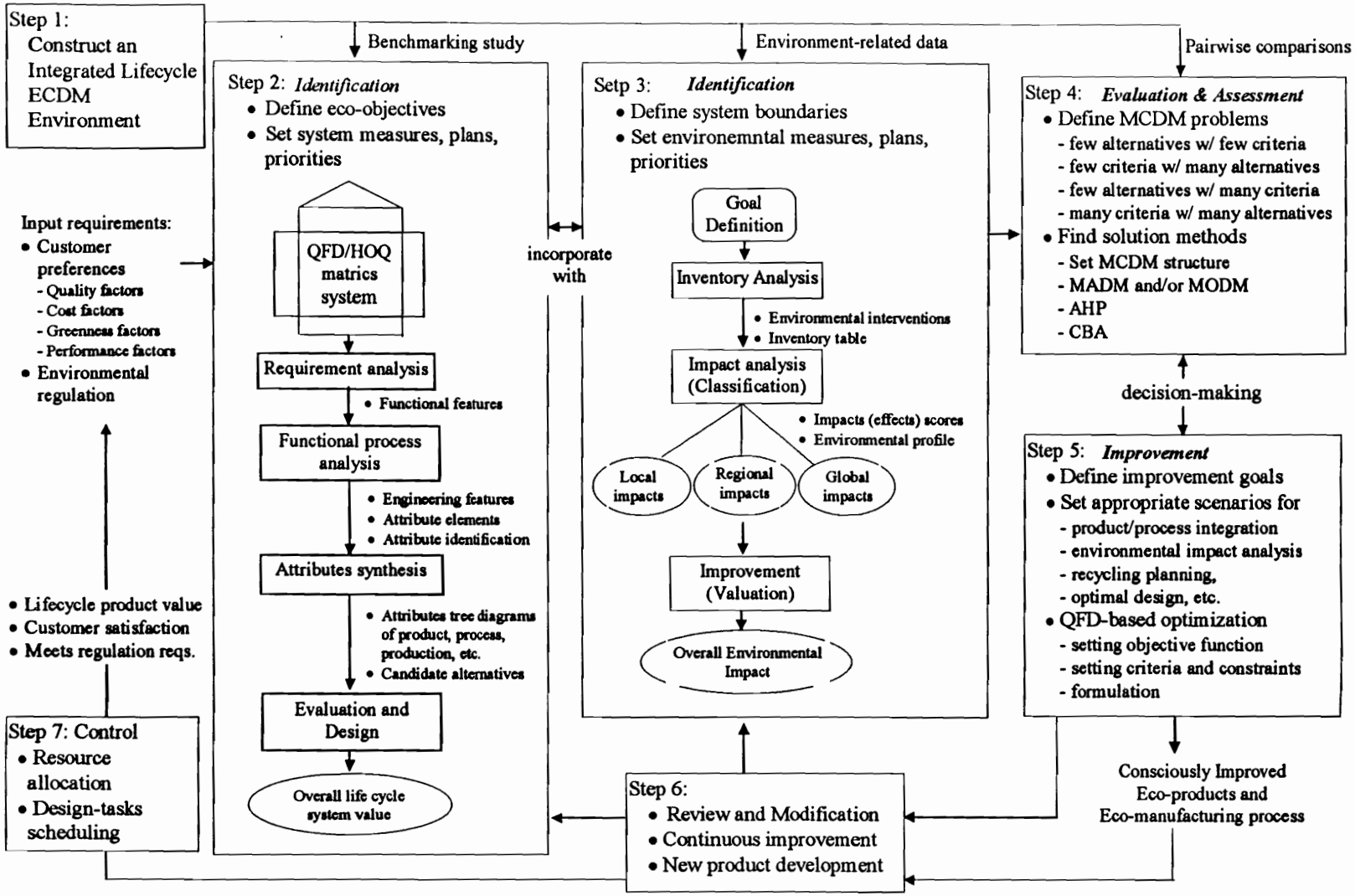


Figure 6.3. Scheme of the proposed temporary Integrated Design Decision-Support (IDDS) system

On the other hand, MCDM, such as the AHP method, is used for decision making in a group set-up, and is employed in prioritizing alternative attributes both of customers and of engineers. Benchmarking[1] is the process of 'learning from the best' in terms of business strategies, business operations, and business processes, and is used to determine possible values of alternative attributes, i.e., all the feasible candidate alternatives that may meet customers' needs and engineering constraints. The benchmarking analysis indicates that there are variations between industries (and within individual system units) with respect to a set of properties associated with attributes of the system's products of concern and with the cycles of the different processes, all of which could have some impact on the ultimate environment performance level (greenness degree) achieved in these ecoproduct units and eco-processes. As mentioned in Chapter 4, integrated QFD, AHP, and Benchmarking are used for environmentally strategic marketing-planning (e.g., recycling plans) and alternative(s) determination. This integrative model has some advantages:

- To assist a team of decision-makers (including engineers and customers) to better understand multiple-criteria decision-making problems, including environmental criteria; and
- To provide systematic tools to facilitate design decision-making and determine alternative associated attributes.

Step 3: Environmental Impact Analysis of the Product and Its Related Processes: The environmental impact analysis (or Life-Cycle Assessment in Industrial Ecology) process is used for the evaluation of environmental impacts of alternatives in terms of an environmental index. LCA provides a decision-making tool for environmentally sound industrial development and green product development as well as for policy decision-making. The LCA model is constructed to predict overall environmental impacts. A detailed operating process has been introduced in Chapter 4. The MCDM is also used in the LCA process. The MCDM problem, as an analysis method in the LCA process, is to rank the inputs (elements of the system product) using the environmental attributes as criteria. In practice, the environmental attributes (or environmental inventories) used for LCA can be identified with other system attributes by QFD method (step 2). MCDM problems (either in the QFD process or in the LCA process or in both) can be solved using several principles, depending on the characteristics of the problem (Chapter 2).

When using MCDM as an analysis method in steps 2 and 3, two alternative ways can be used, depending on the attributes being selected and compared:

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[1] There are three types of benchmarking [Zairi, 1992]: internal, external, and generic. Internal benchmarking studies the best performers in an organization; external benchmarking deals with the best competitors in an industry; and generic benchmarking studies the best business practices in the world.

1) They may range from focused estimation of environmental parameters (e.g., recycling rate, recyclability, and reusability) to full-scale, life-cycle assessment of environmental impacts, but this analysis is separated from other product-related analyses (e.g., reliability, functionality, and durability, especially recyclability, remanufacturability, and reusability). Then go to Step 5.
2) They may be employed in the way of integrating parameter-relationships that show the interactions between environment-related factors and other performance metrices. The information required for decision analysis can be expressed with respect to the metrices. Then go to Step 4.

Step 4: Evaluation and Determination: In efficient green design practice, feasible product alternatives are designed based on in-depth understanding of relevant technologies, supported by engineering guidelines; for example, guidelines of material selection, life extension, design for disassembly, design for recycling (recyclability), and design for remanufacture (discussed in the Chapter 2). Decision-making methods are used to help the design team determine attributes (in terms of performance measurements metrices) of the product design and select from among design alternatives when the trade-offs are complex or when large uncertainties are present.

To achieve optimal solution of a green design problem, it is recognized that most design proposals serve a variety of needs/specifications and their outcomes are described in terms of more then one criterion, some of which may be favored by customer and designers. In the QFD-based IECDM process, all these criteria are 'attributes' identified through the QFD process. Once attributes are identified, the process of design decision analysis can take advantage of modeling tools from the field of MCDM that is broadly categorized as MADM and MODM. From the literature review, both MADM and MODM may be employed for use in a design decision-support framework (see Figure 6.1). Which of the combinations of attributes is preferable is rarely self-evident. The fact is that it is impossible to obtain a perfect design with respect to all the identified attributes.

In the practical QFD IECDM approach, we use MCDM methods for evaluation of different product alternatives and determination of the 'best' product design. To be precise, an appropriate MCDM method is used as an analysis method to assess the proposed design alternatives with respect to the above performance metrics (developed in step 2) and to analyze environmental impact (step 3) as well as performance measurements trade-offs.

Step 5: Design Assessment and Improvement: In order to "close the loop" in the green product development process, synthesis is needed to calculate the cost and profit of the selected product design.

The cost-benefit assessment (CBA) is a widely used tool for design evaluation and optimization. In this research, the CBA model is a mathematical programming problem in which various inputs (such as system product attributes, process characteristics, environmental factors, etc.) are blended in desired proportion to the system product that is produced for sale. The unified structure of the optimization-based CBA model has been proposed in Chapter 5. The CBA model can be useful for various objectives under different scenarios, of both tactical and operational levels, such as purchasing raw materials under recycling operations, developing the product's green design policies, determining product recycling policies in general, and improving existing products or selected alternatives in practice. In such cost-benefit assessment, some parts deal in quantifiable data, while in other parts, judgments are needed.

Step 6: Redesign Process--Continuous Improvement by Design Changes: Product-system design can be roughly divided into a series of problems that involve the selection of an alternative (or concept) or the redesign (or improvement) of that alternative. To achieve the redesign objective, an analytical model is needed for evaluating the design. We define this redesign process in two stages.

Stage 1: Redesign approach with CBA model application: In this stage, both environmental and economic improvements can be achieved through design changes of product and processes according to DFE principles and rules. This general CBA approach can help industry make successful green products that contribute real environmental and cost improvements. According to Hindle *et al.* [1993], products that contribute to real environmental improvements must do two things:

1) They must have a lower overall environmental impact than the alternatives, i.e., these must be measurable improvements over the system product's life cycle of acquiring raw materials, manufacture, distribution, use, recycling, and disposal.
2) They must sell in place of products that have a greater environmental impact. If they don't, they do not contribute their environmental benefit (improvements).

Our integrated CBA model, in the IDDS system, plays such a role in that it is used for measurement of environmental improvements with respect to costs, throughout the product's life cycle. Then, once a benefit has been identified, we can say that the product (or alternative) has contributed to the environmental improvements in different given scenarios. The improvement ratio can be defined as

$$\text{Improvement ratio} = \frac{\text{Planned cost - benefit level}}{\text{Current cost - benefit level}}$$

In practice, the improvement ratio is the function of the redesign and redefinition of the product's attributes. The potential improvement opportunities depend on the system boundaries being focused within the IECDM approach, and also on the principles/methods used in DFE. However, each change of

the product's attributes or PROs (or MROs) policies must lead to an increasing improvement ratio, as indicated in a *design flow chart*. A design flow chart is presented in the next section in order to show how continuous improvement is achieved through design and materials changes according to the rules and principles of DFE. Design priorities, indicated by relative importance in the QFD-relationship matrix, are determined for each potential design change sequentially (see section 6.1.4).

Stage 2: Redesign approach with mathematical programming model application: In the redesign process, optimal solutions are possible; thus, the target values shown in the QFD-matrix must be optimized under certain resource constraints for a particular design problem. Besides the CBA model, there are several methods for design evaluation and optimization. Mathematical programming methods may be employed in this redesign process, where the design attributes (dependent and independent parameters), design decision variables, design evaluation functions (as objective function), and constraint functions are identified through a QFD-relationship matrix. Once the mathematical programming model is constructed, the optimal values of technical characteristics (expressed by design decision variables in the model) can be obtained rather than the target values obtained from the marketing survey. This basic operation is described as follows.

At this stage, several mathematical programming approaches may be employed in the QFD-based IECDM process for the purpose of optimal design. Obviously, a green design is ultimately evaluated with respect to many different criteria, and the ultimate evaluator is the customer. From a design viewpoint, this evaluation is performed by the design evaluation function (DEF), as discussed in Chapter 3. As a partial step in the QFD-based IECDM process, the DFE is addressed by the process given below.

(1) Using relationship-matrix information shown in QFD/HoQ to
   - identify design attributes (dependent and independent parameters),
   - define design decision variables,
   - construct the design evaluation structure (as objective function),
   - define constraint functions, and
   - construct the final mathematical programming model.

(2) Select appropriate solution techniques according to the features of the mathematical programming model constructed for a specific design problem.

Depending on the features of DFE, different programming methods (see Figure 6.2) can possibly be employed. General forms are expressed by equation (3.6) in section 3.2.3 and equation (4.5) in section 4.2.4., which are constructed from a MODM methods approach. Our application of the CBA model is a typical example of a DFE construction that is based on the concept of cost-benefit analysis. Another possible DFE form is presented by multi-attribute utility function form based on the MADM methods

approach and value theory. For dealing with the multi-attribute design problem, multi-attribute utility theory is suggested for integrating environmental issues together with product design and manufacturing concerns simultaneously [see Appendix C].

Step 7: Resources Allocation and Activities Scheduling: Continuous evaluation of the engineering-design project for alternatives selection, resource allocation, and activities scheduling is one of the most challenging decisions that the design-project managers make in an ongoing, environmentally-conscious design and manufacturing process. Using the QFD-based IECDM approach, the proposed IDDS framework should provide resource allocation and design-tasks scheduling for the engineering-design project(s). These functions are designed in the IDDS application to help design-project teams and managers do collaborative work more efficiently and effectively.

Furthermore, Activity-Based Costing (ABC) can be performed for a more detailed cost assessment of the product's life-cycle design, once the activities performed in the different life-cycle processes of the products are identified. Briefly, in the ABC system, the cost of a product equals the sum of the costs of all activities that must be performed throughout the product's life-cycle. The study of step 7 is beyond the scope of this research.

The above process is a prototype for operating the IDDS system. In this integrated DDS framework, attribute generation (or attribute structure diagram) from QFD, and environmental knowledge from LCA studies, together with decision support methods (such as MCDM, including AHP or a design evaluation function or a value function) and cost-benefit assessment programming, can be useful to incorporate environmental aspects into the IECDM approach. In other words, the IDDS is an approach which draws from decision-making support to use environmental information within the decision-making process of configuring (or formulating) a system product. Using an environmental index together with other factors' indices (e.g., performance, cost, quality), it is possible to evaluate a design by comparing costs of cost-friendly systems with costs of environmental-friendly systems. To obtain this result, we have combined one synthesis tool, QFD, and three analysis tools: LCA, MCDM, and the CBA model. Although the computer-based IDDS is beyond the scope of this research, we suggest a QFD-IECDM approach in the next section for implementation of the IDDS system.

Routes Towards the Integrative Design Decision-Support System. QFD-IECDM approach contains elements from LCA methodology naturally, because it incorporating environmental issues into product design and realization. Databases that contain basic environmental factors, environmental data, and LCA results can be translated into DFE-knowledge based or an integrative design decision-support

(IDDS) system. Implementation of a computer-aided IDDS system is beyond the scope of this research. However, the approach for combining QFD-based IECDM and LCA methodology is presented in Figure 6.4. As a data-flow representation of the IDDS framework (Figure 6.3), Figure 6.4 shows the relationship between QFD-based IECDM methodology (Figure 4.2) and LCA methodology and the interaction of knowledge flow and data flow. Routes towards development of the IDDS system may be as follows.

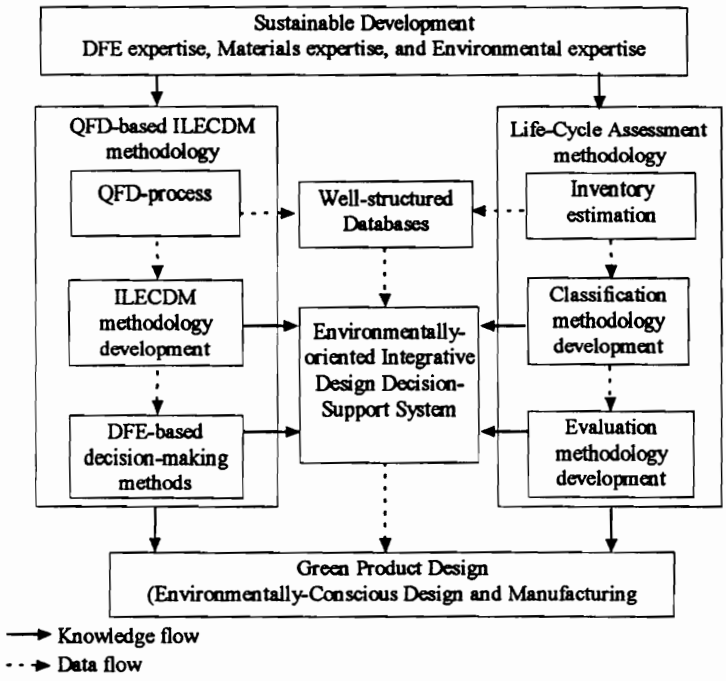


Figure 6.4. Relationship between QFD-based IECDM and LCA in the IDDS system

Basically, in their own company's design environment, designers need to formulate IECDM methodology by extending the existing methodology that takes into account form, function, feasibility, and economics with environmental criteria. The eventual green design problem will always be a weighted balance between the various requirements and possibilities (see Figure 1.5). At this stage, the well-structured QFD-methodology is used for incorporating environmental issues into the IECDM methodology while identifying all possible attributes related to product design; this approach is the so-called QFD-based IECDM process, and data generated from the QFD-process are aggregated into the database for use in design decision-making. On the other hand, workers involved in LCA development focus on the creation of a well-structured database that contains relevant LCA (inventory) results from LCA studies. These results, together with environmental data, will offer useful replies to the questions

defined by QFD-based IECDM methodology, so that the final design decisions can be made through appropriate MCDM methods.

Operationally, in the QFD-based IECDM process, environmental data and LCA results will have to be made available to designers, together with other design factors, in the form of databases. Databases are structured in a way that allows meaningful use of the IECDM methodology with MCDM application. This development can ultimately lead to a DFE knowledge-based IDDS system. This is beyond the scope of the research.

6.1.4. A Flow Chart of Design Selection and Design Changes

To give a reference for operating IDDS, we present the *design flow chart* as one of the possible ways to integrate QFD, LCA, MCDM, and CBA, based on DFE principles and rules. In the practical ecodesign procedure (selections and changes), acceptable engineering changes depend on economic factors in most cases, such as the economic attractiveness of increasing the product's total life-cycle value, the attractiveness of recycling the material, and the existence of end-use markets. Therefore, any design selections and/or changes according to the priorities of engineering-characteristics (attributes) must be economically attractive. In addition, design and redesign products should follow DFE rules and principles. In contrast, the recyclability of a product (and the component-parts) depends on the following factors [Fiksel, 1996]:

- The volume, concentration, and purity of the recycled material
- The quality and secondary useful life of recycled components and/or parts
- The existence of disassembly technologies

Nevertheless, in this section, we establish a design flow chart for dealing with design-decision problems within the IDDS framework. Then, we construct a QFD-process as a mechanism to support the design flow chart.

A Design Flow Chart for Decision-Analysis Problems in IECDM. In the implementation of a design-selection and design-change procedure, the solution represents a trade-off between cost and environmental distress, among others. One cannot expect that the best strategy for dealing with a discarded product (item) is going to always involve 100% recycling. Therefore, the CBA formulation can be used to detect break-even points and points of maximum profit at higher level system design selection under specific design constraints, where profit is measured in terms of energy saving, emissions reduction, recycling represented as monetary units. Furthermore, continuous design improvement is important in the green design process. One cannot expect to redesign every item in a product at the same time in order to

increase the product's environmental performance. Hence, priorities for design changes are a key reference to help the design team concentrate on those redesign items that may make a greater contribution to green improvement or ease in making design changes.

These ideas motivate the implementation of a flow chart for IECDM through design selection and a design change procedure that is a three-tiered approach for implementing QFD-based IECDM (see Figure 6.5):

(1) At the system level, facilitate the product-related attributes (product configuration) and identify alternatives through the QFD process; i.e., choose a product alternative that will satisfy functional and environmental requirements.

(2) At the component-parts level, choose a material that will satisfy application requirements and permit a maximum product/material life-cycle value.

(3) At the detail design level, seek other potential design change opportunities to improve the product's life-cycle value based on DFE rules and principles.

These three goals (or design processes) are linked, since any material choice as design change will impact component-parts compatibility, reparability, disassembility, and others which, in turn, affect the selection of product attributes. As illustrated in Figure 6.5, the mechanisms that support the flow chart include techniques of QFD, LCA, AHP, and CBA, which are performed as the process shown in Table 6.1. We demonstrate this procedure by an example in section 6.2.

For design decisions, the CBA model provides a means that emphasizes simultaneous design decisions throughout the product's life-cycle phases. In the CBA model, costs of purchasing, processing, environmental impacts, and assembly determine the product-production costs; while costs of disassembly, reprocessing, and disposal determine the product-recycling costs. The CBA model emphasizes product-related attributes and environmental concerns for obtaining the optimal product's life-cycle value. To this point, an optimal combination of product-attributes, processes-selection, and disassembly-depth are determined to minimize the product's production and recycling costs.

For reduction of environmental burdens, material selection is the focus in the design procedure. Changes in materials are fundamental to design, and offer many opportunities for reducing environmental impacts throughout a product's life-cycle. In practical design, material selection begins by identifying the nature and source of the raw materials. Then environmental burden (and environmental costs) caused by the material's acquisition, processing, use, and end-of-life product are evaluated. Finally, proposed materials are compared to determine the best choice or to suggest changes. Material-change is performed

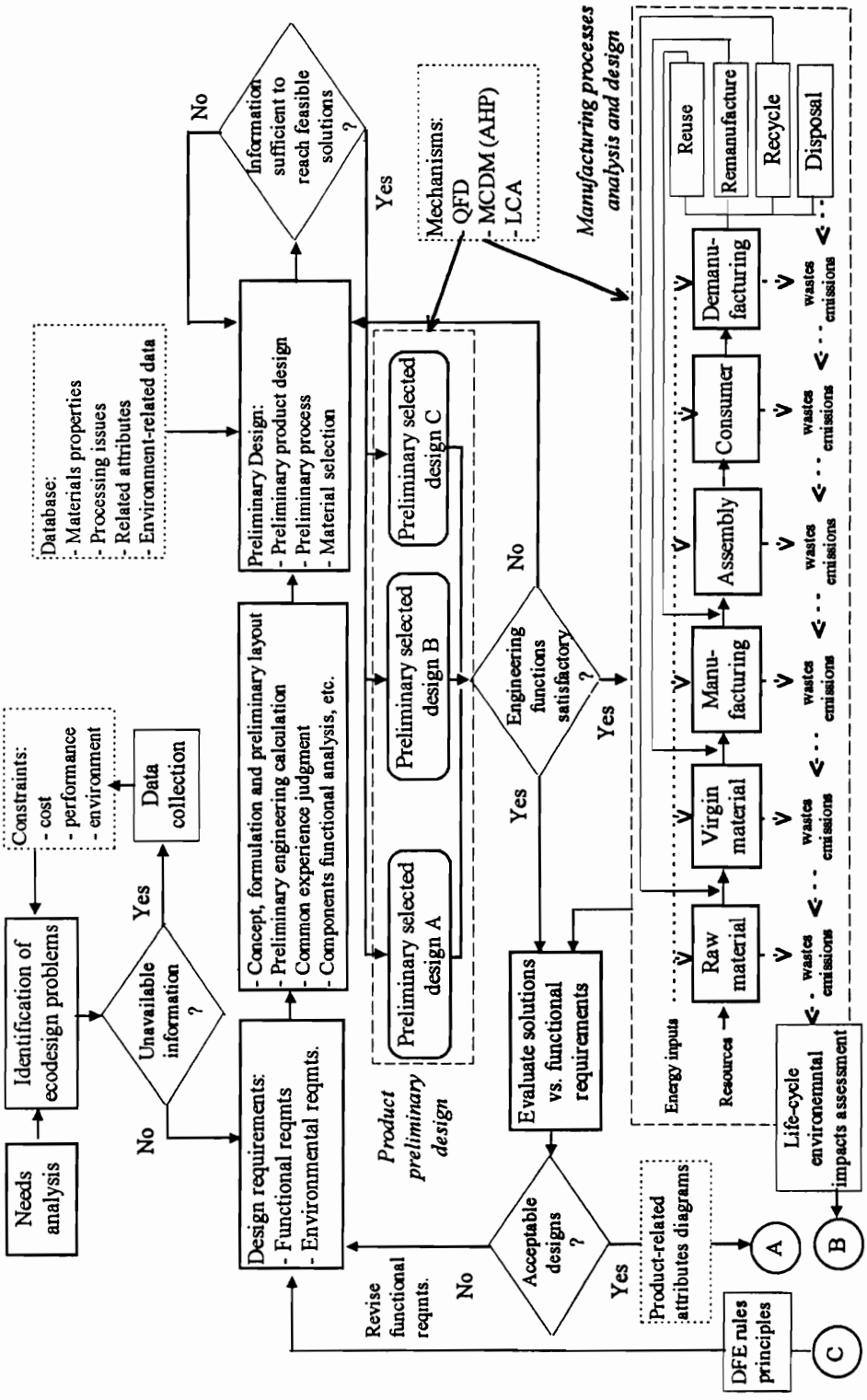


Figure 6.5. Flow chart of design selection and design changes for implementation of IECDM

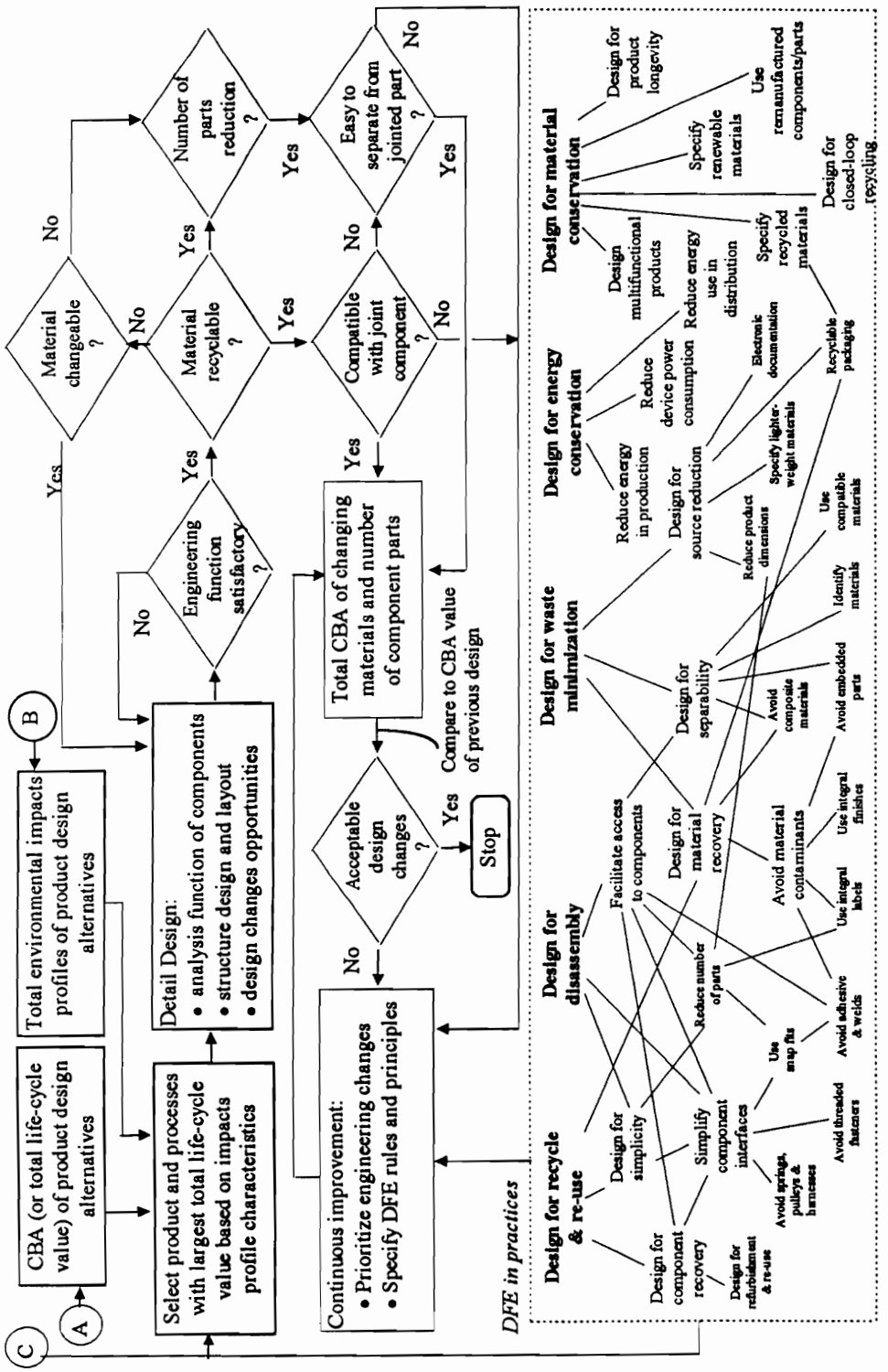


Figure 6.5. Flow chart of design selection and design changes for implementation of IECDM (continuous)

by carefully considering its compatibility with and separability from other component-parts which, in turn, influence the disassembility and recyclability of the product.

In this design flow chart (Figure 6.5), DFE rules and principles for design selection-changes are interrelated and highly complementary or highly conflictive. Design analysis and evaluation are required throughout product development. Therefore, a effective IECDM (more applicable design process at a lower overall environmental impact) requires an integrated approach at the early stages and throughout the design and development process. Ideally, an integrated approach would provide detailed product, process, and environmentally relevant costs as a design proceeds from concept to production, and finally to recycling. The QFD process, LCA, and CBA play such a role for environmentally-conscious product design and development in our IECDM approach. This QFD-based IECDM approach would facilitate generation of concept alternatives to produce a 'best' balance of product-production costs, environmental costs, and other relevant costs that are involved in the CBA model.

A Concrete QFD-based IECDM Process. Many QFD projects use only Phase I, as it provides a means of translating marketing information into product measures for engineering design. However, in the context of IECDM, the product measures should be implemented through methods that are already in place for determining component-parts characteristics, (de)manufacturing-processes characteristics, and controls, in order to obtain enough information for performing LCA and CBA. In the QFD-based IECDM, our approach for implementing this flow chart is on the basis of the traditional QFD process. The QFD process is a four-phase structured activity that begins with a conceptual design and ends with a technical data package, including a product-related attributes tree and process-related environmental relationships. The entire QFD-based IECDM process assures that the product is designed and consistently manufactured to satisfy customer and environmental requirements.

Furthermore , this four-phase QFD-based, IECDM process provides a means of deciding which characteristics of the product are most critical to achieving both customer expectations and reduction of environmental impacts caused by the product and its processes. The design-team can direct its resources to focus on those significant few items in each phase that are most important, most difficult to achieve, or potentially conflicting with each other for green product purposes. We use the information resulted from each phase as input to construct the CBA model and calculate the product's life-cycle value for design selection, in which product-related attributes are determined simultaneously for getting maximum benefit of the optimal product design. On the basis of four-phase QFD framework, the seven-step IDDS (figure 6.3) is achieved by QFD-based IECDM process steps as shown in Table 6.2.

Table 6.2. QFD-based IECDM process steps

Process steps		QFD-based IECDM			
		Phase I: Product Planning	Phase II: Design Deployment	Phase III: Process Deployment	Phase IV: Production Plan
Step 1	Project Plan	• Identify green goals • Identify project boundaries • Identify customers • Identify suppliers • Identify QFD team • Define methods to be used to gather customer and environmental requirements • Identify possible alternatives	• Take the key product measures selected in phase I • Identify internal customers • Identify internal suppliers • Identify QFD team (portion of team members from different specialists may be changed) • Identify possible component-parts alternatives	• Take the key product measures selected in phase II • Identify internal customers • Identify internal suppliers • Identify QFD team (portion of team members from different specialists may be changed) • Identify possible process alternatives	• Take the key product measures selected in phase III • Develop a manufacturing process control and environmental control plan • Identify what process characteristics need to be controlled or monitored
Step 2	Gather customer requirements	• Gather design-related requirements • Identify and classify gathered requirements • List common definitions for gathered requirements • Have customer prioritize needs and requirements • Perform competitive assessment	• Assess the impact of component-parts' characteristics for product on achieving the target value of those measures	• Gather environment-related data (inputs and outputs) for each possible process alternative • Assess processes' influence on the key component-parts characteristics (Note: processes include disassembly processes)	• Identify planning requirements (quality control, maintenance, training) • Identify environmental regulations for environmental control
Step 3	Identify product-related attributes and determine product measures	• Determine product-related measures (especially, environment-related measures) • List common definition for product measures • Identify technical requirements • Identify design-dependent parameters and decision variables from listed measures • Determine target values for product measures and possible constraints	• Establish relationship between product measures and component-parts' characteristics using the same QFD-process steps (step 4 to step 6)	• Identify manufacturing process steps corresponding to each component-part's characteristics • Establish relationship between processes and key component-parts' characteristics using the same QFD-process steps (step 4 to step 6)	• Identify quality (including environmental quality) control steps for each process • Identify the methods to gather the data from quality control steps
Step 4	Product-related attributes assessment	• Assess feasibility of obtaining each target value • Determine technical difficulty for product measures	• Assess feasibility of obtaining each target value • Determine technical difficulty for product measures	• Assess feasibility of obtaining each target value • Determine technical difficulty for product measures	• Assess feasibility of obtaining each target value Determine technical difficulty for product measures

Step 5	Determine relationships and correlation	• Determine relationships between customer requirements and product's measures • Determine correlation among product measures • Correlate requirements and parameters	• Determine relationships between product's measures and component-parts' characteristics • Determine correlation among parts' characteristics • Correlate characteristics and parameters	• Determine relationships between parts' characteristics and process's parameters • Determine correlation among process parameters • Correlate requirements and parameters	
Step 6	Calculate importance weightings and ratings	• Analyze correlation grid for inconsistencies • Benchmark product measures and design dependent parameters • Normalize relative importance to prioritize product measures • Delineate the target values and relative importance ratings for product measures and design-dependent parameters • Determine what product measures to carry on to next phase of QFD	• Delineate the target values and relative importance ratings for component-parts characteristics • Normalize relative importance to prioritize product measures • Select key component-parts characteristics to carry on the next phase of QFD	• Select key process steps (events) for input to the final phase (such as the processes that have critical impacts on environment)	
Step 7	Calculate total life-cycle value using CBA model and select the 'best' design alternative	• Use concept evaluation to determine design alternatives • Use product-related attributes for meeting requirements and to determine production demands • Use recycling context data for each design alternative	• Use component-parts attributes (especially material use) for material selection • Obtain external environmental costs according to selected material	• Use process-related attributes (especially inputs and outputs) for life-cycle assessment (LCA) • Use LCA (life-cycle inventory) to obtain environmental profile for each design alternative	• Use results from operational control • Use internal environmental costs
Step 8	Redesign	• Consider material changes	• Check material compatibility and reparability with other component-parts	• Check process-changes and environmental impacts for material changes	
Step 9	Redesign	• Continuous DFE design changes • Planning optimal redesign problem	• Check influence of design changes on parts characteristics • Use QFD-based optimization to formulate redesign problem	• Check influence of design changes on process-selection and impacts	
Step 10	Redesign	• Dynamic feedback	• Track critical parts characteristics to achieve customer expectations	• Track critical presses characteristics to achieve environmental requirements	

Table 6.2 shows that each phase of QFD consists of six general steps (step 1 to 6) vary slightly for each phase but are essentially the same. The results (outputs) of each phase become the inputs of the mathematical CBA model which, in turn, is employed to optimize the total life-cycle value of products through appropriate selection of product attributes, processes, and recycling policies (step 7). Briefly, in the QFD-based IECDM process, the QFD-based process will provide a means to generate product-related attributes and to identify product alternatives while LCA will provide the product-related environmental impact for use in the CBA model. In other words, IECDM is a ecodesign approach that seeks to simultaneously maximize value in all stages of the product cycle, including manufacturing, assembly, customer use, recycling/demanufacturing, and disposal, while minimizing their impacts on the environment. From the continuous-improvement view, design changes may be needed for increasing the product's life-cycle value, and all potential opportunities of design changes are possibly used, based on DFE rules and principles (step 8 to 10).

6.2. AN EXAMPLE TO ILLUSTRATE THE QFD-BASED IECDM PROCESS

The purpose of the example is to show the applicability of the cost-benefit analysis (CBA) model developed in Chapter 5 to the QFD-based IECDM implemented in section 6.1. This example[2] of the 'Horn design problem' presented to illustrate the QFD-based IECDM process is adapted from the 'Horn selection problem' of Kuppuraju *et al.* [1985] and Mistree *et al.* [1995]. In the problem statement of this example, the design team is required to come up with an appropriate conceptual design for car horn while considering the environmental requirements. Once the alternative concept is selected, the design team is asked to further design the product, select the processes, and determine the demanufacturing processes that give the optimal total life-cycle value. The solution to the example is presented following the four-phase QFD-based IECDM process sequentially; thus, the six steps for each phase are presented first that follows step 7 to step 9 (see Table 6.2). In the example, phase 4 is not considered.

6.2.1. An Example of the 'Car Horn' Selection Problem with Ranking Process Application

The example demonstrates how ranking-process is employed in the QFD-based IECDM process. After product-related attributes are identified in the Phase I matrix of the QFD-process, a ranking process is used to select one 'best' alternative. The selected product alternative is used to demonstrate the rest of the steps of the QFD-IECDM approach with CBA model application.

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[2] I am thankful to Dr. Farrokh Mistree of Georgia Tech for his permission to use the sample 'Car horn design' problem and the ranking process for alternatives selection as well as for other useful information.

Phase I: Product Planning

Step 1: Planning and Identification of Alternatives: Assume that a number of concepts have been developed into alternatives through engineering and refinement. The alternatives considered in this example (Figure 6.6) coincide with those obtained by Kuppuraju *et al.* [1985] and are described as:

Alternative 1: Electromagnetic diaphragm. The diaphragm is attached to the vibrating shaft driven by a rapidly changing magnetic field, thereby creating noise.

Alternative 2: Aeroacoustic horn. High speed rotary vanes force air out through nozzles, producing noise.

Alternative 3: Tape driven horn. Recorded impulses on electron magnetic tape are picked up, amplified, and broadcast.

Alternative 4: Rubber bulb. Solenoid is magnetized and demagnetized alternately. The magnetic core moves up and down, compressing and releasing the bulb or forcing air through reeds to provide noise [Bascaran, 1991].

Then the attributes for each alternative are generated by QFD-process (see Figure 6.7).

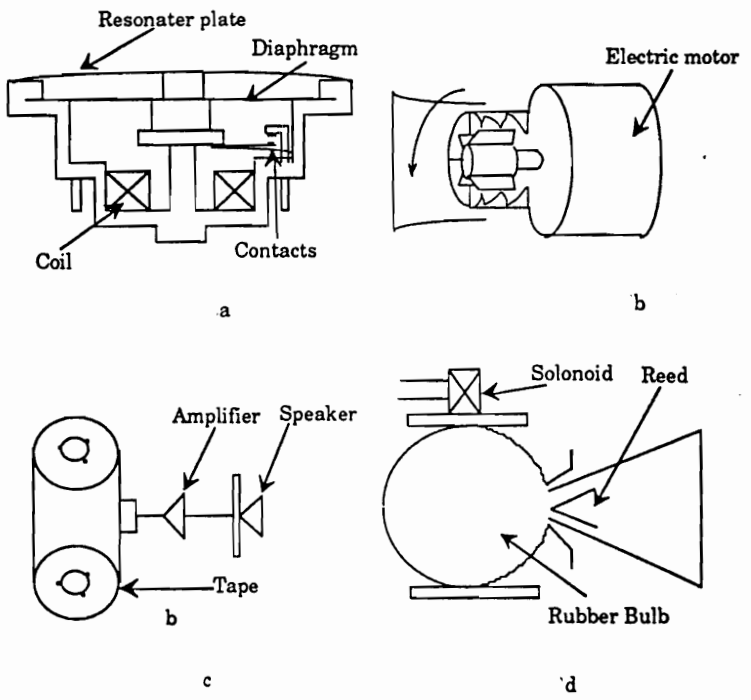


Figure 6.6. Alternatives for car horn design problem: (a) electromagnetic-diaphragm horn, (b) aeroacustic horn, (c) tape-driven horn, (d) rubber-bulb horn.

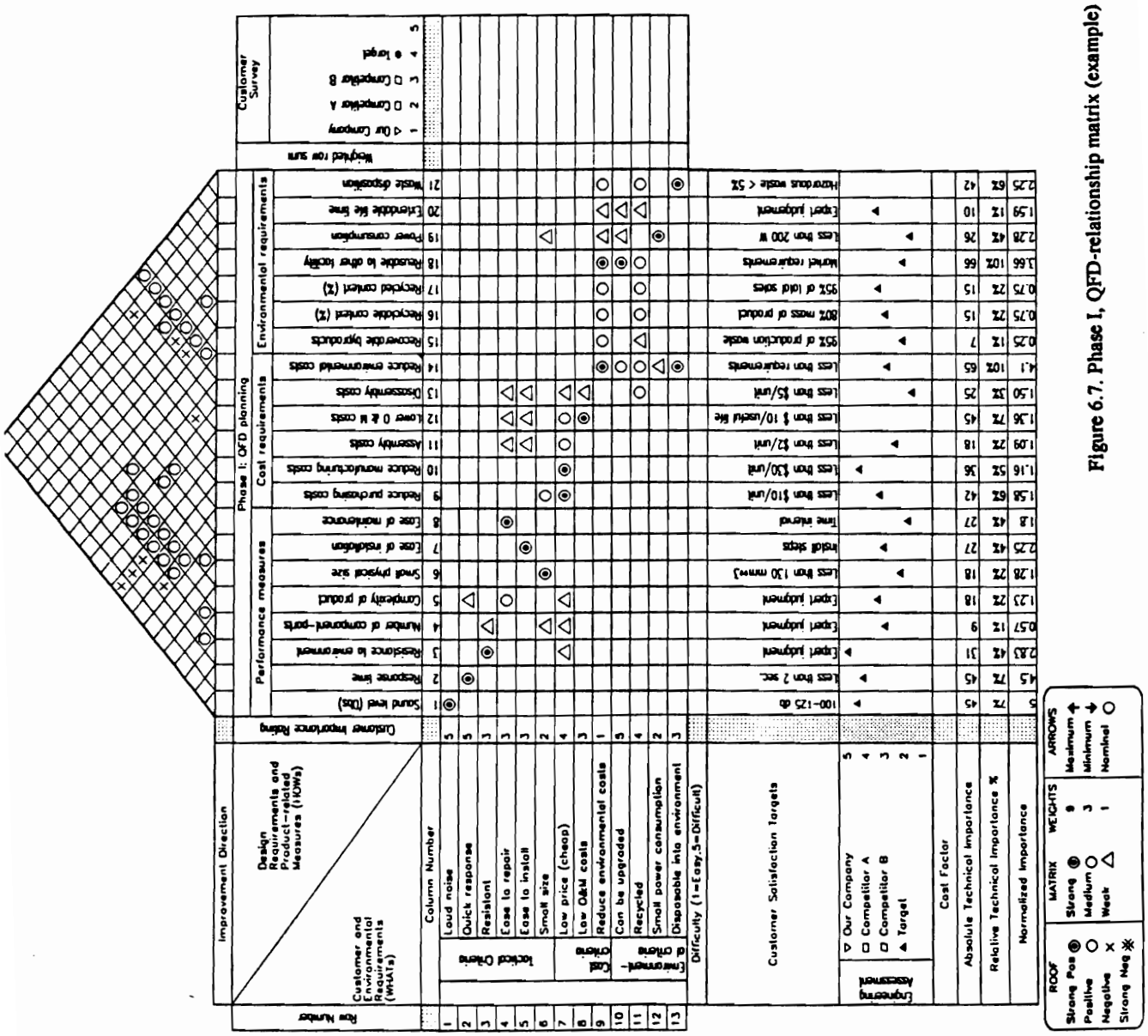


Figure 6.7. Phase I, QFD-relationship matrix (example)

Step 2: Identification of Attributes Based on Customer Preference and Environmental Issues: After the alternatives have been determined, the next step is the identification of product-related attributes by which the alternatives are to be judged and one selected. The QFD-process is employed to involve the transformation of customer-specified criteria and environmental requirements into more complete attributes of the product. The QFD-relationship matrix that is filled by customer requirements and design characteristics (product measures) is illustrated in Figure 6.7. (Note that, for convenience, this step 2 corresponds to steps 2 to 5 in Table 6.2, and the following steps 3 to 5 correspond to step 6 in Table 6.2.)

Once the design alternatives and corresponding product-related attributes are determined and generated, respectively. From environmental context viewpoint, we assume that the car-horn alternatives are designed for reuse and remanufacture but no material recovery). Then, the CBA model can be constructed for determine the product's total life-cycle value (TLCV). The CBA model is reformulated as below.

$$\begin{aligned} \textit{Maximize}\quad TLCV(T) = \sum_{t=1}^{T}\Bigg\{ & \sum_{q\in Q, j\in J_N} P_{q,j}(t)\cdot\xi_j(t)\cdot X_{q,j}(t) + \sum_{q\in Q, j\in J_R}\left\{RP_{q,j}\cdot\lambda_{q,j}(t')\cdot A_{q,j}(t')\cdot x_{q,j}(t')\right\} \\ & - \sum_{q\in Q, j\in J_N} CP_{q,j}\cdot x_{q,j}(t) - \sum_{j\in J} CA_j\cdot\xi_j(t)\cdot A_{q,j}(t)\cdot X_j(t)\cdot AT_j(t) \\ & - \sum_{j\in J}\xi_j\cdot OPCost_j(t) - \sum_{j\in J}\xi_j\cdot MTCost_j(t) \\ & - \sum_{q\in Q, j\in J, j\in J} CDA_{q,j,j}\cdot\xi_j(t)\cdot A_{q,j}(t)\cdot X_{q,j}(t)\cdot DAT_{q,j,j}(t) \\ & - \sum_{q\in Q, j\in J} x_{q,j,j,r}(t)\cdot\sum_{r\in R, j\in J} CDM_{q,j,j,r}\cdot z_{q,j,j,r}(t) \\ & - \sum_{q\in Q, j\in J_N} PCI_{q,j}\cdot PI_{q,j}(t) - \sum_{j\in J_R} RCI_{q,j}\cdot I_{q,j}(t) - \sum_{j\in J} ICI_{q,j}\cdot I_{q,j}(t)\Bigg\}\cdot(1+r)^{-t} \end{aligned} \tag{6.1}$$

Subject to

$$\left\{\sum_{q\in Q} W_{q,j}A_{q,j}(t) - P_j(t)\right\} - (U_j^0(t) - \pi_j^0(t)) \geq U^*(\xi_j - 1) \qquad \forall\, j\in J, t = 1,2,\ldots,T. \tag{6.2}$$

$$X(t) = \sum_{q\in Q, j\in J} X_{q,j}(t);\ X_{q,j}(t) \geq D_{q,j}(t) \tag{6.3}$$

$$D_{q,j}(t) = \left(A_{q,j}(t)\cdot w_{q,j}(t) \Big/ \sum_{q\in Q, j\in J} w_{q,j}(t)\right) \times \begin{pmatrix}\text{Market}\\ \text{size }(t)\end{pmatrix} \tag{6.4}$$

$$\sum_{l \in L} y_{q,j,l}(t) = A_{q,j}(t); \qquad \forall\ q \in Q, j \in J, t = 1,2,...,T. \tag{6.5}$$

$$\sum_{j \in J} AT_{q,j} \cdot \xi_j(t) \cdot A_{q,j}(t) \cdot X_j(t) \le TAT(t) \qquad t=1,2,...,T. \tag{6.6}$$

$$dx_{q,j}(t) = NA_{q,j} \cdot D_j(t) \tag{6.7}$$

$$PI_{q,j}(t) + D_{q,j}(t) = X_{q,j}(t) + PI_{q,j}(t) \tag{6.8}$$

$$PI_{q,j}(t) + D_{q,j}(t) = \sum_{k \in J} \lambda_{q,k,j}(t') \cdot A_{q,k}(t') \cdot X \sum q, j(t') + PI_{q,j}(t-1) \tag{6.9}$$

$$\sum_{k \in K} \lambda_{q,k,j}(t') \cdot A_{q,k}(t') \cdot x_{q,k}(t') + I_{q,j}(t-1) = I_{q,j}(t) + dx_{q,j}(t) + rx_{q,j}(t) + sx_{q,j}(t) \tag{6.10}$$

$$x_{q,J}(t) + I_{q,j}(t-1) = dx_{q,J}(t) + I_{q,J}(t) \qquad \forall\ q \in Q,\ t = 1,2,...,T. \tag{6.11}$$

$$x_{q,k}(t) = \sum_{q \in Q, j \in J} AN_{q,j} \cdot X_j(t) \tag{6.12}$$

$$A_{q,j}(t) \ge \xi_j(t) \tag{6.13}$$

$$\sum_{q \in Q, j \in J} \left\{ DAT_{q,j} \cdot X_{q,j}(t) \right\} \le TDAT(t) \tag{6.14}$$

$$\sum_{q \in Q, k \in J} sx_{q,k}(t) \le TWS(t) \tag{6.15}$$

$$x_{q,j}(t) \le \sigma_{q,j} \sum_{k \in J} \lambda_{q,k,j}(t') \cdot \left\{ A_{q,k}(t') \cdot X_{q,j}(t - h_{q,k} - \sum_{i \in J} \xi_{q,k,i} \cdot h'_{q,k,i}) \right\} \tag{6.16}$$

In our example (see Figure 6.6) there are four types of car horn to be designed and selected. Each design is associated with a set of attributes that are generated by QFD-process. In this example, the number of product j = 1 (electromagnetic diaphragm), 2 (aeroacoustic horn), 3 (tape driven horn), 4 (rubber bulb). The item-related attributes q for each product are generated by QFD-process. In the example, q = 1,2,...,21 (see Table 6.3). The recycling options i = 1, 2, 3. By the decomposition characteristic of QFD-process, theoretically, the CBA model can be formulated for obtaining optimal TLCV in two ways: (1) for use in design evaluation in product level, optimal TLCV is obtained for each car-horn design alternative in aggregation, or (2) for use in design evaluation in item level, optimal TLCV is evaluated for each design item alternative in hierarchy. Then the design alternative (of product design or of item design) with the highest TLCV is selected.

However, as we can see, the model is very complex even through there are only four design alternatives associated with 21 attributes. So, an optimal solution is difficult to obtain for optimization viewpoint. Therefore, in next, we use the third means, i.e., decision-making approach, to get feasible solution by following steps in order to demonstrate the QFD-IECDM approach to ecoproduct design

viewpoint. Therefore, in next, we use the third means, i.e., decision-making approach, to get feasible solution by following steps in order to demonstrate the QFD-IECDM approach to ecoproduct design processes selection as well as production plans with recycling capacity. In next, the car-horn alternative is selected by using ranking process (steps 3 to 6).

Step 3: Weighing relative importance of the attributes: In this step, the Lyman's normalization procedure is used to weigh the importance of design requirements [Lyman, 1990]. The proper weight rating, w_j , is defined as the normalized importance for each technical-design requirement (or product-related attribute) as:

Normalized Technical - Design Importance rating (NTI)

$$= \frac{\text{Individual rating}}{\text{Total importance rating}} = w_j = \frac{\sum_{k=1}^{L} d_k \cdot R_{k,j}^n}{\sum_{j=1}^{N}\sum_{k=1}^{L} d_k \cdot R_{k,j}^n} \tag{6.17}$$

where customer rating d_k represent the degree of importance of customer requirement k, k = 1,..., L. Relative importance $R_{k,j}^n$ denotes a normalization transform on the relationship values contained in the relationship matrix (i.e., HoQ matrix), that is,

$$R_{k,j}^n = \frac{R_{k,j}}{\left\{\sum_{j=1}^{N} R_{k,j}\right\}} \tag{6.18}$$

where $R_{k,j}$ is the quantified relationship between customer requirements, k, and engineering design requirements (or attributes), j ; k = 1,..., L, j = 1,..., N. As shown in equation (6.17), the individual rating reflects the overall importance of the technical characteristics after taking into consideration its relative importance, the rating perceived by the customer, and the environmental requirements imposed by government. Critical characteristics can be pointed out based on the individual ratings obtained, i.e. $\sum_{k=1}^{L} d_k \cdot R_{k,j}^n$.

However, to facilitate the identification process, the NTI rating (equation 6.1), which is given by the ratio of the individual rating to the total importance rating, is employed. A more detailed description of the weighting process is found elsewhere [Lyman, 1990]. Moreover, considering the dependencies (i.e.

technical correlation in the HoQ's roof) and features (such as uncertainty) of the technical characteristics (attributes), a variety of rating formulations are possible (see Appendix D).

Step 4: Rating the alternatives with respect to each attribute: The same idea as the NTI rating for each technical characteristic (attribute) with respect to the customer can be applied for rating the design alternatives with respect to the technical attributes. In other words, the normalized attribute rating of the alternative i with respect to each attribute level j can be defined as

$$\overline{R}_{i,j} = \frac{A_{i,j} - A_j^{\min}}{A_j^{\max} - A_j^{\min}} \tag{6.19}$$

Where $\overline{R}_{i,j}$ is the rating of alternative i with respect to the attribute j. Both $A_j^{\min}$ and $A_j^{\max}$ represent the lowest possible value and the largest possible value, respectively, of the attribute rating $A_{i,j}$. If a smaller value of an attribute rating represents preference, the normalized attribute rating is defined as

$$\overline{R}_{i,j} = 1 - \frac{A_{i,j} - A_j^{\min}}{A_j^{\max} - A_j^{\min}} \tag{6.20}$$

A more detailed description of the rating process for alternatives with respect to attributes is found elsewhere [Bascaran, 1991][3].

Step 5: Ranking the alternatives: Once the product-related attributes (or design requirements in QFD) are identified, the 'best' alternative design concept is often determined in one of three ways: (1) by AHP methods, (2) by a hierarchical multiple-level evaluation process for decision-making with uncertainty [Yang and San, 1994]], or (3) by the Merit-function method. This last method is used in our example. A merit function combines all the individual normalized ratings of attributes $R_{i,j}$ resulting

[3] In the rating process, four types of scales are described by Kuppuraju *et al.* [1985], namely, ratio, interval, ordinal, and composite. The choice of a particular type of scale to model an attribute depends on the nature of available information as presented in the 'how much' row of the QFD-relationship matrix. A ***ratio scale*** is used to measure physical quantities. The numbers used in a ratio scale are generally science-based, computable, or measurable and are therefore categorized as 'hard' information. ***Interval scales*** are created for attributes for which only qualitative or 'soft' information is available. Interval scales are also used to give a qualitative form to information captured by means of an ***ordinal scale*** (identified as expert judgment in the QFD matrix). Once scales of attributes are specified, the alternatives with respect to each attribute can be rated (generally, numbered from 1 to 10, the rating range depending on the number of attributes being specified). Furthermore, for dealing with uncertainty factors and linguistic variables (attributes) in the QFD-process, a fuzzy set is possible in the rating process (see Appendix D) or in defining design space. In such a sense, the so-called fuzzy-QFD become an important field for further research (see Khoo and Ho [1996], Bahrami [1994], and Verma [1994]).

from Step 4 with proper weights w_j obtained from Step 3. In other words, a merit function is the function of both weighting value and rating value of each alternative with respect to each attribute. There are several methods for modeling the merit function. The most frequently used model is the linear model[4], that is,

$$MF_i = \sum_{j=1}^{N} w_j \cdot \overline{R}_{i,j} \qquad i = 1,..., M. \tag{6.21}$$

where M is the number of alternatives (identified in Step 1), and N is the number of attributes (identified in Step 2).

Based on the merit function value, we compute the rank RK_i for an alternative as

$$\begin{aligned} RK_i &= 1 + \text{number of alternatives with higher merit function value} \\ &= 1 + \sum_{p=1, p\neq i}^{N} \beta(MF_p - MF_i) \end{aligned} \tag{6.22}$$

where $\beta(X)$ is the step function defined as

$$\beta(X) = \begin{cases} = 1 & \text{if } x > 0 \\ = 0 & \text{if } x \leq 0 \end{cases}$$

The fact that $\beta(0) = 0$ ensures that two alternatives having equal merit function values have the same rank.

In the ranking process, our method differs from Mistree's ranking method in two ways: (1) we use the QFD-process to help us identify all possible attributes of design characteristics that consider environmental requirements and customer' needs; (2) we obtain weights (NTI rating) of each attribute by normalized importance systematically through the QFD-process. In this way, we can make more consistency among criteria obtained from the customer and the requirements of design, also between product/items design planning and process/production planning. Furthermore, to deal with uncertainty in the design problem, Reddy and Mistree [1992] suggest an interval arithmetic approach in calculating MF_i (see Appendix D).

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[4] There are several methods for modeling the merit function, as follows [Kuppuraju *et al.*, 1985]

Model type	Formulation	Features
Linear additive	$MF_i = \sum_j w_j \cdot \overline{R}_{i,j}$	Simple and straightforward.
Higher order additive	$MF_i = \sum_j w_j \cdot \log(\overline{R}_{i,j})$	Weights the smaller merit function's contributions more than those of the larger ones.
Product	$MF_i = \prod_j w_j \cdot \overline{R}_{i,j}$	May result in inaccuracies if w_j or $\overline{R}_{i,j}$ are zero.

Step 6: Selecting the alternative and critical attributes for the next phase: It is noted that, in practice, ranking is performed by simply sorting the merit function values in decreasing order (without using equation 6.6). Therefore, the alternatives are ranked, with the highest merit function values being preferred. The alternative with highest merit function is selected.

In this example, the relative importance of the design characteristics and target values for each alternative are shown in Table 6.3 (from Figure 6.7). Once the ranking of alternatives is performed, the results presented in Table 6.4 show the merit function values obtained from Step 5 in the 'car horn selection' stage for the given rating and weightings of attributes. In this case the 'Tape driven horn' alternative is preferred when environmental requirements are considered.

Phase II: Component-Parts Deployment.

In phase II, the QFD team translates the key product measures (design requirements) into part characteristics. The part-related attributes (characteristics) are identified through QFD-process steps. The relationship matrix of design-requirements and part-characteristics of the 'Tape-drive-horn' is constructed (Figure 6.8). Note that the QFD-matrix (or HOQ) in Phases 1 and 2 is used iteratively, first at the product-system level to develop system-level attributes, and then at more detailed levels of design. The output of the first system-level specifications becomes the input to a second QFD-matrix, the output of which is a set of subsystem-level attributes. These attributes and their corresponding specifications become the basis for lower-level design matrix of piece parts.

Phase III: Process Planning.

In phase III, the QFD-team translates the key parts-characteristics into manufacturing-process characteristics and demanufacturing-process characteristics for recycling purposes. The relationship matrix of part-characteristics and their associated process-event characteristics are constructed through QFD-process steps. One assumed relationship-matrix is illustrated in Figure 6.9. It is noted that each part-characteristic may be associated with more than one possible process alternatives that perform the part-attribute. Ideally, the process alternative with lowest manufacturing costs and environmental impacts is selected.

Once the QFD-matrix has been constructed, our IECDM methodology extracts and interprets the information useful for product design. We build on the information given, refine and modify it for use in our mathematical CBA model for single design alternative. In the next section, we use the product 'Tape-driven-horn' to illustrate the QFD-based IECDM process and application of the CBA model in the item selection level (Step 7 and Step 8 in Table 2).

Table 6.3. Technical-design attributes and normalized importance for alternatives

Attributes	Statement	Normalized importance	Target value	Actual values			
				Electro. horn	Aero. Horn	Tape horn	Rubber horn
Sound level (dbs)	numeric	5.00	100-125 db	100--120 db	105--115 db	110--125 db	100--110 db
Response time	numeric	4.50	< 2 sec	less than 2 sec	about 1.8 sec	about 1.6 sec	less than 1.9 sec
Resistance to environment	linguistic	2.83	expert judge	good	very good	best	bad
Components no.	linguistic	0.57	expert judge	many	very many	much less	less
Complexity	linguistic	1.23	expert judge	high	medium	less	medium
Physical size	numeric	1.28	< 130 mm^3	less than 130 mm^3	approximate 120 mm^3	less than 130 mm^3	less than 125 mm^3
Ease of installation	linguistic	2.25	install steps	many install steps	many install steps	fewer install steps	many install steps
Ease of maintenance	numeric	1.80	time interval	less than 1.5 hours	less than 2 hours	less one hour	less than 1.5 hours
Reduce purchasing cost	numeric	1.58	< $10 / unit	less than $ 11 per unit	less than $12 per unit	about $10 per unit	about $12 per unit
Reduce manufacturing cost	numeric	1.16	< $30 / unit	less than $32 per unit	about $30 per unit	about $30 per unit	less than $30 per unit
Reduce assembly cost	numeric	1.09	< $2 / unit	about $2 per unit	about $ 3 per unit	< $2 per unit	less than $ 2 per unit
Lower O&M cost	numeric	1.36	<$10/use-span	about $10 per use-span	about $11 per use-span	< $10 per use-span	about $10 per use-span
Disassembly cost	numeric	1.50	< $5 / unit	$4 -- $6 per unit	$3 -- $8 per unit	about $5 per unit	less than $6 per unit
Reduce environmental cost	linguistic	4.10	< requirements	high	medium	very low	low
Recoverable by-product	numeric	0.25	95% of waste	90% of prod. waste	85% of prod. waste	95% of prod. waste	90% of prod. waste
Recycling context	numeric	0.75	80% mass of product	75% mass of product	65% mass of product	80% mass of product	75% mass of product
Recycled context	numeric	0.75	95% of total sold	80% of total sold	85% of total sold	95% of total sold	90% of total sold
Reusable to other facility	linguistic	3.66	market requirements	low	medium	very high	high
Power consumption	numeric	2.28	< 200 W	195 --125 W	120 --130 W	195 -- 120 W	190 --130W
Extendible life-time	linguistic	1.59	expert judgment	short	medium	long	very long
Waste disposition	numeric	2.25	hazardous waste<5%	hazardous waste 10%	hazardous waste 15%	hazardous waste 8%	hazardous waste 10%

Phase II
Part Deployment

	Part Characteristics (HOWs) / Design Requirements (WHATs)	Customer Satisfaction Targets	Importance	Importance rating	Speaker					Amplifer								Continuous tape						
					Size	Response time	Aluminum	Plastic	Reusable	Response time	Size	IC board	Ease of assembly	Ease of disassembly	Power consumption	Reuseable	ABS-polycarbonate	Size	Ease of assembly	Ease of disassembly	Power consumption	Aluminum	Steel	Plastic
Performance measures	Sound level (dbs)	100–125 db	1	5						◉														
	Response time	Less than 2 sec.	2	5		◉																		
	Resistance to environment	Expert judgment	5	5								◉												
	Number of component–parts	Expert judgment	20	2									○	○					○	○				
	Complexity of product	Expert judgment	15	3									△	△					△	△				
	Small physical size	Less than 130 mm**3	14	3	◉						○							◉						
	Ease of install	Install steps	7	4	△						△							△						
	Ease of maintenance	Time interval	9	4										△						△				
Cost requirements	Reduce purchasing costs	Less than $10/unit	11	3			○	○				○										○	○	○
	Reduce manufacturing costs	Less than $ 30/unit	16	2	△		△	△				◉	△					△	△					
	Assembly costs	Less than $ 2/unit	17	2									◉						◉					
	Lower O & M costs	Less than $ 10/useful life	13	3										○						○				
	Disassembly costs	Less than $ 5/unit	12	3										○						○				
	Reduce environmental costs	Less than requirements	3	5			◉	◉							◉						◉	◉	◉	
Environmental requirement	Recoverable byproducts	95% of production waste	21	1			○	○				○									○	○	○	
	Recyclable context (%)	80% mass of product	18	2			○	○				◉									○	○	○	
	Recycled context (%)	95% of total sales	19	2								○												
	Reusable to other facility	Market requirements	4	5					○						◉									
	Power consumption	Less than 200 W	6	4								○				◉								
	Extendable life time	Expert judgement	10	4					○						○						△	△	△	
	Waste disposition	Hazardous waste < 5% mas	8	4													○							
Component–Parts Characteristic Values					Less than 2 in dia.	Less than 1.0 sec	90 % of mass	10 % of mass	100 % part	Less than 1.0 sec.	2 in**2	1 in**2	Less than 30 min.	Less than 1 hour	Less than 20 W	100 % parts	Less than 5 %	Less than 3 X 2 X 1 in	Less than 20 min.	Less than 30 min.	Less than 150 W	70 % of mass	20 % of mass	10 % of mass
Absoulate Technical Importance					2.616	2.500	1.550	2.550	3.000	2.500	1.761	******	2.380	6.250	6.583	1.716	3.000	3.948	2.383	6.250	1.716	3.081	3.081	3.081
Normalized Importance					33	45	65	65	27	45	13	***	29	31	***	36	12	33	29	31	0	67	67	67

MATRIX	WEIGHTS
Strong ◉	9
Medium ○	3
Weak △	1

Figure 6.8. Phase II QFD-relationship matrix (example)

Phase III
Process Planning

Part Characteristics (WHATs) \ Process Parameters (HOWs)		Part Characteristic Values	Importance	Importance rating	Process # 1 (Speaker)			Process # 2 (Amplifer)				Process # 3 (Continuous tape)					Manual assembly			Automatic assembly			Manual disassembly			
					Event # 1.1	Event # 1.2	Event # 1.3	Event # 2.1	Event # 2.2	Event # 2.3	Event # 2.4	Event # 3.1	Event # 3.2	Event # 3.3	Event # 3.4	Event # 3.5	Event # m.1	Event # m.2	Event # m.3	Event # A.1	Event # A.2	Event # A.3	Event # D.1	Event # D.2	Event # D.3	Event # D.4
Speaker	Size	Less than 2 in dia.	11	3	◉													○			◉					
	Response time	Less than 1.0 sec.	13	3			◉										△				△					
	Aluminum	90% of mass	20	2		△													△			△				
	Plastic	10 % of mass	12	3																	○		◉			
	Reusable	100 %	9	4																		◉				
Amplifer	Response time	Less than 1.0 sec.	14	3				◉									◉				△					
	Size	Less than 2 in **2	17	2						◉								△		○						
	IC board	Less 1 in**2	1	5					◉										○		△		◉			
	Ease of assembly	Less than 30 min.	16	2							△							△								
	Ease of disassembly	Less than 1 hour	3	5																						
	Power consumption	Less than 20 W	2	5						△														○		
	Reusable	100 % parts	18	2					△								△					△				
	ABS–polycarbonate	Less than 5 %	10	4							△							○								◉
Continuous tape	Size	Less than 3 x 2 x 1 in	5	5								◉							◉		△					
	Ease of assembly	Less than 20 min.	15	3									◉					△				◉				
	Ease of disassembly	Less than 30 min.	4	5										△					○							
	Power consumption	Less than 150 W	19	2											◉		△				△					
	Aluminum	70 % of mass	7	4												△		○				○	◉			
	Steel	20 % of mass	8	4										△			◉			◉				◉		
	Plastic	10 % of mass	9	4									○					△			△				◉	
Process Parameter Values																										
Absolute Technical Importance					27	2	27	27	47	23	6	45	39	9	18	4	70	62	77	69	31	79	63	81	51	36
					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

MATRIX	WEIGHTS
Strong ◉	9
Medium ○	3
Weak △	1

Figure 6.9. Phase III QFD-relationship matrix (example with hypothetical process)

Table 6.4. Merit function values for car-horn alternatives

Alternatives	Merit function value	Ranking	
Electromagnetic horn	0.479	2	
Aeroacoustic horn	0.412	3	
Tape driven horn	0.523	1	← selected
Bulb and Reed horn	0.324	4	

It is noted that, operationally, in the QFD-based IECDM process (see Figure 6.2), each alternative is required to go through both the third phase of the QFD-process and through the LCA process; then the total life-cycle values for each alternative are calculated. The alternative with the largest total life-cycle value is preferred. For the purpose of demonstration, we select the preferred alternative 'Tape-driven horn' as an example to go through the QFD-based IECDM process. Nevertheless, the influence of the down-stream activities on upstream design activity is still illustrated by this example.

So far, the selection of an alternative through the ranking process has been performed in the QFD-based IECDM process. Consequently, engineering design involves the improvement and redesign of the selected alternative that deals with more detailed design and determination of products attributes in the QFD-based IECDM process. Next, we illustrate the application of the CBA model in two ways: (1) item design with simplified CBA model application, and (2) production planning with simplified CBA model application, using the selected 'Tape driven horn' as the example.

6.2.2. Product Design and Process Selection with CBA Model Application

In previous steps, we have selected one feasible product alternative through the ranking process. The QFD-process results in a set of key product-attributes associated with a set of processes. They generate some possible combinations of product-attributes and processes. Operationally, the TLCV is calculated by a CBA formulation for each possible combination. From an optimization viewpoint, the 'best' combination of attributes-processes is the one that has the largest total life-cycle value. The calculation of product's TLCV is expressed in sequences as the generic CBA model represented in Chapter 5. We use decision-making process to demonstrate the IECDM approach and solve the CBA model instead of using optimization techniques.

(1) Product design (attributes selection) and product sales revenues.

The major revenues come from product sales and product recycling. The profit from product sales depends on the demand in the market, which, in turn, depend on the attributes preferred by customers. We assume that product sales meet the demand that is a function of product-attributes.

Assume that three subassemblies of 'tape-driven-horn' are produced: continuous-tape, amplifier, and speaker, and assume that these three subassemblies are created from single-level attributes, as shown in Table 6.5. Then, the demand that depends on product's attributes can be obtained by equations (6.4). Thus,

$$D_j(t) = \left(\sum_{q \in Q,\, j \in J} A_{q,j} \cdot w_{q,j} \Big/ \sum_{q \in Q,\, j \in J} w_{q,j} \right) \times \left(\begin{matrix} \text{Market} \\ \text{size} \end{matrix} \right) \tag{6.4}$$

Here, j = 3 (tape-driven horn); q = 1 (power consumption), 2 (steel), 3 (low price); 4 (size), and 5 (reusability); and w_3 for each attribute is 0.2, 0.15, 0.22, 0.3, 0.25, respectively (see Table 6.5). In practical problems, this relationship implies that product design is significantly depended on demand or customer preferences.

Table 6.5. Product associated with attributes (example)

Attributes\Subassemblies	Con. Tape	Amplifier	Speaker	w_j	Competitor
1 (power consumption)	1	1	0	0.2	0.1
2 (steel)	1	0	1	0.15	0.2
3 (low price)	0	1	0	0.22	0.2
4 (size)	1	0	1	0.3	0.0
5 (reusability)	0	1	1	0.25	0.3

Then,

$\sum_j A_j \cdot w_j$ is a set of {1×0.2+1×0.15+1×0.3, 1×0.2+1×0.22+1×0.25, 1×0.15+1×0.3+1×0.25,

0.1+0.2+0.2+0.3} ={0.65, 0.67, 0.7, 0.8}

Thus, the $\sum_j A_j \cdot w_j$ values of subassemblies Tape, Amplifier, Speaker would be 0.65, 0.67, and 0.70, respectively. We assume that the corresponding value for the competitor's product equals 0.8; that is,

$$\sum_j w_j = 0.65 + 0.67 + 0.70 + 0.8 = 2.82$$

Therefore, the market shares for the three subassemblies and competition would be as follows:

$$PR(\%) = \{ \frac{0.65}{2.82}, \frac{0.67}{2.82}, \frac{0.70}{2.82}, \frac{0.8}{2.82} \} \times 100\% = \{23.05\%, 23.76\%, 24.82\%, 28.37\%\}$$

In other words, if the company plans to produce the 'tape-driven-horn' in a market with the total amount of the same type of horn at 10,000 units, the company has to produce Tape, Amplifier, and Speaker in amounts of 2305, 2376, 2482, respectively. If the sale price for each subassembly is known, then the profit can be calculated.

Now suppose that this company decides to introduce to market a new Tape #2 subassembly which incorporates attribute 5 (i.e., reusability) but at a new upgrade level of 2. Then the new corresponding value is

$$\sum_j A_j \cdot w_j = 2\ (0.25) = 0.5$$

If this new Tape #2 is incorporated into the marketing mix, then the market share would now become

$$PR(\%) = \{ \frac{0.65}{2.82+0.5}, \frac{0.67}{3.32}, \frac{0.70}{3.32}, \frac{0.5}{3.32}\ \frac{0.8}{3.32} \} \times 100\%$$

$$= \{\ 19.58\%,\ 20.18\%,\ 21.08\%,\ 15.06\%,\ 24.10\%\}$$

If the company plans to produce the 'tape-driven-horn' in a market with total amount of same type of horn at 10,000 units, the company has to produce Tape, Amplifier, Speaker, and Tape #2 in amounts of 1958, 2018, 2108, and 1506, respectively. A more detailed discussion of relationships among customer preferences, product-attributes, and market share can be found elsewhere [Chakravarty and Baum, 1991], where attributes and preference weightings are identified in our example by the QFD-process.

(2) Recycling context and recycling revenues.

The recycling context of the product involves both the recyclable context of the product itself and the recycled context of used products. From the economic considerations point, both the recycled context and the recyclable context may make a positive contribution to recycling revenues. The recyclable context is usually proportional to disassembly cost, but inversely proportional to disposal cost. That is, a tradeoff exists between revenues from recyclable context and disassembly cost.

Assume that three subassemblies (i.e., Tape, Amplifier, and Speaker) are designed with recyclable context (% of mass) and recycled context (% of sales volume) as shown in Table 6.6. Then the recycling revenues can be obtained if recycling benefit coefficients can be identified. Note that in Figure 6.6, the goals of design requirements are 80% recyclable context and 95% recycled context, which provide the direction for redesigning the product. The optimal recycling context can be obtained if a mathematical-based model can be obtained that contains recycling context as a decision variable.

Table 6.6. Recyclable context and recycled context of 'Tape-driven-horn'.

Recycling context	Continuous tape	Amplifier	Speaker
Recyclable context (% mass)	N/A	40%	80%
Recycled context (% sales volume)	N/A	20%	80%

This recycling information (Table 6.6) is used for evaluate TLCV of the 'tape-driven horn.' Further, we assume the production system is a closed-loop system. The returned subassemblies are reused in production of 'Tape-driven-horn'. Therefore, the recycling context also affects the purchasing cost and the manufacturing cost. The relationships between volume of returned products and production volume is assumed linear in our example.

(3) Process selection and manufacturing costs.

To obtain TLCV of the 'tape-driven horn,' we have to simultaneously determine the product alternative and its manufacturing processes. The manufacturing cost depends on the processes being selected, which, in turn, are determined by the product being designed (i.e., the preferred product-attributes). Ideally, processes are selected based on their 'goodness' with product-attributes, their manufacturing and environmental costs, and their impacts on the environment. Therefore, we first have to determine the relationship between product-attributes and their associated processes. To illustrate the interaction among the product, its attributes, and process selection, a simple example is presented. We are assuming that any product being designed can be specified by the attributes which it possesses. The attribute listing procedure is used to describe new products being designed.

In the 'horn-design' problem, we consider the three subassemblies with general sets $\{A_1\}$, $\{A_2\}$, and $\{A_3\}$ as shown in Table 6.4, such that the products are composed of attributes as shown in Table 6.7. Furthermore, for each attribute, the assumed process-characteristic needs for manufacturing are as shown in Table 6.8. Note that each attribute can be processed by one of two process alternatives.

Table 6.7. Product associated with different sets of attributes (an example)

Product (j)	Attributes set #1$\{ A_j^{(1)} \}$	Attributes set #2$\{ A_j^{(2)} \}$
Continuous tape	1,2,4	2,3,4
Amplifier	1,3,5	1,2,5
Speaker	2,4,5	2,3,4
New tape #2	1,2,4,5	

Table 6.8. Attribute associated with process

Attributes	Processes set #1 ($y_n^{(1)}$)	Processes set #2 ($y_n^{(2)}$)
1 (power consumption)	1,3,4,6	1,2,4,6
2 (steel)	1,4,5,6	1,3,5,6
3 (low price)	1,2,3,4	1,3,4,5
4 (size)	1,3,5,6	2,3,5,6
5 (reusability)	3,4,5,6	2,4,5,6

Now, considering the first set of attributes and processes, in order to produce the subassembly 'Tape', processes $\{1,3,4,5,6\}=\{y_1^{(1)} \cup y_2^{(1)} \cup y_3^{(1)}\}$ will be required; to produce subassembly 'Amplifier' will require processes set $\{1,3,4,5,6\}=\{y_2^{(1)} \cup y_4^{(1)} \cup y_5^{(1)}\}$; and to produce subassembly 'Speaker' will require processes $\{1,2,3,4,5,6\}=\{y_1^{(1)} \cup y_3^{(1)} \cup y_5^{(1)}\}$. To introduce the new Tape #2, processes $\{1,3,4,5,6\}=\{y_1^{(1)} \cup y_2^{(1)} \cup y_4^{(1)} \cup y_5^{(1)}\}$ will be required. In other words, if the company decides to introduce new Tape #2 to the market, there is no need to acquire a new process. Thus, new-design Tape #2 can be produced using the same process as that of the original Tape, even though they have a different combination of attributes.

In the process-selection context, the more is attribute information and detailed relationships there is among product-attributes-processes, the more complicated is the design decision-analysis problem will be, not to mention the optimization problem. Furthermore, in the context of ecodesign, if the data of environmental loads for each process (such as energy consumption, air emissions, waste generation) can be measured, then the environmental impacts of each product design alternative can also be analyzed and estimated. The 'best' alternative is the one that has smallest environmental loads, if ecological considerations (or criterion factors) dominate other factors during design evaluation.

To determine the match of product-attributes and processes, several measured approaches are usually used, such as: 'goodness', 'greenness', and 'Figure-of-Merit'. For illustration, they are proposed as follows.

Goodness of Processes with respect to Attribute. We assume that each subassembly can be specified by second attributes-set $\{A_j^{(2)}\}$, and each attribute can be processed by second process-set $\{y_n^{(2)}\}$, as shown in Tables 6.7 and 6.8. Then, the best design is a value of a redefined preference measure of matching problem, that is, matches the process-set to the specified attribute-set to obtain the best 'goodness.' In the context of environmental issues, the optimal solution represents a trade-off between cost and environmental impacts (if the inputs and outputs of each process are known).

Ideally, a simple way to find the 'goodness' score is as follows [see West *et al.* 1989]. We assume that the weightings (or normalized importance) of engineering-attributes with respect to the customer and the weightings of process alternatives with respect to each engineering-attribute are known through the QFD-process, as shown in Table 6.9. Then, the 'goodness' scores are compared as the weighted aggregate score for each process alternative with respect to attribute, that is,

$$\text{Goodness score} = \sum (\text{weightings of process}) \times (\text{weightings of attributes}) \qquad (6.23)$$

For example, the 'goodness score' of matching 'Tape #1' to process $y_n^{(2)}$ is obtained by

Goodness score = 0.2 x 2 + 0.15 x 4+ 0.3 x 3 = 1.9

Table 6.9 shows the results of matching Tape #1 and Tape #2 to $y_n^{(1)}$ and $y_n^{(2)}$ correspondingly.

Table 6.9. Goodness score of attribute and process (example)

Process sets	'Tape'	attribute set #1	(w_j)	'Tape'	attribute set #2	(w_j)	goodness	score
	1 (0.2)	2 (0.15)	4 (0.3)	2 (0.15)	3 (0.22)	4 (0.3)		
$y_n^{(1)}$	{1,3,4,6}	{1,2,3,4}	{1,3,5,6}	{1,2,4,5}	{1,2,3,4}	{1,3,5,6}		
weights	(3)	(2)	(2)	(2)	(4)	(2)	1. 5	1. 78
$y_n^{(2)}$	{1,2,4,6}	{1,3,4,5}	{2,3,5,6}	(1,2,4,5}	{1,3,4,5}	{2,3,5,6}		
weights	(2)	(4)	(3)	(4)	(1)	(3)	1. 9	1. 72

Therefore, as shown in Table 6.9, the attribute-set $\{A_j^{(1)}\}$ and the process-set $\{y_n^{(2)}\}$ are designed and selected for producing the subassembly 'Tape'. However, it should be noted that economic and environment-burden factors should be involved in process selection, because one process may require different production costs and generate various environment-burdens when it is used to process different attributes selected. In contrast, an attribute may be processed by a different process that results in different production costs and environment-burdens. Therefore, in our methodology, the 'total life-cycle value' is measured instead of "goodness' to show the best match between attribute-set and process-set. Once the corresponding cost-coefficients are known, the manufacturing costs can be estimated.

Using the Analytical Hierarchy Process (AHP) with Figure-of-Merit Application. By pairwise comparisons, process alternatives can be selected to process the item. Here, we present how a modified AHP method can help in process selection associated with design product. One of the selected methods for determining multi-criteria trade-offs is to use a simple-weighted utility function. The utility value represents the 'Figure-of-Merit (FOM)' of a design alternative, in this stage the process alternative. It can be expressed as

$$FOM = \sum_{j=1}^{N}\sum_{p=1}^{L}\left\{f_p(m)\cdot\sum_{i=1}^{I}A_i\left(1-\frac{F}{F_{Base}}\right)\right\} \tag{6.24}$$

where

j the item of a product that is processed, j=1,2,..., N; N is the total items that are processed.

p the process that is selected to process item, p=1,2,.., L. The combination of product item and processes is determined by the evaluated *FOM* values.

i all quality factors (process dimensions) concerned, i=1,2,..,I.

$\underline{A}$ the weighting values describing the relative importance of the process dimensions (or quality factors); $\underline{A} = [A_1, A_2, \ldots, A_I]$.

$f_p(m)$ the mass fraction factor in process p; we assume that the process's quality factors are all linear to the mass processed in that process.

F the target value (or design value) of a process alternative.

F_{Base} the baseline value of each process dimension (quality factor).

The relative weights (A_i) for a process prioritization matrix depend upon the attributes that are associated with the process and that can be determined by comparison to the output dimensions. For process selection, we address some of the main quality factors manufacturing designers are facing in their decision-making process. We assume that the quality factors addressed in the process are environment, cost, and performance. Using the AHP approach for calculation of FOM and for process selection, we construct the framework for analysis in Figure 6. 10. Since major decisions are seldom made by a single individual, we have structured the hierarchy to incorporate different perspectives in different levels: goal, criteria, objectives, and proposed solutions.

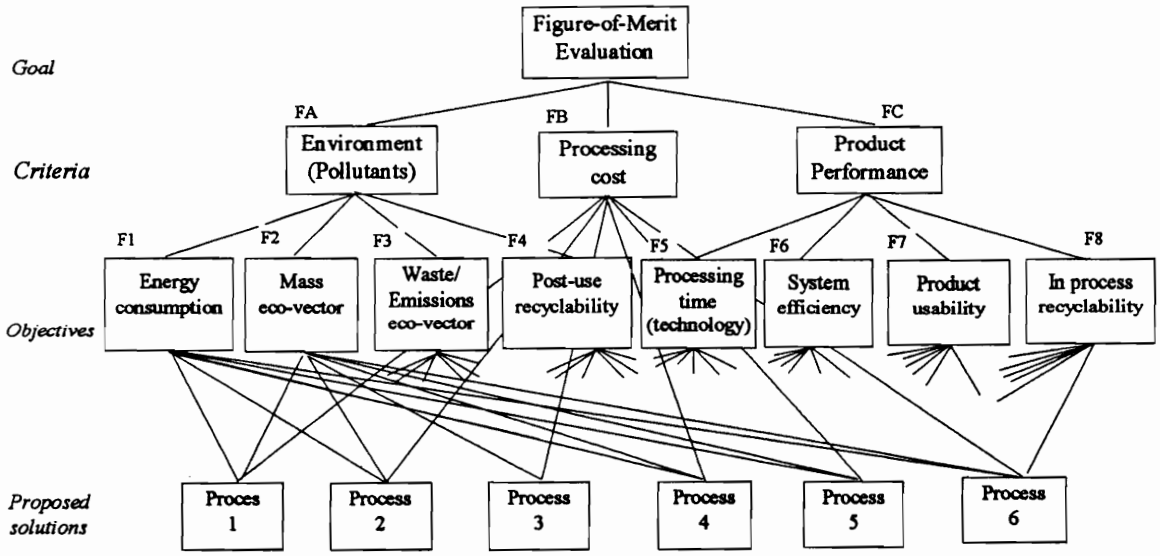


Figure 6.10. Hierarchy structure for 'Figure-of-Merit' for process alternatives selection.

In Figure 6.10, the eco-vector is defined as a multidimensional vector whose dimensions correspond to particular environmental loads (EL) identified for LCI (Life-Cycle Inventory) analysis in processes [Aelion *et al.*, 1995]. The environmental load category grouped in each eco-vector depends on

product characteristics. The eco-vector is used for obtaining pollutants generated in the process. For example, the product of the mass flow of a process stream times its corresponding mass eco-vector mass will give the rate of pollutant release generated up until this process step. Similarly, the energy eco-vector and the waste eco-vector are used for expressing the pollutants generated by the energy stream and the waste stream, respectively. Usability applies to all aspects of a product with which a user interacts, including maintenance procedures. All these quality factors can be deployed by using the QFD-process for practical problem and considerations.

The criteria for adapting a process to produce the designed item should be based on the 'Figure-of-Merit' for process acquisition. The characteristics of the 'Figure-of-Merit' might be categorized under the following three criteria: environment, processing time, and system performance. Once the weighing values $\underline{A}$ for each possible process (determined by Phase-III QFD process) have been obtained using the AHP method, we can use equation (6.24) is to calculate the *FOM* of the designed product containing items J that are processed by selected processes L.

Now, take the item 'tape' with attributes {2,3,4} as an example. The attributes {2,3,4} are processed by process sets {1,2,4,5}, {1,2,3,4} and {1,3,5,6}, respectively. For convenience, we neglect the cost criterion. The weighting values $\underline{A}$ for each possible process are obtained from the AHP-process in Table 6.10. Then, if values of quality factors F and F_{Base} for each process are given, the *FOM* for each process can be calculated by

$$FOM_{\text{For each process p=1,2,3,4,5,6}} = \sum_{i=1}^{i=8} A_i \left(1 - \frac{F}{F_{base}}\right) \tag{6.24}$$

Now, if the mass fractions of the processes are all the same and assumed to be 1, then the *FOM* for producing item-associated attributes {2,3,4} by process sets #1 and #2 (see Table 6.8) are obtained respectively by

$$FOM_{\substack{\text{For item Tape} \\ \text{with } \{2,3,4\} \text{ by set \#1}}} = \sum_{P=1,2,4,5} FOM_p + \sum_{p=1,2,3,4} FOM_p + \sum_{p=1,3,5,6} FOM_p$$

and

$$FOM_{\substack{\text{For item Tape} \\ \text{with } \{2,3,4\} \text{ by set \#2}}} = \sum_{P=1,2,4,5} FOM_p + \sum_{p=1,3,4,5} FOM_p + \sum_{p=2,3,5,6} FOM_p$$

As a result, the process set with the higher FOM value is selected. In a practical problem, the manufacturing process module is specified according to the practical item being produced, and the data for the environmental factors are difficult to obtain or measure. This lack of data becomes the critical issue in selecting the appropriate process and solving problems in ECDM domain.

Table 6.10. Weights of processes w.r.t. objectives and the corresponding composite weights

Process	Weights w.r.t. F1	Weights w.r.t. F2	Weights w.r.t. F3	Weights w.r.t. F4	Weights w.r.t. F5	Weights w.r.t. F6	Weights w.r.t. F7	Weights w.r.t. F8	Composit e weights
1	0.2314	0.1243	0.2361	0.0768	0.1983	0.0347	0.3214	0.1851	0.2314
2	0.1223	0.0324	0.2145	0.2346	0.0564	0.1432	0.1123	0.0367	0.1370
3	0.0214	0.2602	0.1279	0.1435	0.0342	0.3457	0.0978	0.2301	0.2045
4	0.1312	0.1326	0.0176	0.0563	0.3450	0.2301	0.1784	0.0349	0.2431
5	0.2213	0.1923	0.2305	0.2934	0.2134	0.1685	0.0889	0.1430	0.0673
6	0.2724	0.2591	0.1734	0.1954	0.1527	0.0778	0.2012	0.3702	0.1167

Using the Greenness Merit-Function. Another way to select a process is using the 'greenness merit' method. As discussed in Appendix B, we propose a *greenness-merit function* as one of specific quantitive measures of the product without using detailed LCA methodology. This greenness-merit function provides a way to assess the product's greenness rapidly. The 'greenness' score of merit of a product is defined as the cumulative 'greenness' score-of-merit of the subassemblies and processes that make up the product. The product's greenness-merit function is then expressed as

$$MF_{\text{product greenness}} = 1 - \sum_{q=1}^{Q} m_q \cdot w_q = 1 - \sum_{q=1}^{Q} w_j \cdot f(\mu_{q,k}) \tag{6.25}$$

The product's greenness is a useful measure for selecting a product alternative for environmental purposes (see Appendix B for details), especially in the early design stage. However, this greenness-merit function approach requires further research beyond the scope of this report. Therefore, we suggest that "greenness" issues should be viewed as one measure for product design, together with other measures.

(4) The effect of material property on total cost:

Material selection is one of the major factors that determine the environmental costs addressed in the CBA model, considering the external-environment cost (social cost of emissions) of aluminum, steel, and ABS-polycarbonate. Table 6.11 shows the various external-environment costs of each material. Note that the evaluation of various materials was conducted with available data. The material properties and the external-environment costs are the same for different companies, but the material purchasing costs and the manufacturing costs as well as internal-environment costs of a selected material will vary for different companies. Both manufacturing and internal-environment costs are controlled by the manufacturers.

Now, we assume that the company produces 10,000 'speakers' in period t. Using the data in Table 6.11, we can substitute the external-environment cost data into the CAB formulation (equation 6.1) while assuming that other cost components are fixed, that is

Table 6.11. External environmental cost varies.

Material Types	External Environmental Cost ($/Kg)	
	Raw material	Recycled material
Aluminum	0.10~0.25	0.014~0.06
Steel	0.06~0.09	0.006~0.020
ABS-polycarbanate	0.08~0.17	N/A

$$
\begin{aligned}
\text{Total cost } (C_t) = {} & [\text{Total material required for production in period t, K}]\ (\text{Kg}) \\
& \times [\text{Manufacturing costs } C_m + \text{Internal Environmental costs } C_i + \\
& \text{External environmental costs } C_e]\ (\$ / \text{Kg}) \\
& - [\text{Total recycled material weight in period t, K'}]\ (\text{Kg}) \times \\
& [\text{External environmental cost } C_e^+]\ (\$ / \text{Kg}) \\
= {} & K \times [C_m + C_i + C_e] - K' \times C_e^+ \\
= {} & K \times (C_m + C_i) + (K \times C_e - K' \times C_e^+) \qquad (6.26)
\end{aligned}
$$

An hypothetical diagram is illustrated in Figure 6.11. to express equation (6.26). Consider steel as an example, in order to replace steel with aluminum, the corresponding $C_m + C_i$ of aluminum will increase in order to remain at, at the least, the same level as the total cost of steel. Results indicate that for the same required material weight, the total cost of the product really depends on the combination of material property, manufacturing, and environmental costs.

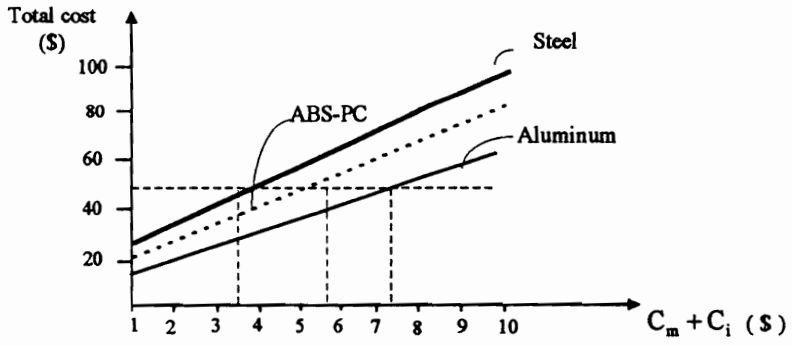


Figure 6.11. Impact of material properties and external-environment costs on total cost of the subassembly 'speaker'.

(5) Effect of complete Life-Cycle Costs (CBA model) on product design

To illustrate the application of CBA formulation in design-selection and DFE in design changes, the following design scenarios were constructed, based on 'horn design' example. Although fictitious, they reflect realistic ecoproduct development issues.

Assume that three types of 'Continuous tape' are designed. In selection of these 'Tape' alternatives, the example applies the concept of complete life-cycle cost to the design of product. This example will show how the complete LCC affects product alternative selection. The company is designing new products. In selecting the product alternatives, the company has the following goals:

- to minimize total (complete) life-cycle costs,
- to increase the recycled context of product or decrease the proportion of products that are incinerated or landfilled, and
- to reduce environmental impacts to society (reduce environmental costs).

The example assumes that the 'Tape' alternatives are designed associated with different purchase costs, production costs, and environmental costs (because of using different material) disposal costs, and useful lives. In addition, the operating and maintenance costs (e.g., inspection costs, system repair costs, and worker training costs) can also differ. In addition to the revenue of product sales, the different recycled contexts of products also is considered as part of revenue.

In the following example, the CBA equation is applied to calculate the total life-cycle value of the design alternatives to show how recycling considerations affect the product design. Table 6.10 illustrates an analysis of several alternative types of 'Tape' that can meet customer needs. While 'type-C' (with 80% recycled context) is more costly initially, it has a longer expected lifetime (35 years), low environmental costs, lower operating and maintenance costs, and much lower disposal costs (since it is the most recyclable) than other alternatives. These lower costs more than make up for the initial capital costs incurred to design and manufacture the product. This complete life-cycle cost perspective shows that the 'type-C tape' is preferred, although its sales revenue is lower because of its higher unit price. Furthermore, there are environmental benefits as well. Because 'type-C' can be mostly recycled, their use virtually eliminates the need to landfill or incinerate spent material.

Next, considering design improvement of the 'type-B tape' (original design), the following scenario illustrates how design changes affect LCC. This example shows how DFE principles could be applied during product design and how CBA equation works during the design change. Because of take-back regulations, the design team must be concerned with design issues that affect end-of-life costs, increasing product disassembly and recovery of high-value materials considering environmental costs. The design team has threefold primary redesign goals:

- to reduce the product's total life-cycle cost,
- to increase the recycled-material context of the 'type-B tape', and
- to reduce environmental impacts.

To achieve these goals, the design team has identified several opportunities. First, they will reduce the number of different materials that are used in the 'type-B tape'. Other design changes are:

- Identify a recycled material for the product that satisfies all engineering requirements, although it is modestly more expensive than the alternative; thus, recycled context increases from 20% to 60%.
- Identify an appropriate disassembly sequence that can reduce disassembly time using principles of Design For Disassembly (DFD); thus, operating/ maintenance costs and recycling/disassembly costs are reduced.

Previous examples had show how the ranking process is used for determining the 'best' alternative, how a process is selected for performing specific attributes of the selected alternative, and how environmental costs affect the materials selection. In the following, an example demonstrates how the CBA model is employed for use in product design in the QFD-based IECDM process. A numerical example shows the applicability of the CBA model in production planning concerning recycling issues. We assume the market size and demand of the 'Tape-driven horn' as given by Table 6.12, where the market share of the product 'Tape-driven horn' is calculated by $\frac{(0.65+0.67+0.70)}{2.82} = 0.7163$ from Table 6.5.

Table 6.12. Market size and product demand

Period t	1	2	3	4	5	6	Cumulating
Market size *t*	13,96	16,75	16,75	15,36	12,56	8,38	
Demand *D(t)*	1,000	1,200	1,200	1,100	900	600	6,000

The recycled (returned or recollected) rate is given by Table 6.13, where the total recycled context is 90% of the sold products. The product consists of three items, the data for which are given in Table 6.14, in which three types of tape with different attributes are given. Using the data in Table 6.14, the TLCV for each type of tape is calculated by using simplified equation (6.1).

Comparing the life-cycle costs associated with the new design with those for the original design highlights the economic benefits (see Table 6.15). It shows that the 'Type-B tape' is preferred over the 'type-C tape' after it has been redesigned for recycling (i.e., increasing recycling context). This example illustrates a method for using the CBA analysis tool developed in the research that may be used to analyze design changes using DFE rules and principles.

The 'tape-driven-horn' is selected. Assume that the amplifier and speaker are already designed, so that, only the 'tape' is to be considered. According to the calculation of life-cycle-value (see Table 6.16), the 'type-C' tape is then selected before redesign. After redesign, the 'type-B' tape is selected with attributes {2, 3, 4} which are processed by the processes set of {1,2,4,5}, {1,2,3,4} and {1,3,5,6}.

Table 6.13. Recycled context rate

Utilization period	1	2	3	4	5
Recollected rate	0.2	0.3	0.2	0.1	0.1

Table 6.14. Cost data of three types of tape.

Price/Cost coefficient		Item tape types Tape A	Tape B	Tape C
Selling price	($/unit)	3.833	3.667	3.167
Purchase cost	($/unit)	0.078	0,130	0.500
Fixed cost	($)	1,000	1,000	1,000
Manufacturing cost	($/unit)	0.065	1.000	1.200
Set-up cost	($)	500	500	500
Assembly cost	($/unit)	0.112	0.250	0.217
External environmental cost	($)	N/A	N/A	N/A
Internal environmental cost	($)	N/A	N/A	N/A
Operating & Maintenance costs	($/unit)	0.083	0.100	0.072
Demanufacturing cost	($/unit)	0.000	0.100	0.400
Disassembly cost	($/unit)	0.000	0.100	0.100
Recovery cost	($/unit)	0.000	0.100	0.200
Dumping cost	($/unit)	0.500	0.100	0.100
Reusable ratio		N/A	20%	80%
Product inventory-holding cost	($/unit)	N/A	N/A	N/A
Items inventory-holding cost	($/unit)	N/A	N/A	N/A

Table 6.15. Comparison of alternative products

Types of 'continuous tape' in tape-driven-horn	Product sales revenue	Recycling revenue	Total acquisition cost	Total production cost	Operating /maintenance cost	Total recycling-related cost	Revenue - LCC (PV) (r=6.6%)
Type-A tape (Non-recyclable)	$ 23,000	$ 0	$ 470	$ 8,500	$ 500	$ 3,000	$ 6,732 (5 years)
Type-B tape (20% recycled context)	$ 22,000	$ 4,400	$ 780	$ 9,000	$ 600	$ 2,400	$ 7,188 (10 years)
Type-C tape (80% recycled context)	$ 21,000	$ 16,800	$ 3,000	$ 10,000	$ 430	$ 4,800	$ 7,503 (15 years)

Table 6.16. Comparison of original design and new design

Types of 'continuous tape' in tape-driven-horn	Product sales revenue	Recycling revenue	Total acquisition cost	Total production cost	Operating/ maintenance cost	Total recycling - related cost	Revenue - LCC (PV) (6.66%)
Type-B tape (original) (20% recycled context)	$ 22,000	$ 4,400	$ 780	9,000	$ 600	$ 2,400	$ 7,188 (5 years)
Type-B tape (redesign) (60% recycling context)	$ 22,000	$ 13,200	$ 2,000	9,500	$ 600	$ 4,500	$ 9,816 (10 years)
Type-C tape (80% recycling context)	$ 21,000	$ 16,800	$ 3,000	10,000	$ 430	$ 4,600	$ 7,503 (15 years)

(6) Production Planning Application with Recycling/Demanufacturing Capacity

Although product design and process selection issues (as in previous examples) are important, the viability of recycling and remanufacturing schemes is also significantly affected by the production systems in which they are realized. In such a case, a numerical example related to the recycling plan of the items is illustrated.

If assume the product 'Tape-driven horn' consists of three items (driver, tape, and speaker), the data for the items driver, tape, and speaker are given in Table 6.17 with the same demand as in Table 6.12 and the recycled context rate as in Table 6.13. As an example of CBA model application, using equations (6.9), (6.10), (6.11), (6.12), (6.13), and (6.15), Table 6.18 shows the required quantities for the item 'Tape' with its specified attributes. In the production plan, reusable items are used throughout the planning period, and some amount of not-reusable but remanufactured items are used starting in period 3 due to delay time of remanufacturing. The tapes are disposed after period 6 since that is its limitation of useful life. After the production plan has been developed, using the data in Table 6.17, the product's TLCV can be calculated by using equation (6.1) for a given production plan.

Table 6.17. Cost data of the three items: driver, tape, and speaker.

Price/Cost coefficient		Items		
		Driver	Tape	Speaker
Selling price	($/unit)	10.000	3.167	5.000
Purchase cost	($/unit)	7.000	0.500	3.000
Fixed cost	($)	2,000	1,000	1,000
Manufacturing cost	($/unit)	3.000	1.200	2.000
Set-up cost	($)	2,000	500	1,500
Assembly cost	($/unit)	3.000	0.217	1.000
External environmental cost	($)	N/A	N/A	N/A
Internal environmental cost	($)	N/A	N/A	N/A
Operating & Maintenance costs	($/unit)	2.000	0.072	1.000
Demanufacturing cost	($/unit)	0.500	0.400	0.500
Disassembly cost	($/unit)	0.500	0.100	0.200
Recovery cost	($/unit)	2.000	0.200	5.000
Dumping cost	($/unit)	0.100	0.100	0.100
Reusable ratio		80%	80%	95%
Item inventory-holding cost	($/unit)	0.010	0.010	0.010
Items inventory-holding cost	($/unit)	N/A	N/A	N/A

In the practical problem. the production planning with recycling capacity depends on product structure (number and type of items in product) and recycling options which, in turns, affects the product's total life-cycle value. Therefore, a simple way toward maximum TLCV is to adjust the ratio of number among reused, remanufactured, and disposed items within certain constraints, while other factors are fixed. In fact, production plans are obtained only when product and process are designed and selected. As a result, our example discussed above has illustrated the QFD-based IECDM process from product design, process selection, to production planning while considering environmental and recycling issues simultaneously.

Table 6.18. Quantity of production for total life-cycle value (one feasible solution)

	Period t	1	2	3	4	5	6
	Demand	1,000	1,200	1,200	1,100	900	600
	Disposal capacity	N/A	150	150	150	150	150
	Recollected rate	0.2	0.3	0.2	0.1	0.1	N/A
Driver item	Reuse rate	N/A	0.4	0.6	0.6	0.5	0.4
	New purchase	1,000	920	894	872	802	517
	Reused	0	80	156	48	41	29
	Remanufactured	0	100	126	102	52	50
	Disposed	0	100	150	30	40	30
	Inventory	0	0	24	78	5	4
Tape item	Reuse rate	N/A	0.8	0.6	0.6	0.4	0.2
	New purchase	1,000	840	868	907	800	477
	Reused	0	160	132	93	30	80
	Remanufactured	0	100	152	73	60	40
	Disposed	0	100	100	100	40	40
	Inventory	0	0	48	27	10	3
Speaker item	Reuse rate	N/A	0.8	0.5	0.5	0.4	0.4
	New purchase	1,000	840	898	910	815	526
	Reused	0	160	102	79	31	31
	Remanufactured	0	100	152	90	46	41
	Disposed	0	100	100	89	45	40
	Inventory	0	0	48	21	8	3

(7) Redesign For Environment with Reverse Engineering Application.

Existing products returned from the consumer may not be considered for DFE initially. In a sense, it is recognized that designers are also responsible to redesign and/or upgrade the existing product for environmental protection reasons, which may be performed by a Reverse Engineering process (see Appendix E for details).

In the context of green issues, taking the item 'speaker' as an example, materials substitution is thought to be much less likely to happen for the reasons of recycling than for broader economic or financial reasons. Therefore, Redesign-For-Environment becomes the good reason for doing the Reverse Engineering process, which can be achieved by going through the same design flow chart (see Figure 6.5) and design process steps (see Table 6.2) once the QFD-matrix is constructed (see Figure 6.12).

Now, we select material for the speaker with environmental considerations. We assume that the QFD/HoQ for the speaker is obtained by the Reverse Engineering process discussed in Appendix E, as illustrated in Figure 6.10. From the QFD-matrix, we can develop a material selection model at minimum cost while meeting engineering and environmental requirements; following these steps.

Identify Attributes from Reverse Engineering Process and Customer Requirements: As Figure 6.12 shown, design attributes {1,2,3,4} are identified from existing attributes by the reverse engineering process, and design attributes {5,6,7,8} are considered with environmental requirements for non-toxicity and recyclability. The attributes and ranges are summarized and classified in Table 6.19.

Table 6.19. Redesign attributes with environmental considerations

Attributes	Statement	Actual value (from test)	Target value (requirements)
Speaker weight loads	numerical	0.5 kg	0.4 kg–0.5 kg
Speaker diameter	numerical	10 cm	6—8 cm
Speaker depth	numerical	6 cm	3–6 cm
Speaker thickness	numerical	0.5 mm	≤ 0.5 mm
Material density	numerical	2.7 tons/m^3 (Aluminum)	selected material
Material stress	numerical	420 Mpa (Aluminum)	selected material
Manufacturing costs	numerical	N/A	≤ 850 $/ton
External environmental cost	numerical	0.10–0.25 $/kg	≤ 0.5 $/kg
Internal environmental cost	numerical	N/A	≤ 0.05 $/kg
Material deflection	numerical	≤ 0.05 mm deflection	≤ 0.05 mm deflection
Total speaker cost	numerical	20 $/unit	≤ 15 $/unit

Define Design Decision Variables and Parameters: The design-team identifies eight engineering characteristics that influence the customer's attributes. The relationship between decision variables and parameters is formulated by their correlation based on their physical principles. Table 6.19 summarizes the design variables and their feasible ranges.

Construct a Design Evaluation Function with Constraints: After the design variables and parameters are identified by the QFD-optimization approach, a mathematical model for redesign is developed as

$$\text{Minimize} \quad TC = A(D,d)\cdot h\cdot \rho\cdot (MCost + EECost + IECost) \tag{6.27}$$

Subject to

$$\sigma_d = k_1 \frac{W}{h^2} S_1 \tag{6.28}$$

$$\delta_d = k_2 \frac{W\cdot A(D,d)}{E\cdot h^3} S_2 \tag{6.29}$$

$$T_C = 0 \tag{6.30}$$

$$R_P = 1 \tag{6.31}$$

where

$MCost$ = unit manufacturing cost of a speaker
$EECost$ = external environmental cost
$IECost$ = internal environmental cost
ρ = the material density (g/m^3)
W = the weight of the speaker, representing the speaker performance
k_1 = stress coefficient for speaker disc
k_2 = deflection coefficient for speaker disc
E = the Young's modules of the material
σ = the material stress (MPa)
σ_d = the strength designed (MPa)

δ = the allowed material deflection for environmental resistance

δ_d = the designed deflection (mm)

D = the diameter of the speaker (cm)

h = the thickness of the speaker (mm)

$A(D,d)$ = the speaker area as a function of its diameter D (cm) and depth of disc d (cm)

T_C = the toxicity of the material, 0 represents not toxic; it is related to the cost components (objective function) in some function form to demonstrate how it affect the design from environmental consciousness viewpoint.

R_P = the recyclability, 1 represents recyclable; again, it is related to the cost components in some function form.

S_1 = safety factor for strength design

S_2 = safety factor for stiffness design

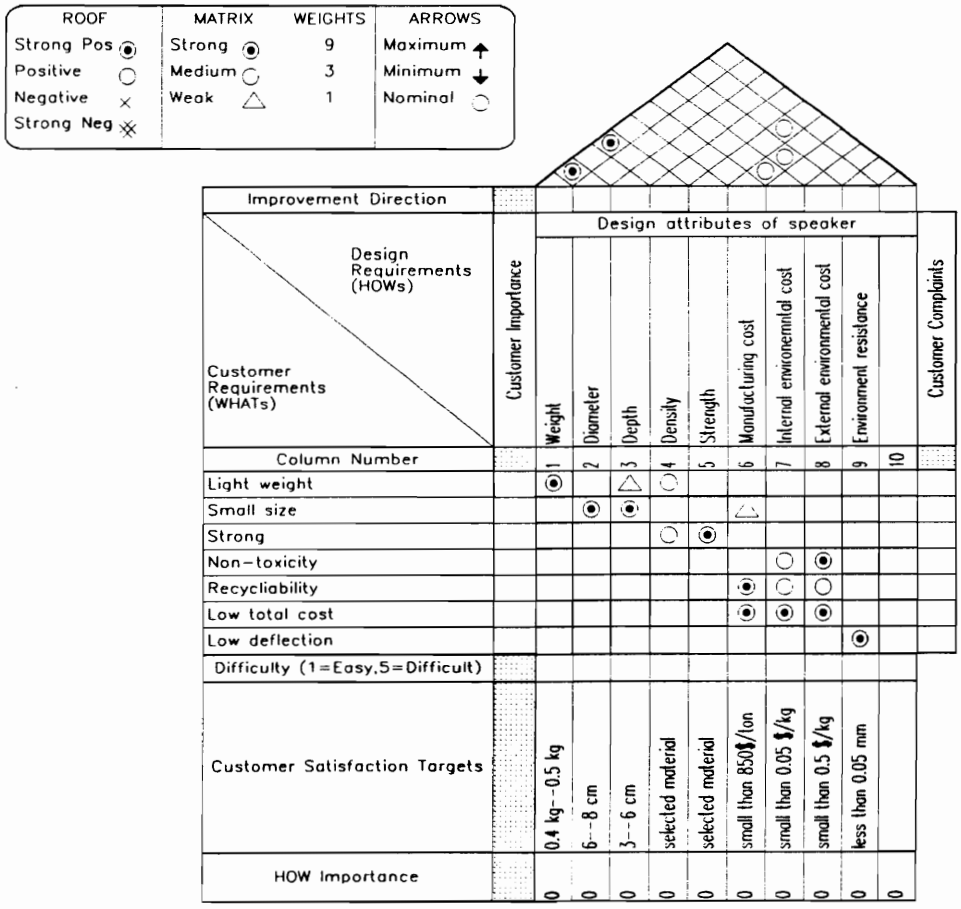


Figure 6.12. QFD-matrix (Phase I) for speaker

6.2.3. Discussion of the QFD-IECDM Decision Process with CBA Application

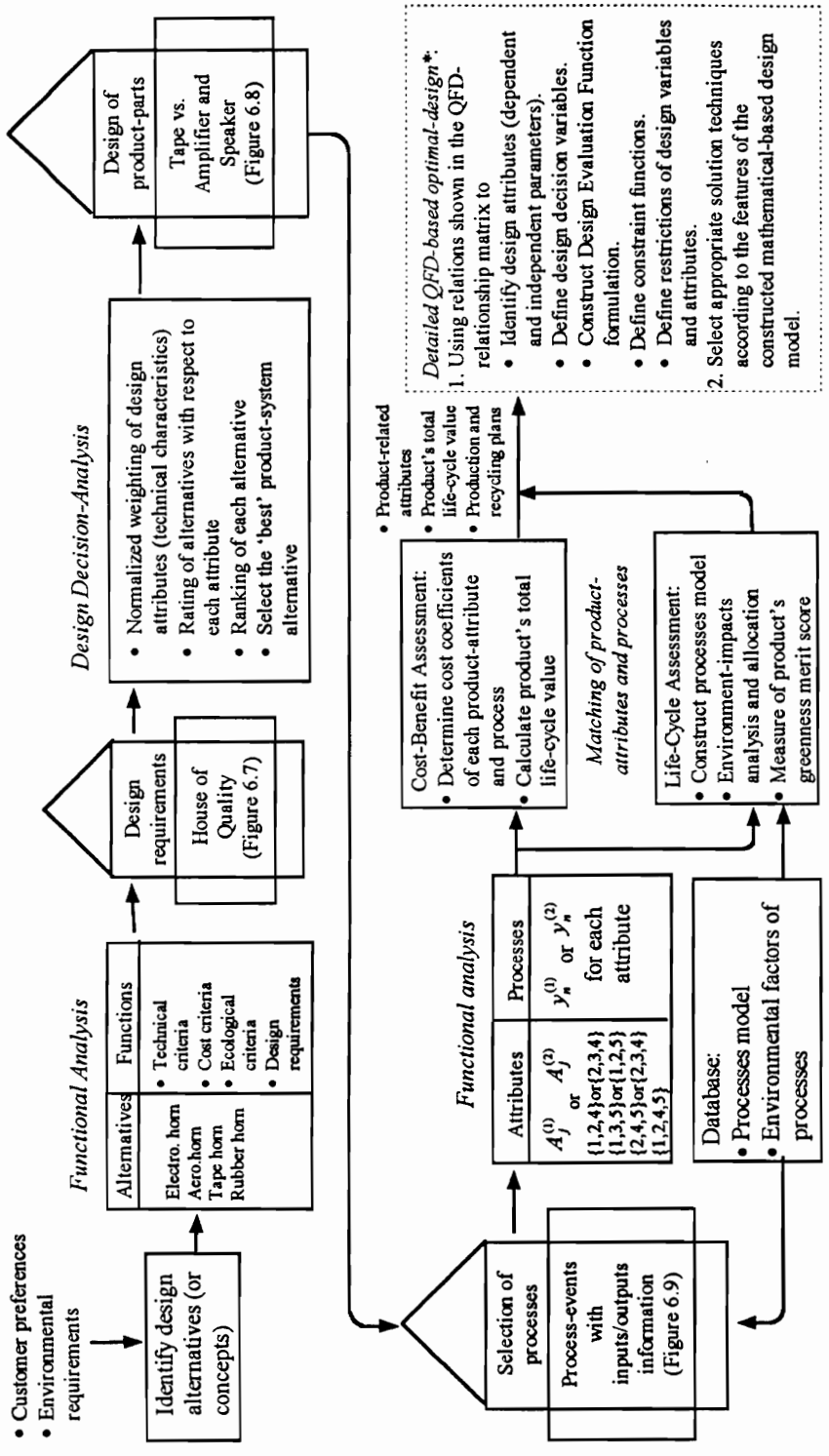
In the above examples, a QFD-IECDM process was used to identify environmental requirements in the 'Horn-design' problem while maintaining other performance and quality owing to the quality-features of the QFD-process. The purpose is to illustrate the applicability of the QFD-based IECDM process. A summary and some discussion is given follow:

Summary. The QFD-matrix shown in Figures 6.7 to 6.9 provides the information required in the IECDM approach. These figures contain only parts of the full analysis, but provide an illustration of ranking and a comparison of various key attributes involved in design alternatives (i.e., different types of horn). The results of the QFD-based decisions-analysis led us to choose the 'Tape-driven-horn' out of other alternatives (see Figure 6.13). In the design of subassembly 'Continuous-tape', the results of the QFD-based IECDM analysis led us to change the material in order to increase recycling context from 20% to 60%. In addition, the concept of a QFD-based optimization approach is mentioned for use in the continuous-improvement stage (detail design stage) that can provide ongoing advantages such as design characteristics with an optimal target value. However, this detailed optimal-design approach is beyond the scope of this research (see Appendix C).

The QFD-IECDM used in the example can be visualized in graphical terms as illustrated in Figure 6. 13. For each possible design alternative, the product design, process selection, product recycling options, and disassembly sequences are determined following prioritized sequences. The design and analysis are centered around the following sequential scenarios:

- The 'best' product-design alternative (or materials selection) has the largest ranking scores from the QFD-based decision-analysis process;
- The 'best' matching manufacturing process is the one with the smallest environmental impacts (or the largest greenness-merit) based on the product-attributes of the 'best' product determined;
- The 'best' PROs/MROs is the greatest of the product's end-of-life value, based on the product-attributes of the 'best' product determined, and may form the prioritized options of reuse, remanufacturing, recycling, and then disposal.
- The 'best' disassembly sequence contributes positively to disassembly profits based on the best PROs for the part's subassemblies.

In the IECDM approach, using the TLCV formulation in the mathematical CBA model, the product's TLCV can be calculated for each item design-alternative of the 'Tape-driven horn.'. Then the product with greatest life-cycle value is selected, as shown in Table 6.15 and 6.16.



* the QFD-based optimal design problem is included for further study (see Appendix C).

Figure 6.13. QFD-IECDM for maximization of the product's total life-cycle value

The QFD-matrix requirements presented in Figure 6.13 show how the QFD-IECDM approach was employed to analyze and select the product attributes and processes being examined through a decision-analysis approach. Figure 6.13 incorporates elements of the QFD-IECDM process including ranking process, LCA techniques, and cost-benefit formulation. In the practical problem, instead of LCA techniques, we use 'goodness' or 'AHP' or 'greenness' to help determine the process.

In our example, the identification of alternatives and attributes are performed by QFD-process. A ranking process is employed to choose the best conceptual alternative. Once the alternative that best meets the requirements identified in the Phase-I QFD-matrix is established, a further analysis is performed on the subsystem products. Next, in selection of the manufacturing process, product-related attributes come in as inputs (such as raw material), and are processed by a set of specified processes. By analyzing various options of the product attributes (such as steel and aluminum) with the different processes, the product can be systematically optimized for cost-benefit performance and environmental impacts reduction. The result from such an optimal-design process is a set of product-attributes that maximize the product's TLCV.

Discussions and Observations. In addition to the discussion above, some other concepts should be pointed out as follows.

On Advantages to adopting the QFD-based IECDM Approach: Many advantages exist for adopting the QFD-IECDM approach. For example,

- The QFD-process requires a cross-functional team from marketing, design, and manufacturing. For example, we did not discuss marketing for target values and competition. Marketing share is determined by those attributes that are identified and preferred.
- The complete QFD-process aggregates the information that each specialized group in a company provides to the next group in the product-development process, assuring that customer and environmental requirements are translated into a manufacturable, environmentally compatible, and marketable product.
- In the QFD-process, only the key items (attributes) in each phase are carried onto the next phase. It is the QFD philosophy that most companies have a product development process that can handle the less critical requirements and that the QFD-team should concentrate on the most critical requirements that need special attention. Even priorities of key requirements can provide redesign decisions sequentially for continuous improvement purposes.
- Adopting the QFD-based IECDM process can discover potential opportunities for environmental quality improvement earlier in the product design stage (i.e., product planning at the first QFD-

phase), which, in turn, facilitates rapid time to market and meets environmental requirements due to the features of the conventional QFD-process.

- The QFD-based IECDM process provides necessary and appropriate information into the CBA model for design analysis and evaluation, which, in turn, provides information to the design-team in order to make simultaneous decisions in product-design and process-selection simultaneously.

On the simultaneous product-design and processes-selection: In our example, we proposed three feasible methods for process selection. The first, the 'goodness' measure, is the simplest. The 'goodness' score as defined in the example is a simple way to measure the matches between product-attribute and its associated processes. Using weightings generated from the QFD-process, the highest goodness score means a good match between product-attribute and the process it preceded, while involving customer preference from design to manufacturing process. The second method, 'Figure-of-Merit' evaluation with AHP application, when dealing with uncertainty, provides an effective way to select a process set to produce the designed product's items. However, the AHP method cannot represent constraints on attributes, and cannot handle large numbers of alternatives or attributes easily. By combining AHP and QFD, the constraints of attributes may be specified through the QFD process. Finally, the 'greenness' score can be defined as a way to decide the best product alternatives based on the product's greenness with respect to process-attributes, with focus on environmental concerns. This approach is worth study for delineating nonlinear relationships between mass and manufacturing process step.

However, it should be noted that the highest goodness-score or Figure-of-Merit or greenness-score does not necessarily mean that the product's total life-cycle value is optimum. Economic factors should be involved in process-selection. Economic considerations may be extremely complex, especially at the early design stage, yet they are important factors in the evaluation of the production processes. Therefore, production costs should be used as a 'goodness' measure. This is one of reasons that the optimization-based CBA model is developed. In other words, the 'optimal process' is selected only when it makes a positive contribution to the product's total-cycle value. This concept is also true for the design and analysis of disassembly or/and its sequence. Nevertheless, the 'optimal-process' and 'optimal disassembly-degree' is iterative in nature. A change in product-design (or attribute) may require analysis to ensure conformance of the design (attribute) to the manufacturing-processing needs and disassembly-processing needs. This change, in turn, generates a new look at the 'goodness' measure and a new look at life-cycle cost, performance, environmental impacts, and product-design trade-offs. This new look leads to the QFD-based IECDM in our research.

On the production planning with recycling capacity: In the example, the production planning is clarified concerning recycling issues over the product's life cycle in the system after the product has been

designed and process has been selected. So that the manufacturing activities can elegantly adapt to the ecological environment in terms of recycling options efforts. Again, we use CBA model for analyzing how recycling issues affects production planning and then TLCV. We suggest adjusting the ratio among reused, remanufactured, and disposed items towards the 'best' TLCV corresponding to a specific production plan.

On adopting the Life-Cycle Assessment: A complete LCA is defined as an objective process to: (1) develop an inventory of the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and waste related to the environment; (2) assess the impact of the energy and materials used and the releases to the environment; and (3) evaluate and implement opportunities to effect environmental improvements. When a LCA is employed in green product design, Navin-Chandra [1991] suggested that LCA should occur after the product has been designed and product's life cycle is determined.

In the QFD-based IECDM, LCA is used after the Phase-III QFD-matrix is deployed, i.e., LCA is used after the product and processes are determined. The design team uses the results of the LCA as one of design factors to evaluate product design. Nevertheless, environmental factors should be incorporated into design process that starts from Phase I QFD-matrix. Matrices play an important role in locating design attributes that need to be changed throughout product development. DFE guidelines [Fiksel 1996] is applied in the QFD-IECDM process (or in the design flow chart) that merely provide the design team with an opportunistic direction in which to search the design space for a low environmental impact design solution. Designers must ultimately evaluate the new design with a LCA that occur after product and process are designed. Unfortunately, lack of data that LCA requires makes adapting LCA in the design process very difficult.

In our example, hypothetical data are assigned to the processes that process the specified attribute. However, the lack of information of environmental-burdens makes even inventory-assessment very difficult. Instead of going through inventory-assessment, we present the concepts of 'Figure of Merit' and 'greenness-merit-function' that helps the design-team select the product-alternatives in the early design stage. The product with a high 'greenness' score is selected, that ensures its associated processes have the smallest impact on the environment. This 'greenness' approach requires further study; it may be a way to define 'ecounits'.

On the mathematical CBA model: In this study, we demonstrated how CBA model can be formulated for ecoproduct design and its realization (Chapter 5). The CBA model, within QFD-based IECDM approach, can be solved for obtaining the best green product design. Owing to the QFD-process

features, we can break down the product-system into subassemt
system breakdown approach can be achieved using a system-mc
model is then constructed into as detailed a level as required.
traceable by the QFD-process, and the relationships between leve
modeling tool. In other words, the generic CBA model, theoretic
evaluation in aggregation level or for item design evaluation in
complication, we did not attempt to solve it for optimization appr
example, the cost-benefit formulation is used to calculate a produc
decision-making approach to obtain a feasible solution (section 6.2.2).

...ue proposed

On the production planning with recycling/remanufacturing capacity: Considering production planning with CBA model application, the CBA model could be useful as a guide in company's constructing a production plan with recycling concerns, a practical production problem. In the example, we has also examine how environmental and recycling affect the product design by using CBA formulation in QFD-IECDM decision-making process. In our example, the production plans are clarified concerning recycling issues over the product's life cycle, after the product and process have been designed, the manufacturing can elegantly adapt to the ecological environment in terms of recycling options efforts. Again, we used formulation of CBA model, with the objective of maximizing the product's TLCV, for analyzing how recycling issues affects production planning. We also suggest to examine the ration of item number among reused, remanufactured, and disposed items towards the 'best' TLCV corresponding to a given particular product plan.

On formulation of QFD-based optimization problems: In this chapter, we mention that QFD-based optimal design approach can be the further study for detail ecodesign within IECDM methodology. A example was used to show how QFD-based optimization technique can be applied in redesign the speaker by considering environmental issues. We illustrated a way for dealing optimal design problem based on QFD-relationship matrix. Related works are referred to Appendix C for details.

CHAPTER 7

CLOSURE AND RECOMMENDATIONS

We use 'closure' instead of 'conclusions' here to emphasize how research on the IECDM is a dynamic and continuing process by which new and old ideas/knowledge combine to provide new 'insights' and 'results.' 'Conclusions,' on the other hand, represent the final 'truth,' something that is not easily achieved in the kind of dynamic, flexible, and continuing process characteristic of the development of the IECDM methodology. The results of this research aim at stimulating designers to consider environmental criteria in the early stages of the product development cycle and at providing added knowledge for the development of IECDM within the ECDM domain.

The work reported in this dissertation focused on developing an applicable QFD-based IECDM methodology that can be incorporated into an integrated design decision-support (IDDS) framework for use in green product design and development. In this chapter we extract and summarize what we have learned from our investigations. Then, based on conclusions drawn from the hypothetical problem represented in Chapter 6, we identify the contributions of this research and evaluate our efforts; then we re-evaluate our objectives and research methods and, finally, recommend several opportunities for future research.

7.1. CLOSURE

In this dissertation, we have presented a QFD-based IECDM methodology, a mathematical CBA model, and an IDDS framework with a design-flow-chart application for incorporating environmental criteria into green product and process design. Roughly stated, our IECDM problem is defined as: given the customer and environmental requirements, develop a IECDM methodology for green product design that results in maximization of the product's total life-cycle value (TLCV). Initially, through investigation, we specified a clear ECDM domain within Industrial Ecology. Then, we proposed various state-of-the-art techniques that had been reported in the literature. After we defined our IECDM problem, we developed an integrated approach that led to a generic IECDM methodology for dealing with problems in the ECDM domain. Finally, for implementing the proposed IECDM methodology, we developed a tentative integrated design decision-support (IDDS) framework for long-term development.

7.1.1. Research Contributions

The overarching contribution of this dissertation is the introduction of an integrated approach for the development of eco-products and eco-manufacturing processes as well as demanufacturing within Industrial Ecology. This research proposes a novel approach to integrate environmental issues, performance criteria, economic concerns, and customer preferences in the concurrent product/process-design activities. The IECDM approach integrates a decision-analysis tool with a QFD-based design technique to improve decision-making in ecodesign. This IECDM goes beyond the current state of ECDM practice in the following ways:

- It considers problems in the ECDM domain through the life-cycle based system approach (i.e., system-oriented, life-cycle analysis, and closed-loop mode);
- It includes customer preferences and environmental requirements in product ecodesign;
- It maintains the highest quality design as defined by the customer and the QFD-team, while involving environmental impact considerations;
- It obtains not only an evaluation of a feasible design, but also a formal methodology for finding the 'best' product's TLCV through design decisions made over all life-cycle phases;
- It integrates individual methods for life-cycle synthesis, analysis, and evaluation to aid (eco)design decision-making throughout the product development cycle.

Main Contributions. This research produced a novel integrated approach including a generic IECDM based on the QFD decision-support framework. It also contains a mathematical CBA model, based on the LCC assumption, which is used at the design stage for design evaluation and production planning. This IECDM will support designer(s) in formulating and solving problems within the ECDM domain that involve environmental regulations and customers' preferences. Research reported in the literature has not attempted to merge the green design process with manufacturing/production and demanufacturing/recycling processes nor with different state-of-the-art techniques for concurrent (eco)design. This study is one of the first to integrate these concepts into the ECDM domain, both qualitatively and quantitatively, on a sound methodological basis.

We present a generic IECDM methodology that provides a structured engineering design procedure for green product development, so that the product is designed functionally, ecologically, and economically. On the basis of a well-structured QFD process, the IECDM methodology is feasible in both academic and industrial terms. Within the IECDM methodology, we adapt various design methods and engineering design methodologies in different stages of the product development cycle through a well-

defined product design evaluation and optimization procedure. This unique product design procedure bridges the gap between design evaluation concepts and optimization techniques.

We use the modeling methodology to formulate the concurrent IECDM problem together with recycling and LCA concerns. It enables the unstructured product design problem (with environmental issues) to be systematically arranged in a decision-making sequence and then grouped into a hierarchical design structure. The product design structure is presented in terms of attributes.

Although the use of design for recycling/remanufacturing has been advocated by other research, few have addressed the formulation of structured design issues and the integration of LCA information into product/process design activities. Thus, the analytical model developed in this research is unique. A unified approach is employed to formulate a structural framework for cost-benefit analysis among product design, manufacturing processes selection, and recycling determination at the design stage of the green product development process. In addition to the major contributions to the ECDM field cited above, equally important benefits to industry and to ECDM education can be derived from this research.

Benefits to Industry. Eco-competition is the goal of world-class manufacturers. A proper methodology should help managers and designers make better decisions for green product development. The purpose of QFD-IECDM development is to help a firm maintain competitiveness during green product/process evolution in the following possible ways:

(1) By providing a QFD-IECDM methodology for product/process (eco)design, so that designers will have concise guidelines for synthesizing a viable (eco)design that takes into account customers' preferences and environmental regulations.

(2) By applying a cost-benefit based model (CBA model), so that the firm can estimate the product's TLCV for use in analysis and evaluation, and can simultaneously consider the product's recycling/demanufacturing capacity and its environmental impacts.

(3) By using the fundamental IDDS framework, we believe it will be possible to develop a computer-aided tool or a knowledge-based support capability for a concurrent green design.

Allenby [1994b] argues that DFE should be regarded more as an approach than as an existing implemented system. However, the IECDM that has been developed herein is more than an approach because it can be implemented. It is a comprehensive and feasible methodology that will bridge the gap between industry and academia as both try to understand ongoing environmental, regulatory, and consumer preferences in addition to industrial behavior.

Benefits to Teaching. Universities have a unique role to play in influencing the evolution of industrial ecosystems through the ECDM paradigm in engineering systems design. This influence can be

achieved by showing how environmental consideration of key design features can be balanced with other design factors such as cost, functional performance, reliability, time, and quality. This research provides potential benefits for education of the next generation of engineers by incorporating environmental factors into engineering design-related curricula.

Once an IECDM has been developed, it can be easily translated into a structured topic that can be taught in the *applied system engineering* curricula, so that system engineering and design fundamentals are completely learned. A sample might be:

(1) Design For Functionality: fundamentals and essentials of systems engineering and concurrent engineering, life-cycle engineering and process/product design, design evaluation models, cost-effectiveness method, design for X.

(2) Paradigm of ECDM and DFE: IECDM system framework, design for disassembly and disassembly sequences, enhanced life-cycle economic models and LCCA, material recovery models, computer-aided DFE of product/process based on CAE/CAD.

(3) Life-Cycle Analysis and Life-Cycle Assessment: industrial ecology as a system, energy consumption, material flow cycles, product useful life cycle, process and product design.

(4) Environmentally Conscious Design and Manufacturing: material substitutes in product design, material environmental compatibility, process/product measurement ecounits, process/product evaluation models, quantitative measurement for IECDM.

(5) QFD-based IECDM methodology: QFD applications, QFD and process/product design, formulation of QFD-based optimization problems, QFD-based IECDM methodology for design.

(6) Modeling Methodology for IECDM Problems: Basic optimization and modeling techniques, cost-benefit analysis model, other costing methods, ABC model.

The above list should be covered in the IECDM engineering curriculum to help students get the whole idea in life-cycle system engineering and concurrent engineering. Further specific topics related to the field should be updated as new technology is developed and as real cases are studied. Finally, environmental considerations must be incorporated into the curricula of other disciplines, such as design, business, law, economics, and public policy.

Engineers need a good understanding of the interaction between the technological, economic, ecological, and functional systems at various scales of industrial organization. This proposed module aims to ensure that all engineering students, through the well-designed IECDM engineering curriculum, are aware of the LCA methodology in the industrial ecosystem, the environmental effects (or constraints) in product design and in its manufacturing process with demanufacturing capacity, the LCCA of incorporating environmental effects in product/processes design, and how to synthesize an ecodesign that includes an evaluation of environmental impact of the product during its life cycle(s).

7.1.2. Evaluating the Dissertation Objectives

The critical evaluation of this research must be an internalization of the relationship(s) between the problem setting and related research issues and the present efforts. Therefore, we recapitulate our objectives as outlined in Chapter 1 followed by the corresponding evaluation.

Objective (1): Investigate various approaches and methodologies for development of the IECDM system:

- Investigate various aspects that contribute to environmentally sound industrial development and to the development of IECDM methodology;
- Contribute to the paradigm of environmentally-conscious industrial development, i.e. environmental friendliness; and
- Gain insight into the engineering process of IECDM through methodological approaches.

Evaluation: Through investigation on industrial ecology and ECDM as well as related state-of-the-art techniques applied to implement the ECDM, as presented in Chapter 2, various insights are obtained that help in development of IECDM methodology based on 'integration-emphasized' and 'life-cycle based system' approaches.

Objective (2): Identify and define the characteristics of the IECDM system, with specific reference to the role of environmentally-oriented product design and development:

- Define and describe what is meant by "Integrated" and "Life Cycle."
- List and identify desirable features of the IECDM system.

Evaluation: We have explicitly stated that the IECDM is characterized not only by the increment of environmental considerations but also by extending the life cycle (see Chapter 3). The IECDM approach is based on Life-Cycle Design and a Concurrent Engineering platform for designing products and processes simultaneously while including environmental concerns as a part of the design requirements. We can claim that our methodology can be, and should be, used in Life-Cycle Design or/and Design for Environment within Concurrent Engineering.

However, there also are several requirements (limitations) for developing an effective IECDM methodology. These are:

- Cost information (and cost coefficients), especially environmental costs, must be obtainable.
- Environment-related data (such as inputs and outputs of processes) must be given for use in the LCA.

- The product-related attributes, identified by the QFD-process, must be designed hierarchically so that design changes can easily be made and the attributes tree can work on different levels of complexity, accuracy, and user friendliness.
- The QFD-based IECDM methodology should be constructed as a robust design procedure while incorporating environmental requirements for any related problems in the ECDM domain.
- The CBA model must be easy to extend in order to deal with more detailed design-related activities even though the interrelationships between modules of design, manufacturing, operation, and demanufacturing still exist through the product's life cycle.

The practical aspect of our research is related to fundamental principles of methodological development. According to Allenby [1994b], five fundamental principles upon which we must depend, in development of IECDM methodology, are:

- Methodology should be comprehensive and system-based.
- Methodology should be multi-disciplinary and include technical, legal, economic, political, and cultural dimensions to the maximum extent possible.
- Mitigation of environmental perturbations can be achieved by focusing on technology, and developing policies and practices that encourage the evolution of environmentally preferable process and product technologies.
- Economic actors, including private firms, must internalize environmental considerations and constraints to the extent possible, given existing exogenous constraints on firm behavior (e.g., laws such as the antitrust statutes or the prices of inputs and competitive products).
- Policies and regulations must reflect the need for experimentation and research as different paths and methodologies are tried.

All of the above are encompassed in development of the IECDM methodology.

Objective (3): Identify and define the integration issues to be considered in the development of the IECDM system:

- Review the various current approaches and methods that contribute to ECDM.
- Select and integrate proven methodologies essential to the development of the IECDM system.
- Identify the ecoproduct realization system and its boundary.

Evaluation: All individual methodologies incorporated in the QFD-based IECDM are based on their relationships, which we can assess and, most of all, trace to determine if an ecoproduct has been designed consistently with its manufacturing and demanufacturing processes. The CBA model can reflect the interrelationships (see Chapters 2 and 5). The question is, are the CBA model and the environment-related costs accurate enough to support (eco)design decisions ?. Although this question is hard to

answer, it is extensible to the desired detail by representing the CBA model as an IDFE0 modeling system, which, in turn, can be broken down to the detailed level necessary.

Objective (4): Develop the QFD-based IECDM system that is constituted by individual methodologies.

- Extend the QFD-based methodology to identify attributes and alternatives for a product and its related processes.
- Identify the QFD-based IECDM process for a design decision-analysis problem through a well-structured design flow chart.

Evaluation: QFD-based IECDM methodology, as discussed in Chapter 4, when viewed as a tool for solving any problem in the ECDM domain, provides not only a qualitative approach but also a quantitative sensitivity analysis that depends on characteristics of the attributes identified in the QFD-matrix. Operationally, the QFD-based IECDM design is a three-phase procedure: A ranking process has been employed for selecting design alternatives at the conceptual design phase. Next, a comprehensive preliminary design flow chart, based on the QFD mechanism together with the LCA, MCDM, and CBA model, is used for design of product and process. Finally, for the purpose of continuous improvement within green issues or redesign issues, a QFD-based optimization approach has been integrated into the methodology for formulating optimal design problems systematically and for finding optimal target values of the engineering design characteristics.

Objective (5): Formulate the optimization-based Cost-Benefit Assessment model:

- Identify the cost components and their relationships in a product realization system.
- Formulate a mathematical CBA model that relies on the information generated by the QFD matrix and LCA for design-evaluation in the QFD-based IECDM process.

Evaluation: Regarding of the CBA model (see Chapter 5), where life-cycle costing is incorporated, there are two types of decisions: decision variables regarding product design and process selections and decision variables representing the final production and recycling quantities of product and items. The objective function for the mathematical CBA model is to maximize the present-worth of the product's TLCV; that is, the sum of the product's selling and recycling revenues minus the costs for current manufacturing and future demanufacturing.

Solution of the CBA model, from the optimization perspective, may or may not be obtained directly, depending on problem size. The parameters most likely to affect problem size are the product complexity, the number of product types produced, the number of product and process alternatives, the number of time periods, and the number of recycling option combinations. Nevertheless, solution of the model should be a nearly optimal matching of product design and process solution as well as recycling

options and their respective quantities, including costly environmental impacts and imposed environmental regulations. Collection of actual data for the CBA model is important to validate that the model provides meaningful analyses for the design-team, manufacturing engineers, and managers. However, due to the lack of actual data and the large scale of the problem, the optimization issue of the CBA model is beyond the scope of this research. Instead of optimization, we have developed a design-decision process for solving a problem that has been illustrated by an example in Chapter 6.

The QFD-based IECDM methodology has been developed for solving any problem (other than the CBA model) in the ECDM domain with minor modifications in format. When all possible customer requirements and environmental requirements are considered, the QFD-process may become time-consuming. But, there is no other alternative that can successfully transfer every requirement into quantifiable design characteristics. The benefit gained from this research is that we now have a QFD-IECDM methodology that helps green product development while meeting ultimate user requirements.

Objective (6): Illustrate the QFD-based IECDM as well as the CBA model through a hypothetical example. The example will demonstrate the applicability of the IECDM methodology in solving problems in the ECDM domain.

Evaluation: On conclusions drawn from the hypothetical problem 'car horn design' (see Chapter 6), we have illustrated the applicability of the QFD-based IECDM through product design, process selection, total life-cycle value evaluation, and production planning, considering environmental and recycling issues simultaneously to meet the customer's requirements and environmental regulations. This hypothetical illustration shows the applicability of QFD-IECDM methodology.

Through the critical evaluation above, we believe that our methodology derived from environmentally-oriented product design and development has encompassed the desired results (objectives), and our work has met the expected objectives. The potential benefits of using QFD-based methodology in an ecoproduct development system include versatility, tractability, flexibility, acceptability, and the ability to assess the cost-benefits of product design alternatives.

In summary, this research presents an integrated modeling approach to facilitate decision making in green product design and development, which captures not only manufacturing/demanufacturing capacities but also environmental impacts over time for green product design and process selection as well as determination of recycling options. Through accomplishing the research tasks and achieving the research objectives, this study will contribute towards the goals of practicable applications in industry and theoretical research in academia. Although the IECDM methodology is developed only in generic form

here, it can be applied to a specific industry or ECDM problem through further refinement and modification.

In addressing problems in the ECDM domain, each firm is unique; each organization faces its own environmental challenge. ECDM problems should be treated with applications-oriented ecoproduct design and development techniques. A real case study is necessary in any further study. To a large extent, implementation of a successful QFD-based IECDM methodology significantly depends on the nature and format of the data that are available and acquired to support it. Nevertheless, the proposed IECDM paves the way for restructuring green product design and development for any environmentally-conscious firm facing its own problems in the ECDM domain. Its own greening strategy will have to be adapted when it attempts to produce an environmentally sound product.

7.2. RECOMMENDATIONS

The primary aim of this research is to gain insight into the design paradigm for use in the ECDM domain within an industrial ecosystem. In completing this study and attaining the research objectives, the foundation for a focused area of research in the QFD-IECDM system has been established. We have addressed future work in all the chapters presenting our research, and now we summarize and identify a number of future research opportunities that can be expanded. These are:

(1) A theoretically sound QFD-IECDM model verification/validation method is not currently available (especially a QFD-based optimization model) due to the nature of the QFD process. The example in Chapter 6 is used to demonstrate the developed QFD-IECDM approach. An example simply shows how the novel QFD-IECDM works and exhibits the differences between solutions based on different approaches. An investigation of how to incorporate systematic methods to validate solutions to the QFD-IECDM with different QFD and DFE approaches needs to be conducted.

(2) The methodologies developed in this research addressed IECDM in the design stage, but they are generic in nature, and could be applied to any product domain, or to other stages of the product development cycle. However, the quantitative measurement of environmental effectiveness may vary for different applications. Future work could apply the procedure to actual industrial products, but would require the collection of data from a specific industry that will support the environmental impact assessment for each design alternative through the LCA methodology. The ultimate goal would be to establish an environmental information system and a product

(re)configuration system for a variety of product domains. A short-term research project could be the development of an ecological information system that addresses the following issues:

- the integration of environmental factors into the increasingly constrained process of engineering design for different industries;
- the role of knowledge-based systems for supporting IECDM;
- a measurement system of environmental impacts (greenness merit) for process design and selection (see Appendix B).
- a specific LCA system to support IECDM decision-making for different industries (see Appendix A for reference).

(3) On the basis of this well-constructed environmental information system, further research could explore the possibility of expanding the existing CAD/CAM and CAE systems associated with IECDM methodology (see Section 3.2.3 for details). This integrated CAD/CAM and IECDM system would aim to improve the effectiveness and efficiency of DFE, such as design for recycling (DFR) and design for disassembly (DFD). Eventually, the green techniques of recycling and disassembly processes should be considered simultaneously in order to avoid secondary environmental impact to society. In addition, computer-aided and automation techniques must be investigated for design of eco-factory and disassembly automation with the CIM/FMS applications in practice.

(4) In this research, cost-benefit analysis model is emphasized in order to integrate the IECDM concept with economic (e.g., LCCA) and ecological factors (e.g., LCA) in the product development cycle to meet customers' preferences and environmental regulations. This study has presented a mathematical Cost-Benefit Analysis (CBA) model, which is a nonlinear integer programming problem with a single objective function. The complexity of the CBA model and lack of realistic data make it impossible to find an appropriate method for achieving an optimum solution at this research stage. Optimization techniques of the product/processes ecodesign, with respect to economic factors, was not a central research focus in this study. However, the CBA model has already captured the features of environmental and demanufacturing concerns, and it has been illustrated by an example (Chapter 6). Future study could look into the application of optimization techniques that are capable of new algorithm development to get a real optimization solution.

(5) In addition to the proposed CBA model, from a mathematical programming viewpoint, the model can be expanded to be a multi-objective analysis model, as expected in the IECDM methodology (Chapter 4). Thus, in addition to the objective of total life-cycle value, other objectives could be constructed for observing the behavior of a more complex product-development system. Possible extensions of the CBA model with other objectives are proposed in Appendix E.

(6) From the "best" design viewpoint, the proposed integrated approach makes our QFD-based IECDM process more valuable to industry by quantifying customer and environmental information. The proposed IECDM approach provides an evaluation-optimization procedure for determining the best design of product-related attributes and their associated processes by using the proposed CAB model at the system level. Furthermore, the QFD-based optimization approach may be applied for formulating optimal design problems (see Appendix C) in practice. For detailed optimal product-design, we can use the QFD-based IECDM process to construct an optimal design model in which we use the Design Evaluation Function (DEF) or the multi-attribute utilization function or another appropriate function to express the relationships of decision variables and attributes.

Operationally, for determination of the "best" target values in the QFD-matrix, the DEF derived by the QFD-based optimization approach represents design attributes (design-dependent and design-independent parameters) and the relations between them. The rows of the QFD-relationship matrix defining the relationship between design-attributes and design-variables form constraints on the objective function and define feasible design alternatives in design space. After this optimal design model has been constructed, a formal optimization-procedure can be performed to identify the design-attributes (or engineering characteristics) and their associated parameters (or target values). As defined, the design-attributes include all possible product-related attributes. Therefore, such an optimal-design approach may be used to determine the 'best' target values of the design characteristics.

(7) Disassembly of the existing product and redesigning it for the environment are also important problems in the ECDM domain. We recommend exploring the Reverse Engineering process for dealing with the problems related to disassembly sequence and depth and to product redesign to meet environmental requirements. In addition, Value Engineering (VE) may be incorporated into IECDM, starting from product (re)design, for prevention of environmental costs and a costly product. The RE approach with VE application in the IECDM is briefly discussed in Appendix F.

(8) In addition to the proposed IDDS approach (see section 6.1.3 and Figure 6.4), a Knowledge-based support system is another means toward an IECDM methodology, in which a blackboard technique may be applied. This concept is explained as follows.

The QFD model is well suited for concurrent engineering in which the marketing staffs, product designers, and process engineers participate in a team effort using cross-functional and interdisciplinary approaches. As defined, concurrent engineering is the integrated infrastructure of our QFD-based IECDM methodology in which different methods are employed based on common information. This is the way we incorporate environmental issues in concurrent design. In addition, efforts are being continuously made to develop computational frameworks to support concurrent engineering, such as knowledge-based support for concurrent design. As a matter of fact, applying IDEF3 models might be a way to define a knowledge-based system in the early stages of developing a knowledge-based IECDM (KB-IECDM), once the QFD-based IECDM process represented by a general-purpose description of processes (see Figure 7.1) has been defined.

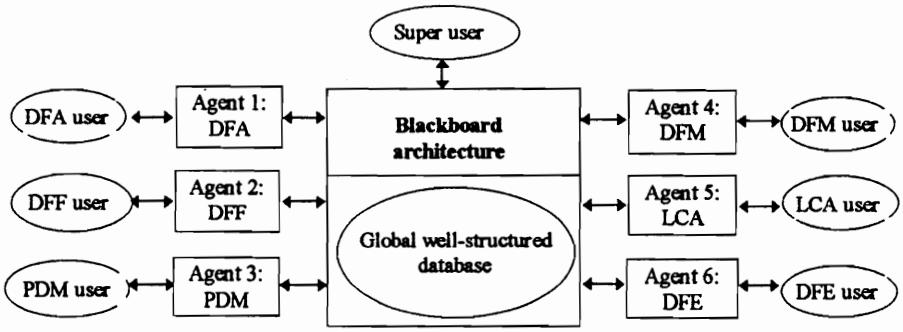


Figure 7.1. Integration through blackboard and interactions

These attempts lead to application of blackboard techniques for integration of systems of Design For Assembly (DFA), Design For Functionality (DFF), Design For Manufacturing (DFM), Life-Cycle Assessment (LCA), Product Data Module (PDM), and Design For Environment (DFE) through shared memory. Consequently, blackboard architecture is likely to be useful in modeling and supporting concurrent design for relatively routine artifacts, in which sufficient control knowledge may be defined to establish hierarchical (or non-hierarchical) control (decision making) of the design process. This benefit may lead to construction of a blackboard environment for green product design.

(9) Last but not least for future research, consider the environmental cost in industrial ecology: Activity-Based Costing (ABC) is gaining ground rapidly over conventional costing systems. The ABC approach has the potential for efficient and effective cost assessment in the context of designing for life-cycle environmental impact. It is recognized that the process (diagram) for LCA also illustrates generic high-level life-cycle activities for a product. From the LCA diagram we can immediately identify the highest level of life-cycle activities followed by the ABC approach to estimate specific environment-related costs.

These life-cycle activities can be broken down into the low-level activities that are only valid for the specific case under investigation. Further, if the inputs (raw materials and energy) and outputs (waste emissions and waste) for each activity are considered, an Activity-based environmental impacts analysis may be developed. In other words, if the activities that impact the environment can be cost drivers, then ABC-based methods can be applied whenever the activities in the IECDM are described in sufficient detail to have cost drivers assigned. Thus, the crux in developing an ABC model is to identify the activities that will be present in the green product design and development cycle, including activities in the demanufacturing/recycling process of the returned product. Also, the environmental information system should contain accounting data, including environmental costs required for design decision-making.

Appendix A: Environmental databases and LCAs models overview

In industrial practice, the LCA methodology can be complex, time-consuming, and expensive. Thus, companies are reluctant to go through the LCA process unless there is an urgent need (e.g., if a product is threated by regulation or competition because of its perceived environmental impact). The purpose of this section, Appendix A, is to summarize the features of some available LCA software.

LCA methodology will increasingly be an acceptable and useful procedure for assessing the environmental impact caused by products and processes in industry. A critical issue for LCA is the need for accurate data, either local or global. Several approaches have been developed to make LCA more 'user-friendly'. These include eco-indicators (used in software models such as SimaPro) and qualitative (or semi-quantitative) matrix approaches. Table B lists some publications that contain LCA data. Once the LCA study has been carried out, resulting in environmental databases for all the stages of the complete cycle, including inputs and outputs, an Environmental Impact Assessment (EIA) may be utilized to assess the true cost of the product to the environment when integrating LCCA methodology. EIA may be seen as a separate discipline but it is an integral part of any LCA study. If possible, EIA, LCA, and LCCA should be integrated into a complete green design information/management system for evaluation of green design alternatives.

Many engineers agree that LCAs are useful for identifying opportunities for pollution prevention, resource conservation, and waste minimization; and LCAs should be integrated into ILECDM approach for environmentally-sound product development. However, without an agree-upon (or standard) approach, the results of the LCA method are not always consistent. The discrepancy can be traced largely to two factors: accounting methods in inventory analysis, and data collection when performing LCAs. For example, the study of different system boundaries defined by industrial ecologies may use various accounting methods. Data may be unobtainable because of their confidential nature or because of a lack of methodology or resources for obtaining data. With respect to data acquisition and treatment, Table A.1 gives an overview of the various tools and methods used worldwide in LCA studies of complex products.

Table A.1. Environmental databases and LCA models [Source: Holloway *et al.*, 1994; Alting and Legarth, 1995, etc.]

Database/LCA model (Developed by)	Data coverage	Use on complex products	Impact assessment	Features
Boustead Model (Boustead Consulting; UK)	General	Yes	No	It is essentially an inventory tool without an impact assessment feature. Database includes energy production scenarios, transport processes, and material processing for various organic and inorganic materials.
TEAM tool (Eco-bilan; French)	General	Yes	Yes	TEAM features both a database and an impact assessment function. The tool has been used on complex products.
EPS-tool (Ryding and Steen, Institute for Product Development; DK)	General	Yes	Yes	Computer-based LCA software using Environmental Priority Strategies (EPS). EPS is used to define indices from which the environmental impact of a product or system can be calculated and presented in a quantitative form. (Environmental Load Units-ELU).
PEMS (PIRA International; UK)	General	Yes	Yes	PEMS (PIRA Environmental Management System) is a spreadsheet-based LCA program. The model is intended for use by a range of companies and contains a large amount of data.
EcoAssessor (PIRA International; UK)	General	?	Yes	PIRA, on the basis of the PEMS tool, markets a less extensive tool, the EcoAssessor, for users wanting a simplified tool.
IDFA (Y. Virtanen)	Large system studies such as recycling, trade			Very large and comprehensive database. Operating under dBase IV data represent Western European averages in 1990. Features material manufacture, transport, and energy conversion.
LCA Inventory Tool (Rydberg and Svensson)	Packaging			Computer-based tools for formulation and calculation of product life-cycles. Only selected data included, but extra data may be purchased separately. Calculation achieved by construction of flowcharts.
PLA (Danish Technical University)	General			Lifeway software tool was developed as part of an educational programme. Intended for use by non-academics coorporating with external experts. Intended to be developed into a full-fledged expert system.
REPAQ (Franklin Associates, Ltd.; US)				REPAQ is a LCI software program. Products, processes and packaging can be evaluated with REPAQ (TM). Users may use its database and enter their own data through the custom materials feature. This feature allows entry of data for any process for which LCI data can be gathered.
EcoManagers (TM) (Franklin associates, US, and Pira International; UK)				EcoManager (TM) uses a software program developed by Pira International of the UK in combination with US life cycle inventory data from the Franflin Associates, Ltd. (FAL) database. Developed for use with Microsoft Excel (TM), EcoManager (TM) utilizes spreadsheets and program codes to guide the user through the construction of a LCI, access

				data from the database, perform file management functions, edit existing data and produce graphics and reports.
SimaPro (Guinèe *et al.*, Pré Consulting; NL)	General	Yes	Yes	Developed by Prè Consultants Ltd in the Netherlands, this is probably the most widely used LCA data model. Computer-based and helps designers compare different alternatives on an environmental basis. The database contains environmental data collected in Europe by several well known companies, most data are taken from BUWAL and Van den Burgh and Jurgens, which is reported and publicly available. Data can be copied or changed, and new data can be entered.
Matrix approach (AT&T; USA)	Semi-quantitative	Yes	No	Semi-quantitative tool is fast but crude, and largely relies on the direct subjective assessment of environmental severeness of product-related environmental parameters. It provides a starting point for environmentally-conscious product development, but does not allow for the more complex design of product life cycle.
Pre-LCA tool (Battelle/Digital; USA)	Semi-quantitative	Yes	No	The same features as the Matrix approach; it applies a score system to quantify key life cycle parameters.

(For more detailed information on LCAs , refer to "LCA Software Buyers' Guide," 1994, Atlantic Consulting, 15 Whitehall Park, GB-London N19 3TS (Fax: +44-71-2810966)).

Appendix B: An Approach on the Product Greenness Merit

Attempts to generate the ILECDM approach for use in green engineering, which includes environmental, economical, mechanic, and other design considerations, run aground when we try conform ILECDM with the requirements of quantitative measurement. In keeping with principles of QFD in the ILECDM approach, we present a way to develop a measurable set of metrics characterizing environmental, economic and functional factors in green product design. The purpose of this appendix B is to answer the following question:

What are efficient and effective metrics to quantify and enhance the ILECDM approach for engineering-system design in industrial ecology?

In this appendix B, a set of environmental factors generated from each different industry is aggregated into a alternative set of unified units that indicate the level of environmental concern occasioned by choosing one alternative instead of another, i.e., *greenness*. In addition, life cycle cost assessment is introduced to illustrate how environmental issues affect manufacturing economics. Briefly, this study develops a quantitative-measurement system for evaluation of the effectiveness of the ILECDM approach in green engineering systems. In other words, the ultimate purpose of this appendix is to explore the essential performance quantitative measurements and the idea of ecounits as indicators of environmental impacts caused by products and processes in different industries.

B.1. Development of a Product's Performance Metrics

Once the teams of eco-product and eco-manufacturing development have become familiar with the QFD-based ILECDM methodology, they will incorporate questions about product requirements and environmental concerns into discussions with potential customers (internal and external). On the basis of this assessment of customer needs and competitive, regulator and internal issues, the eco-design team will establish the top priority product-performance/ecological issues and record (quantitatively and qualitatively) these issues into appropriate elements within the DFX matrix (for system performance issues) and the DFE matrix (for environmental issues). In this study, these two matrices are discussed in general terms.

Systems Parameter Dimensions -DFX matrix. Traditionally, the system (eco-product or eco-manufacturing) performance may contribute to the environmental impacts. In the design of manufacturing systems, process designers are concerned with the parameters "quality" and "productivity", from which we derive another parameter, "merit index".

Quality of system performance is measured by Mean Time Between Failures (MTBF), where the Time Between Failures (TBF) is the period between consecutive failures during which the equipment unit redresses its useful service. For a given equipment unit with an ID#, the quality of performance is denoted by: $\sigma_{Te\#}$. Productivity of system performance is measured by the Mean time the maintainer takes to repair a unit equipment, Mean Time To repair (MTTR). For a maintainer with an ID#, the productivity of performance is denoted by: $\sigma_{tm\#}$. Merit Index (N), defined as the ratio of quality of performance to productivity of performance, is then a measure of an overall performance "Quality". These parameters are summarized in the Table B.1 as an example.

Table B.1. Quality and productivity attributes

units / parameters	Equipment (e)	Maintenance (m)	Shop (s)	Defect (d)
MTBF (T) (quality)	σ_{Te} (equip. quality)	σ_{Tm} (Maint. quality)	σ_{Ts} (Shop quality)	σ_{Td} (Def. quality)
MTTR (t) (productivity)	σ_{te} (Maintainability)	σ_{tm} (Maint.-Productivity)	σ_{ts} (Shop-productivity)	σ_{td} (Def.-productivity)
Merit Index (N)	$N_e = \frac{\sigma_{Te}}{\sigma_{te}}$	$N_m = \frac{\sigma_{Tm}}{\sigma_{tm}}$	$N_s = \frac{\sigma_{Ts}}{\sigma_{ts}}$	$N_d = \frac{\sigma_{Td}}{\sigma_{td}}$

Quality parameters ate limited only to the following domains: quality of performance (T), productivity of performance (t), and merit index (N). It is noted that: Each of the above domain spaces is distributed among any of the following: equipment performance (e), maintenance performance (m), and defect performance (d); each of the above plane spaces is further distributed between any of the following sub-planes: equipment performance (e#), maintenance performance (m#), and defect performance (d#). It is also to be noted that at sub-plane level, performance pertains to that of the equipment unit, or the individual maintenance or defect.

When the end-of-life value of the product is considered, these performance attributes can be expressed as utility functions or loss functions. Consequently, the multiattribute-utility function approach and the time-variable loss function approach are used for evaluation of the product's end-of-life value.

Representation of Environmental Loads via the Environmental Profile. The environmental (loads) profile should be involved in green design methodology. As discussed in Chapter 3, an environmental profile is constructed for use as one of the measurements in green-design evaluation and alternatives selection. In such an approach, ecodesign displays described by the energy profile and the durable products profile may be merged by one environmental load profile that becomes one critical criteria (measure) for evaluating alternative product design and process selection. Basically, the

environmental profile is the culmination of environmental factors caused in the process. In order to accurately account for these environmental factors in a design process, it is necessary to incorporate elements from LCA methodology in a green design methodology (such as the ILECDM methodology). However, in a practical design problem, the environmental factors are unknown at the early stage of a particular product design. Therefore, a substitution method is needed to explore the environmental impact of the product being designed at the early development stage. To this point, the concept of greenness merit is proposed as follows.

The Development of a Product-Greenness Merit Function. In the context of green-design and LCA, detailed information on subassemblies, materials used, and byproducts generated by the processes is required. However, in the early design stage, the detailed LCA process can not be performed. A major difficulty in performing a detailed greenness evaluation is the lack of environment-related information on many of the subassemblies in use at the early design stage. Here, the product's greenness considers all environmental factors of processes that produce the particular product. Therefore, we propose a *greenness-merit function* as one measure of products without using detailed LCA methodology. This greenness-merit function provides a way to assess a product's greenness rapidly.

The 'greenness' score of merit of a product is defined as the cumulative 'greenness' score of merit of the subassemblies and processes that make up the product. A product's greenness-merit function can be expressed as

$$MF_{\text{product greenness}} = 1 - \sum_{q=1}^{Q} m_q \cdot w_q \tag{B.1}$$

Where w_q is the normalized weighting of items q with a set of design attributes. The index q denotes the number of items in a product. For the example in Chapter 6, q denotes 'tape', 'amplifier', and 'speaker' in the 'tape-driven-horn'. m_q is the environmental-impact score of greenness-merit for items q, which is obviously a function of environmental-factors (pollution elements in the process), $\mu_{q,k}$, that is

$$m_q = f(\mu_{q,k}) \tag{B.2}$$

Where $\mu_{q,k}$ denotes environmental factors such as energy consumption, air emissions, liquid discharge, solid waste, and so forth. This function depends on the processes model (layout) used to process the particular subassembly (or attribute). Once this function is modeled, the product's greenness is obtained. For example, if the process is modeled sequentially, the product's greenness-merit function can be defined as

$$MF_{product\ greenness} = 1 - \sum_{q=1}^{Q} m_q \cdot w_q = 1 - \sum_{q=1}^{Q} w_j \cdot f(\mu_{q,k}) \qquad \text{(B.3)}$$

The product's greenness is a useful measure in selecting product alternatives for environmental purposes. However, this greenness-merit function approach requires further research that is beyond the scope of this research. Nevertheless, *greenness* should be one measure for product design. Consequently, we need to define a standard to measure 'greenness', an ecounit, for use by different industries and countries. To this point, the matrix form is still suggested.

Environmental-Factors Dimensions - DFE matrix. As discussed in the previous section, product-greenness is defined as a function of environmental-factors within the process or process model. In merit function development, a large number of parameters is needed to describe fully the energy and raw materials requirements of any industrial system, as well as the solid waste emissions and emissions into air and water. It is tempting to seek ways of combining the data to reduce the number of parameters in a set of ecounits. For example, by combining all energy sources into a single gross energy requirement or by combining air and water emissions into critical volumes. Nevertheless, this variety of environmental parameters may be considered in matrices through all life-cycle aspects, as shown in Table B.2, which lists life cycle stages on the horizontal axis and environmental-factors categories on the vertical axis. Each element should be carefully described for the different industrial categories and applications. Based on these pollution-elements definitions, each high priority issue may fit into one or more elements within the matrix.

Table B.2. Environmental factors (or pollution attributes) in a product's life cycle

process-steps / environmental factors	Material extraction (e)	Manufacture (m)	Packing (p)	Distribution (d)	Utilization (u)	Retirement (s)	Recycle (r)
Energy consumption (E)	μ_{Ee}	μ_{Em}	μ_{Ep}	μ_{Ed}	μ_{Eu}	μ_{Es}	μ_{Er}
Material consumption (M)	μ_{Me}	μ_{Mm}	μ_{Mp}	μ_{Md}	μ_{Mu}	μ_{Ms}	μ_{Mr}
Air emissions (A)	μ_{Ae}	μ_{Am}	μ_{Ap}	μ_{Ad}	μ_{Au}	μ_{As}	μ_{Ar}
Liquid discharge (L)	μ_{Le}	μ_{Lm}	μ_{Lp}	μ_{Ld}	μ_{Lu}	μ_{Ls}	μ_{Lr}
Solid wastes (S)	μ_{Se}	μ_{Sm}	μ_{Sp}	μ_{Sd}	μ_{Su}	μ_{Ss}	μ_{Sr}
Health, Safety & Ergonomic (H)	μ_{He}	μ_{Hm}	μ_{Hp}	μ_{Hd}	μ_{Hu}	μ_{Hs}	μ_{Hr}
Merit index (M)	M_e	M_m	M_p	M_d	M_u	M_s	M_r

For practice, environmental impact control parameters, which are manageable, are limited to the following domains: energy consumption (E); material consumption (W); air emission (A); water pollution (P); solid waste (S); and health, safety & ergonomics (H). Each of the above domain spaces is distributed through the product's life cycle: material extraction (e); manufacture (m); packing (p); distribution (d); use and service (u); disposal (s); and recycling (r). The "Merit index" (M) of environmental performance is measured by the parameters that have contributed to environmental impacts. It is noted that each merit index of environment performance is a function of selected parameter domains, but not necessarily of all of them. These parameters are summarized in Table B.2. Note that, by definition, the health/safety/ergonomic factor is generally not considered in ECDM.

As a general function, the environmental-factors (attributes) are expressed as:

$$\mu_{q,k} = \phi(m_1, \ldots, m_j) \tag{B.4}$$

where $\phi(\ )$ is a weighting-factor function for the byproducts m_1, m_2,...,m_j for a process step k. The process steps may include reuse, recycle, recovery, and disposal, each step generating a byproduct that has impact on the environment. Therefore, the product-greenness merit id defined as

$$MF_{\text{product greenness}} = 1 - \sum_{q=1}^{Q} w_j \cdot f(\mu_{q,k_1}, \mu_{q,k_2}, \ldots, \mu_{q,k_n}) \tag{B.5}$$

where k_n are all the process-steps that process an item q. In green-design evaluation, the product alternative with the largest greenness score is selected. When product development goes to the production/construction phase, we can check the actual environmental profile with the model expressed by equation (B.5). Redesign may be performed if necessary to continuously reduce environmental impacts caused by product production. Related to the CBA model proposed in Chapter 5, the environmental costs in the model may be replaced as a cost function of greenness-merit.

B.2. The Ecounits Approach with Product-greenness Merit Application.

In practice, environmental impact in the field of ECDM can focus on the following environmental loading (burden) subjects: pollution, material, and energy, without considering the impact on human health and safety. From a measurement viewpoint, a method is needed to compare the pollution created, the energy used, and the solid waste generated by different products/materials in processes during all stages of their cradle-to-grave life cycle. Because the impacts by a manufacturing process may take several forms for different area (e.g., region, state, and nation), we allow for individual

consideration of each of these consequences, called "*ecounit effects.*" Summing the value of each ecounit effect yields the "*environmental loading index* (ELI)" in units of environmental load (ELU) per unit of material consumed or processed, for example, ELU/Kg, where ELU can be a unit of pollution, material, or energy. Since these ecounit effects were specified according to their relevance to the "burden" subjects, the ELI represents the total environmental loads (or burden) of the process in the field of ECDM. Since environmental regulation in terms of the "ecounit effects" may differ from area to area, a set of "*ecounits*" corresponding to the "ecounit effects" need to de defined. For example, the ecounit of energy for a specific area can be derived for the ecounit effect of energy used in the process, thus

$$\text{Ecounit})_{\text{Energy}} = \frac{\text{Energy used in processes (activities)}}{\text{Energy regulated on processes (activities)}} \times 100\%$$

As expected, ecounits are developed as an index of greenness or environmental compatibility of product and its processes from different areas. One may use "ecounits" as standard values that are structured by critical environment-related parameters or matrices and scaled between 0 and 1 with a green process, 1 being a perfect greenness, 0.5 being a average, and any other thing below 0.2 being poor and undesirable. In the more general form, the ecounit for the environmental load index for different industrial categories can be derived as:

$$\text{Ecounit})_{\substack{\text{Environmental load} \\ \text{for industrial categories}}} = \left[\frac{\text{Actual environmental loading effects}}{\left(\text{government allowance of environmental loads}\right)^{k}}\right] \cdot \begin{pmatrix} \text{ELU unit} \\ \text{conversion} \\ \text{constant} \end{pmatrix}$$

where the exponent k is in positive whole numbers to represent the strength of impact of environmental legislation imposed by government. With ecounits' application in green design, we can make sure that the environmental criteria have the same basis for product design from area to area.

The work in this appendix provides a potential opportunity to develop a new measure, 'greenness' of product, that will be used in green engineering for design evaluation. Associated with 'greenness', a proper 'ecounit' needs to be developed as a basic reference in design evaluation in order to make sure that design specifications related to the environment are the same in different industries and countries. On this point, a further study is needed.

Appendix C: Formulation of a QFD-based Optimization Problem

In Appendix C, only a brief overview of QFD-based optimization is presented. Here, QFD-based optimization means the efforts on using QFD-based information to construct a mathematical model of the optimal design. Two model constructions are briefly reviewed as follows.

Multi-objective Approach with QFD-based Optimization. Before we show how QFD can be applied to solving an optimization problem, let us denote the following (see Figure C.1):

HH: A correlation matrix defined by HOWs versus HOWs

WH: A sensitivity matrix defined by WHATs versus HOWs

WW: An influence matrix defined by WHATs versus WHYs

HM: A feasibility matrix defined by HOWs versus HOW MUCHs.

In order to extract and interpret information useful for the optimization problem, Prasad [1994] has represented a general QFD-based optimization problem as a multi-objective programming formulation: Find a vector of design variables $v\{D$, where $v\equiv\{\text{HOWs}\}$, that minimizes the objective function $F_{pj}(v)$ where

$$F_{p,j}(v) = \sum_{i=1}^{i=n}\left[\left[wh_{i,j}\right]^T * \left\{ww_i\right\}_p\right] \tag{c.1}$$

or

$$\left\{F(v)\right\}_p = \left[WH\right]^T \left\{ww\right\}_p \tag{c.2}$$

where $i = 1,\ldots,n$; $j = 1,\ldots,m$, and p is a column index of the WH matrix, and satisfy the following constraint equations

$$\left\{v_j\right\} = \left[HH\right]\left\{v_i\right\} \tag{c.3}$$

$$hm_j^L < v_j < hm_j^U \tag{c.4}$$

or

$$\left\{hm^L\right\} < \left\{v\right\} < \left\{hm^U\right\} \tag{c.5}$$

In equations (c.1) to (c.5), the vectors $\{wh\}$ and $\{ww\}$ belong to the QFD/HoQ relational matrices, *WH* and *WW*, respectively. Lower and upper bounds vectors $\{hm^L\}$ and $\{hm^U\}$ belong to the QFD/HoQ *HM* matrix. It is noted that if some attributes (elements) in the matrix are expressed in linguistic form, the formulation may be expressed as a fuzzy multi-objective optimization problem [Rao, 1987].

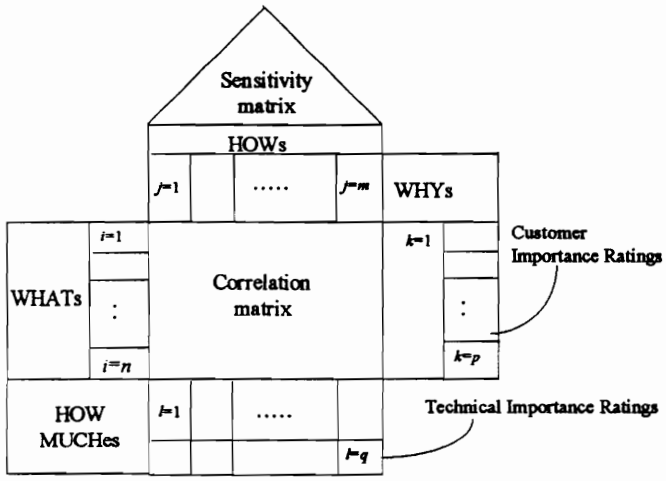


Figure C.1. House of Quality--terminology and conventions [Prasad, 1994].

Multi-attribute Utility Theory Approach with Optimal Design Application. A QFD-based optimization problem can be expressed with a multi-attribute theory application. This approach is to show how the multi-attribute theory is employed in the QFD-based optimal design application. One of the possible optimal design models in the design stage, based on the approach of multi-attribute utility function, has been proposed by Locascio and Thurston [1993 and 1994]. The optimal design problem is expressed as a form of mathematical program describing the multi-attribute quality of the design as

$$\underset{y \in R^m}{\textit{Maximize}} \quad Q[\mathbf{X}(\mathbf{Y})] = \frac{1}{K}\left\{\prod_{j=1}^{J}\left[K \cdot w_j \cdot U_j\left(x_j(\mathbf{Y})\right)+1\right]-1\right\} \tag{c.6}$$

$$\text{subject to} \quad x_j = g_j(y) \qquad \text{for } j = 1,2,...,J.$$

$$y_i^L \le y_i \le y_i^U \qquad \text{for } i = 1,2,...,J.$$

$$x_j^L \le x_j \le x_j^U \qquad \text{for } j = 1,2,...,J.$$

where

$Q[\mathbf{X}(\mathbf{Y})]$ = the total design quality.

$U[\mathbf{X}]$ = the overall utility of an alternative characterized by the vector of attributes $\mathbf{X} = \left(x_1(\mathbf{Y}), x_2(\mathbf{Y}), \ldots, x_n(\mathbf{Y})\right)$.

$x_j(\mathbf{Y})$ = the performance level of attribute i which is defined as a function of design decision variable $\mathbf{Y}$; in practice, the functional relationship of $x_j(\mathbf{Y})$ is determined by correlation (dependencies) in the QFD/HoQ matrix.

$U_j(x_j(\mathbf{Y}))$ = the single attribute utility function (or preference function) for attribute j that is defined as a function of design variables **Y**.

j = 1,2,..., J, attributes identified in the QFD-relationship matrix.

w_j = the single attribute scaling constant, which is obtained from the normalized importance of attributes in the QFD-process.

K = the normalizing constant, derived from

$$1 + K = \prod_{j=1}^{J}\left(1 + K \cdot w_j\right) \tag{c.7}$$

For manipulating uncertainty reflecting designer choice, variations of equation (c.6) can be expressed as

$$E[U_i(\mathbf{X})] = \frac{1}{K}\left\{\prod_{j=1}^{J}\left[K \cdot w_j \cdot E\left[U_j\left(x_j(\mathbf{Y})\right)\right] + 1\right] - 1\right\} \tag{c.8}$$

where

$$E[U_j] = \int_{x_j,\min}^{x_j,\max} U_j(x_j) \cdot f(x_j) dx_j \tag{c.9}$$

and

$$1 + K = \prod_{j=1}^{J}\left(1 + K \cdot w_j\right) \tag{c.10}$$

$E[U_i(\mathbf{X})]$ = the expected value of the overall utility $U_i(\mathbf{X})$ for the i^{th} alternative.

$E[U_j(x_j)]$ = the attribute utility functions which depend on the probability density functions $f(x_j)$ for the individual attributes.

$f(x_j)$ = the probability density functions.

The Goal Programming Model with QFD-based Optimization. In most practical QFD problems it may not be possible to attain all of the customer's needs or goals. Goal programming allows the achievement of most of these, taking into consideration their relative importance. Lee [1995] has proposed QFD-based optimization problems with a Goal Programming (GP) model. For developing the GP model, the objective function is represented by an achievement function in GP. The achievement function is minimized, term by term, in a lexicographic function. Consequently, the goal constraints are expressed by equations of the auxiliaries y_i^- and y_i^+. Then, for the QFD optimization problem, the GP model developed is

$$Min \quad F = \left\{\left(\sum d_i y_i^-\right), \left(y_b^+\right), \left(\sum -d_i y_i^+\right)\right\} \tag{c.11}$$

Subject to

$$r_{i,1}x_1 + r_{i,2}x_2 + \cdots + y_i^- - y_i^+ = g_i \quad i = 1,\ldots,m. \tag{c.12}$$

$$c_1x_1 + c_2x_2 + \cdots + c_nx_n - y_b^+ + y_b^- = B \tag{c.13}$$

$$M_j \geq x_j \geq 1 \qquad j = 1,\ldots,n. \tag{c.14}$$

$$y_i^+ \geq 0, \qquad y_i^- \geq 0 \qquad i = 1,\ldots,m. \tag{c.15}$$

where

y_i^+ represents the overachieved level of the i^{th} goal.

y_i^- represents the underachieved level of the i^{th} goal.

$r_{i,j}$ denotes correlation between customer needs and design characteristics in the HoQ matrix (after being normalized).

x_j denotes design characteristics of the 'HOWs' variables.

d_i denotes the relative importance of coefficients obtained by the neural network.

g_i denotes goals to meet customers requirements.

As the formulation shows, this model includes the goal constraints and a constraint representing the budget (or cost) goal, B. It also includes an upper limit on the percentage change of the characteristic values. In the achievement function, F, the first term insures that the under-achievements of the goals are minimized. The second term in the achievement function insures that the budget is not exceeded. If the budget goal, B, is more important than the customer needs goals, g_i, then the relative position of the first two terms in the achievement function should be transposed. The third term in the achievement function insures non-dominance of the solution if the optimum values of the first two terms are zero. The resulting solution from minimizing the achievement function F will provide the best compromise in the variables x_j values. Concerning environmental issues, we may add another goal in the achievement function and some constraints related to environmental impacts to this GP model approach to QFD-based optimization problems.

In summary, we may pay more attention to QFD-based optimization because it constructs an optimal (eco)design problem systematically using aggregated information in a QFD-matrix. Related work can be found in Locascio and Thurston [1993 and 1994]. Moreover, since uncertainty exists in the early (eco)design stage, the IECDM approach should consider the uncertainty issues. Related discussions of uncertainty considerations can be found in works by Otto and Antonsson [1993] and Tian *et al.* [1994], where uncertainty is considered in design problem with utility application.

Appendix D: Variety of Ranking Formulation

A common approach to design evaluation uses a weighted average of attribute levels. In Chapter 6, a ranking process for alternatives selection is introduced. A 'normalized importance rating' or 'weighting factor' is determined for each attribute, which is often thought of as its 'relative importance.' The performance levels and weighting factors are then combined to express overall value, as a 'merit function' in equation (d.1),

$$MF_i = \sum_{j=1}^{N} w_j \cdot \left(\frac{A_{i,j} - A_j^{\min}}{A_j^{\max} - A_j^{\min}} \right) \tag{d.1}$$

or

$$MF_i = \sum_{j=1}^{N} w_j \cdot \left(1 - \frac{A_{i,j} - A_j^{\min}}{A_j^{\max} - A_j^{\min}} \right) \tag{d.2}$$

Another form, 'figure of merit' is also used as

$$FOM_i = \left[MF_i = \sum_{j=1}^{N} w_j \cdot \left(\frac{A_{i,j} - A_j^{\min}}{A_j^{\max} - A_j^{\min}} \right) \right] \Big/ \sum_{j=1}^{N} w_j \tag{d.3}$$

or

$$FOM_i = \left[MF_i = \sum_{j=1}^{N} w_j \cdot \left(1 - \frac{A_{i,j} - A_j^{\min}}{A_j^{\max} - A_j^{\min}} \right) \right] \Big/ \sum_{j=1}^{N} w_j \tag{e.4}$$

where

- FOM_i = the figure of merit, a numerical value which represents the relative desirability of a design alternative i of several attributes $j = 1,...,N$.
- w_j = the weighting factor assigned to each attribute j.
- $A_{i,j}$ = the attribute level for a particular design alternative i.
- $A_j^{\max}$ = the maximum level of attribute j exhibited by all designs under consideration.
- $A_j^{\min}$ = the minimum level of attribute j exhibited by all designs under consideration.

The purpose of this Appendix D is to show how the features of attributes (such as dependencies and ambiguity) in the QFD-relationship matrix affect the ranking process used in the QFD-based ILECDM for alternatives selection.

D.1. Consideration of Dependencies Between Technical (Design) Characteristics

Considering the dependencies (the roof of the QFD/HoQ matrix) among technical characteristics, Lyman's [1990] normalization procedure (equation 6.1) can accommodate dependencies of design

requirements. To represent dependencies among design requirements (or attributes), the notation, $\gamma_{j,l}$, is introduced to denote elements of the correlation matrix (the roof of the HoQ), describing the correlation between design requirements j and l, that is,

$$\gamma_{j,l} \equiv \underline{\nu}_j \cdot \underline{\nu}_l (= \cos(\underline{\nu}_j, \underline{\nu}_l)) \tag{d.5}$$

Where $\{ \underline{\nu}_l \}$ is the unit vectors that span the design requirements (or attributes). Lyman then suggests a generalized normalization procedure of the form described by

$$w_{k,j}^{norm} = \frac{\sum_{l=1}^{N} \gamma_{l,j} \cdot R_{k,l}}{\sum_{j=1}^{N} \sum_{l=1}^{N} \gamma_{j,l} \cdot R_{k,j}} \tag{d.6}$$

A more detailed description of the generalization of Lyman's normalized weightings of design requirements is found elsewhere [Wasserman, 1993]. In our example, the normalization procedure (equation 6.1) is used; thus, we assume that all design requirements are independent. Nevertheless, if some of the design requirements are dependent, equation (d.6) may be used.

D.2. Application of Possibility Theory for Attributes in QFD

Considering the linguistic attributes in QFD/HoQ, Khoo and Ho [1996] presented an approach focused on the application of possibility theory and fuzzy arithmetic in QFD in order to address the ambiguity. A brief discussion follows.

Possibility theory focuses primarily on an impression (or preference) such as 'voice of the customer.' If d_k and $R_{k,j}$ denote the input and the coefficients respectively, a typical linear possibility system, Y_j, can be modeled as:

$$Y_j = d_1 \cdot R_{k,1} + d_2 \cdot R_{k,2} + \ldots + d_L \cdot R_{L,k}$$

or

$$Y_j = \sum_{k}^{L} d_k \cdot R_{k,j} \tag{d.7}$$

Fuzzy numbers, which can be considered as a possibility distribution, are used to describe the coefficients. That is

$$R_{k,j} = \left[\alpha_{1,kj}, \alpha_{2,kj} \right] \tag{d.8}$$

where $R_{k,j}$ is now a symmetrical triangular fuzzy number represented by the interval $\left[\alpha_{1,kj}, \alpha_{2,kj}\right]$.

Note that equation (d.7) closely resembles the individual rating equation (6.1) described in Chapter 6. In the case of a crisp linear possibility system, i.e., when the spread of the triangular fuzzy number is equal to zero and the inputs to the system are non-fuzzy, the equations become identical. Thus, the individual rating equation can be considered as a special case of equation (d.7). The advantage of adopting equation (d.7) in the ranking process lies in its ability to address both linguistic and crisp variables (attributes) at the same time. Therefore, the normalized technical importance rating (equation 6.1) can be generalized as:

$$w_j = \frac{\sum_{k=1}^{L} d_k \cdot R^n_{k,j}}{\sum_{j=1}^{N}\sum_{k=1}^{L} d_k \cdot R^n_{k,j}} \qquad \text{(d.9)}$$

and $$R^n_{k,j} = \frac{R_{k,j}}{\left\{\sum_{j=1}^{N} R_{k,j}\right\}}; \qquad R_{k,j} = \left[\alpha_{1,kj}, \alpha_{2,kj}\right]$$

where $R_{k,j}$ and d_k denote the relative importance of the j^{th} technical characteristic (attribute) with respect to the k^{th} customer need in the QFD-relationship matrix and the importance of the k^{th} customer need perceived by the customer, viz. customer rating , respectively. Further study in this rating work is needed for use in the QFD-based ILECDM process. Nevertheless, under the well-structured QFD-based ILECDM methodology, we should take into account the application of fuzzy theory, especially for description of environmental factors in the process.

D.3. Considering Uncertainty Issues in the Ranking Process

During the early stages of green-project initiation, the information available to a designer may be uncertain (vague or imprecise). However, the information obtained progressively along the design time line increases in quality. By representing the normalized attribute ratings and relative importance of the attributes as interval numbers, Reddy and Mistree [1992] incorporate uncertainty in the design selection (ranking process); thus, the merit function (equation 6.5) can be rewritten in interval notation as follows:

$$MF_i = \sum_{j=1}^{N} w_j \cdot \overline{R}_{i,j} \qquad i = 1,\ldots, M. \qquad \text{(d.10)}$$

where

MF_i is the merit function for the i^{th} alternative in interval form = $\left[MF_{1,i}, MF_{2,i}\right]$,

w_j is the relative importance of the j^{th} attribute in interval form = $\left[w_{1,j}, w_{2,j}\right]$, and

$\overline{R}_{i,j}$ is the normalized rating of the j^{th} attribute for the i^{th} alternative in interval form = $\left[\overline{R}_{1,ij}, \overline{R}_{2,ij}\right]$.

The rank for each alternative is now represented as an interval integer number:

$$RK_i = \left[RK_{1,i}, RK_{2,i}\right] \tag{d.11}$$

where $RK_{1,i}$ is the best possible rank for the i^{th} alternative, and $RK_{2,i}$ is the worst possible rank for the i^{th} alternative. Then equation (6.6) is rewritten as

$$RK_{1,i} = 1 + \sum_{p=1, p\neq i}^{N} \beta\left[MF_{1,p} - MF_{2,i}\right] \tag{d.12}$$

$$RK_{2,i} = 1 + \sum_{p=1, p\neq i}^{N} \beta\left[MF_{2,p} - MF_{1,i}\right] \tag{d.13}$$

Finally, to obtain the best possible rank for the i^{th} alternative, designers may compare the highest possible merit function value for the i^{th} alternative against the lowest possible merit function value for the other alternatives. To obtain the worst possible rank for the ith alternative designers may compare the lowest possible merit function value for the i^{th} alternative against the lowest possible merit function values for the other alternatives. Detailed discussion of interval arithmetic is referred to Reddy and Mistree [1992].

D.4. Considering Nonlinear Value of Attributes

The assumed linear relationship in equations (d.3) and (d.4) is not always valid. Thurston [1991] presented a nonlinear merit form. Assume modification of equation (d.3) to allow the possibility that the value derived from attributes level A_j is some nonlinear function $v_j(A_j)$; then the overall 'nonlinear merit' or *NLM* is expressed as

$$NLM = \sum_{i=1}^{N}\left[w_j \cdot v_j(A_j)\right] \Big/ \sum_{i=1}^{N} w_j \tag{d.14}$$

Since the *FOM* and *NLM* are based on different scales, it is inappropriate to compare the magnitude of values obtained from *FOM* and *NLM* equations for the same design alternative. Only the resulting ordinal ranking of design alternatives should be considered [Thurston, 1991].

Appendix E: Extension of the CBA Model

When CBA model is expressed as a mult-objective mathematical programming model, other objectives are incorporated. For example, one of the objectives for manufacturing system with recycling capacity under consideration is to maximize the recycling rate for each item recycled from the product (beyond an expected level). Now, let $R_{q,j}$ be the recycled rate, which is defined as the ratio of recycling item with attribute q to the quantity of that recycled item, for production of product j. The recycling quantity is the total quantity of items for reuse, for remanufacture, and for material recovery. The quantity of the reused part is $ux_{q,1}(t)$. Let the remanufacturing rate, $\lambda_{q,j}$ (q=1,...,Q; i = 1,2), be the remanufacturing items against the remanufacturable ones. The objective function in terms of recycling rate $R_{q,j}$ can be expressed as:

$$Maximize \quad R_{q,j} = \sum_{t=1}^{T} \left\{ ux_{q,j}(t) + \lambda_{q,1} \cdot ux_{q,1}(t) + \lambda_{q,2} \cdot rx_{q,2}(t) \right\} \Big/ \sum_{t=1}^{T} DX_q(t)$$

with recycling rate constraints as:

$$R_{q,j} \geq R_{q,0} \qquad q=1,..,Q$$

where $R_{q,0}$ is the specified expected level of the recycled item $q^{'}s$ recycling rate.

If quality attributes are specified in product design, the total utility of such quality attributes can be considered as the objective function for determining an appropriate product utilization life cycle, thus

$$Maximize \quad \left(\sum_{q \in Q} W_{q,j} \cdot A_{q,j} - P_{b,j}^{0} \right)(t) - L(A_{q,j}, TM_{q,j}, t)$$

Where $L(A_{q,j}, TM_{q,j}, t)$ is the loss function of a quality attribute, and $TM_{*,j,j}$ is the value target of utility of a quality attribute.

Another objective function, but not the last, may be related to the environmental impacts of the product during its life cycle due to energy consumption, mass material treatment, and waste generation, thus,

Minimize Pollutants = f(energy eco - vector, mass eco - vector, waste eco - vector)

In the formulation of objectives, appropriate constraints are required for specific problems in the ILECDM domain.

Appendix F: Reverse Engineering[1] Approach for Disassembly and Redesign-For Environment[2]

The purpose of this Appendix F, as part of a future study, is to show how reverse engineering can be explored for dealing with problems related to optimal disassembly sequence and depth, and to product redesign for meeting environmental requirements. In this study, a conceptual reverse engineering methodology is presented for use in redesign and disassembly problems. It is recognized that one of the most important advantages of the IECDM methodology is that it proposes rethinking of existing designs and new creativity.

F.1. Introduction

By coupling advances in reverse engineering with advances in the QFD-IECDM decisions process, we have the potential to revolutionize the use of the Reverse Engineering (RE) in problems related to product disassembly and Redesign-For-Environment, namely RE-IECDM. The significant difference between QFD-IECDM and RE-IECDM is that the latter identifies all product-related design characteristics (attributes) by performing the RE process on the existing product. If the identified design specifications cannot meet the customer's new needs and environmental requirements, then the product is redesigned.

We present an RE-IECDM process for use in redesign of the existing product to meet environmental requirements with disassembly application. This RE-IECDM methodology focuses on the process steps needed to disassemble/redesign and represent a current product-system. Contemporary tools and techniques in engineering design are utilized at each stage in the reverse engineering process to meet this goal. The methods used in the RE-IECDM process, viewed singularly, are no different than the methods used in other design methodologies. However, their specific use for product disassembly and representation provides a novel context for application in environmentally-conscious design.

F.2. Relating A Reverse Engineering Application to Disassembly Problem.

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[1] I am thankful to Dr. Kristin L. Wood of the University of Texas at Austin for his information and suggestions on Reverse Engineering approach.

[2] Here, the purpose of redesign is to upgrade an existing product to meet the goal of green product development, which is called Redesign-For-Environment. Redesign of an existing product is recognized as an effective way to make the existing product greener and more competitive. The redesign process also requires three iterative activities: design synthesis by reverse engineering, design analysis by idea generation and modeling, and design evaluation by prototype testing and simulation, in order to get concrete experience, abstract conceptualization, and active experimentation, respectively. In a practical redesign problem, disassembly comes before redesign. Redesign-For-Environment is a practical way to show how to adapt a given (existing) product to desired environmental requirements.

Disassembly of end-of-life products is considered as the process of developing a set of disassembly processes for a complex hardware system by an orderly decision-making for recycling of that product. These disassembly processes are being prepared by persons other than the original designers, without the benefit of any of the original assembly drawings or other documentation. Recycling decisions are made in the disassembly process step-by-step. Generally, these recycling decisions include:

- Reuse
- Not reuse, but reproduction (remanufacturing)
- Not reuse, not reproduction, but recovery materials
- Dump or landfill

Reverse Engineering is the process of developing a set of specifications (or generally *attributes*) for a complex hardware system by an orderly examination of specimens of that system, and by someone other than the original designers, primarily based upon analyzing and dimensioning a specimen or collection of specimens [Rekoff, 1985]. Documentation results from RE may be used for the class of problems known as redesign and disassembly. In a sense, the disassembly sequence is generated by the process of reverse engineering for redesign and/or recycling.

In undertaking a reverse engineering effort for the purpose of reproducing a hardware item, we present this example with the following objectives: (1) to show how reverse engineering is applied to a disassembly and redesign problem, and (2) to show how the RE approach with IECDM application can be used to redesign an existing product to meet environmental requirements. The ultimate goal, for further research, is to develop novel process-steps for use in generation of a disassembly sequence and redesign.

F.2. Factors in the Disassembly and Redesign Problem

The factors that are important in conducting a disassembly process are the distinctions between disassembly and traditional assembly design, considerations that influence the recycling decision-making, and things that are critical to the preparation of criteria.

The Feature of Hierarchical Structure. As discussed in Chapter 5, to unambiguously describe a complex product, one might describe a structural hierarchy of System, Subsystem, Assembly, Subassembly, Component, and Part. However, if one views the decomposition of a system (end-of-life product) into its constituent parts, the subsystems, the decomposition of a subsystem into assemblies, the decomposition of assemblies into subassemblies, and the decomposition of subassemblies into components as the same generic disassembly process, then one need only contemplate a two-level hierarchy to describe the disassembly process. The two level hierarchy is: *Item* and *Elements*, which is used to describe the

superior-subordinate relationship in unique terms. For example, system is the item that is a combination of subsystem elements, and component is a combination of part elements.

For the greatest benefits to the environment from disassembly for recycling and redesign, the disassembly/redesign process necessarily starts at a high level in the equipment hierarchy and progresses down to the lowest level until further decomposition is not possible without destroying the integrity of a part. Once the item is destroyed, it is a non-value-added disassembly activity from the reuse/remanufacturing viewpoint, while it may certainly be value-added for material-recovery activities. For example, an electronic product would not be decomposed beyond the diode, resistor, capacitor, or transistor level. However, one might be required to decompose a transformer to its core, wire, and insulation to acquire expected value-added elements.

The Features of Uncertainty and Fuzzy. A disassembly/redesign methodology with RE application is developed based on the premise that a complex hardware system can be characterized as a hierarchical structure. The key feature of this type of disassembly (for end-of-life products) problem is its uncertainty of process. When applied to a specific level in the hardware structural hierarchy, it is used to uncover the internal particulars of a specific item of that level in terms of the elements (that are subsets of that item) located in the immediately subordinate level and how those elements are interconnected with certain functions. Because this type of disassembly problem has uncertain criteria, the problem, separated from other optimization problems, has what is called *fuzziness*. In any realistic disassembly problem, the criteria for recycling decision-making is not precisely defined for each item decomposition step; the disassembly steps are fuzzy.

In this step, all possible disassembly sequences are generated through the RE process. However, this disassembly process captures information that contains linguistic information that may be difficult to quantify on a 1...5 or 1...10 linear scale. For example, the disassembled item may be described as pretty good, good, or bad, and the cost for disassembly operation may be expressed as high, medium, or low. Moreover, the disassembly level (depth) may be represented as fuzzy function. The criteria for determining the 'best' disassembly sequence or redesign relative importance are also fuzzy. Furthermore, uncertainties in further disassembly conditions may be accounted for by probabilistic and predictive analysis and evaluation. Indeed, even when one attempts to rate a particular possible disassembly solution, one must deal with uncertain information. For these uncertainty and fuzzy considerations, the deterministic CBA model developed in Chapter 5 cannot be used. However, to demonstrate the RE-ILECM process conceptually, we assume that information obtained from reverse engineering is deterministic.

Recycling Criteria. In the decomposition step of the disassembly process, one must recognize that there are some kinds of criteria (factors), with equal or weighted importance, that are required for making redesign/recycling decisions on the decomposed item. In general, these criteria are:

- functional (product performance)
- dimensional (physical attributes)
- end-of-life product value (due to recycling or performance upgrade)
- process cost (e.g., disassembly, testing, sorting, documentation costs)
- environmental input (material attributes).

The functional criteria describe how the product and its subsets work. If the decomposed item meets functional specification requirements for reuse, then it is recyclable or worth being further decomposed to the subordinate level. Dimensional criteria establish the part dimensions (lengths, tolerance, fits, threads, etc.). In case the dimensional specifications do not meet requirements, the decomposed item may either be reused or remanufactured, if it meets functional criteria, or be further decomposed.

In the disassembly process, in general, the ratio between the cost of activities that generate added value of the end-of-life product (from the customer's point of view) and the total process cost is an important parameter for defining recycling criteria and for selecting the "best" disassembly process alternative. This ratio is defined as disassembly-process-performance (DPP), which is generally represented as

$$\text{DPP} = \frac{\text{Value - added}}{\text{Cost committed}} = \frac{C_{V_a}}{C_{D,p}}$$

Of course, determining process performance requires a detailed analysis to identify the disassembly activities that decompose the product to a certain level following the recycling criteria. If recycling-oriented manufacturers have the right tools, they can design their disassembly processes and assess the value of these processes from the recycled product user's point of view, and see how much value their processes add. In the context of the life-cycle approach, the activities of production/manufacturing and of disassembly/demanufacturing are interdependent during estimating the product's total life-cycle value. Therefore, in the context of RE-IECDM, the modified CBA model is used as decision criteria for determining the disassembly sequence. We can define the cost-revenue analysis model based on the CBA model (equation 5.22) as

$$R_{R/C} = \frac{\text{Total Revenues}}{\text{Total Costs}} = \frac{SB + RB}{MCOST + OCOST + RCOST + ICOST}$$

F.3. RE-IECDM Process for Disassembly Sequence Generation and Redesign for Environment

Operationally, reverse engineering initiates the redesign process, wherein an existing product-system is observed, disassembled, analyzed, tested, and documented in terms of its functionality, configuration form, physical principle, manufacturability, disassembly sequences, and assemblability. In other words, the outputs of the reverse engineering process should be all possible product-attributes as defined in Chapter 5. All these attributes (or design specifications) could be redesigned to meet new customer needs and/or environmental requirements. The dissembled items are for either redesign or recycling purposes.

Taking the similar concept and advantages of the RE process, the disassembly procedure for redesign/recycling can be described as a five-step sequence that is applied at the "item" level of a generic two-level hierarchy to make recycling decisions for the elements that make up the item. The decomposed "item" is specified in terms of the configuration of its elements, the interface between elements, and the functions performed by these elements. Recycling decisions are made depending on the cost-benefit criteria.

Reverse engineering creates a hierarchy of disassembly operations and redesign processes. These generic procedures consist of the following sequenced steps, which are performed from the top system level to the lowest material level, as illustrated in Figure F.1. Figure F.1 provides an overview of what fundamental steps are involved at each product level in order to analyze QFD interfaces for disassembly and redesign as well as reverse engineering processes. A brief textual description of each process step is provided below, in addition to the methods used per step. A disassembly sample problem is used to demonstrate each process step, including the expected results for determination of disassembly sequences and further redesign for the environment. The specific problem for this RE-IECDM process is the 'Tape-driven horn' used previously.

Step 1: Assimilate existing system information: The objective of assimilating existing products and information is to provide a comprehensive understanding of the apparatus and the function that it performs by comparing the end-of-life product that is to be decomposed and a similar existing system. This step may provide available information of the higher level equipment to be uncovered. Efforts in this step are performed for use in the downstream activities of the RE process. The information on the existing product is documented for each product level. The fundamental efforts include:

- Predict existing product-system behavior by
  - ♦ examining the product from all views (for getting physical attributes)
  - ♦ developing system block-box model (for getting operational attributes)

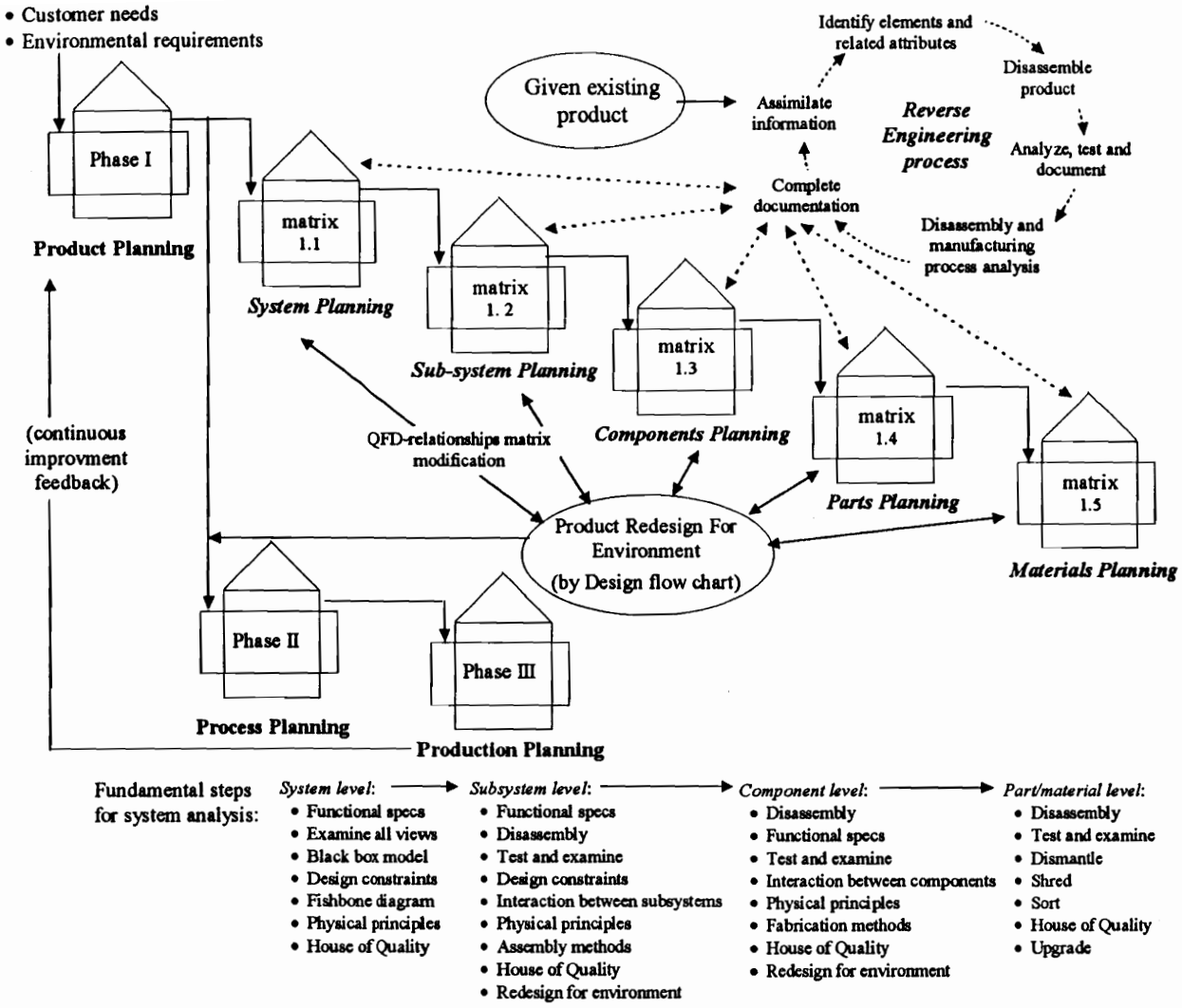


Figure F.1. Documenting the design specifications resulting from reverse engineering in the QFD-process.

- ◊ to observe how the product should work
- ◊ to observe how the product does work before disassembly

• Describe a global block-box (system behavior attributes) including:

- ♦ functionality
- ♦ inputs/outputs
- ♦ operational
- ♦ environment-related issues.

• Identify product-related attributes by the QFD-process:

- ♦ gather customer needs and environmental requirements as the goal of existing-product redesign.
- ♦ develop customer/engineering attributes (specifications):
  - ◊ compare the new product-attributes required by the customer and existing product attributes obtained from Reverse Engineering process.
  - ◊ determine and list the primary distinguishing features between the redesign under study in reverse engineering compared to new benchmark designs.
  - ◊ construct a QFD/HoQ matrix and create an attributes table (functional dependency matrix) to
  - ◊ identify decision variables and parameters (independent and dependent),
  - ◊ provide quantification and benchmarketing of each (re-)design attributes,
  - ◊ develop the redesign problem with an appropriate mathematical model.

• Describe an operational process to provide the functional analysis for operating activities.

To achieve these objectives, some fundamental steps are required in each product level for assimilating information from the existing product (see Figure E.1).

Step 2: Identify Elements and Product-Related Attributes: The objective of this step is to postulate how the item is reduced into its elements so that the disassembly process (path) can be specified from item to elements. The action of postulating the elements of an item is the action of adding an additional lower level to the equipment breakdown hierarchy. In practice, this step is the system engineering action with uncertainty where one establishes a design concept that will be help to guide the disassembly system layout so that the amount of product recycled is the same as the end-of-life product.

Figure F.2 shows the block-box of 'Tape driven horn'. The information obtained is classified by affinity diagram (Figure F.3). The QFD-process is similar to that of Figures 6.7 to 6.9, except that the attributes are identified from both a new design process and a RE process (see Figure F.1). If the existing product-attributes cannot meet design requirements, then redesign activities are required.

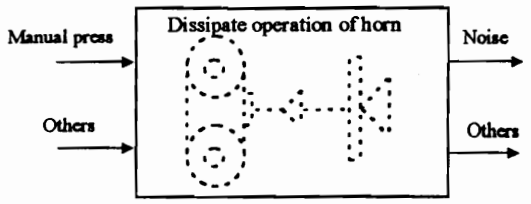


Figure F.2. A block-box model of the 'Tape driven horn'.

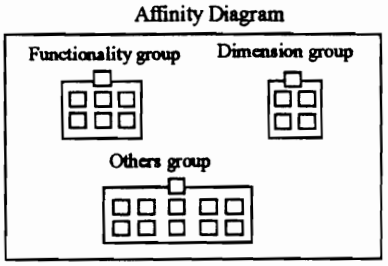


Figure F.3. Affinity diagram for grouping information

Once a set of elements that can make up the item have been postulated, one should next postulate the function that each of the postulated elements performs and also test their functions to see if they are functional or not. In addition, one would like to make a record of the configuration aspects of each element decomposed from the item by sketchers or photographs prior to disassembly so that one does not have to rely on memory for relative positioning or orientation of the decomposed product. Using information obtained from Figures F.2 to F.4, we can construct a primary QFD/HoQ matrix of existing product.

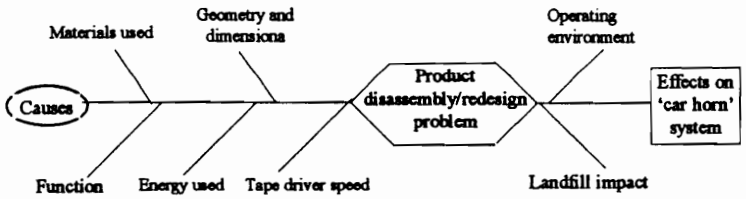


Figure F.4. A cause-effect diagram for defining environmental impact problems.

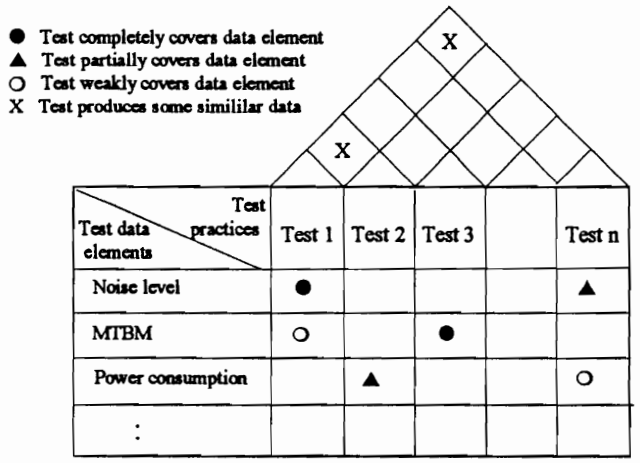
Step 3: The Disassemble product with representation by AND/OR Diagram: Disassembly process is a non-destructive technique in reverse engineering and implies the extraction of the desired and poisonous items-elements and/or materials for the purpose of recycling and/or redesign. The objective of the 'disassemble' step is to decompose the item and also isolate the elements of that decomposed item, identify the interconnections among the elements, establish the interfaces between the elements and the

world outside the item, and make recycling decisions among the elements. In practice, this step includes the following subprocesses:

- create a plan for disassembly of existing product
- create a plan for examination and test of the disassembled items/elements
- document disassembly operations and disassembled items/elements.

Based on this information, the disassembly process is determined for layout planning of the disassembly plant and far required equipment purchases.

In practice, the development of an effective and efficient test plan relies upon a process or methodology for developing the test plan. The HoQ technique for designing quality into products can be modified to assist in integrated test planning [Bardenstein and Gibson, 1992]. A modified QFD-matrix for cost-efficient test planning can be expressed (Figure F.5) where Integrated Test Planning (ITP) is incorporated with the QFD technique in order to create a benefit in increased product quality and quality management. This idea of a QFD approach with ITP application is adapted in the reverse engineering process for use in testing the disassembled item. In the context of reverse engineering, this modified QFD-matrix is used for testing the disassembled item in order to determine its usage (such as recycling options or redesign).



Test data elements \ Test practices	Test 1	Test 2	Test 3		Test n
Noise level	●				▲
MTBM	○		●		
Power consumption		▲			○
:					

Figure F.5 A QFD approach for integrated test planning (an example)

To begin with, both QFD and ITP start by identifying all 'customer' requirements: for the QFD process, this is the 'voice of the customer,' for the ITP, this is the collection of all system requirements and specifications which must be tested and validated during reverse engineering or product disassembly operations. This QFD-ITP plan is developed for use in the RE process, which will insure that:

- all test requirements and criteria are included

- all disassembled items/elements are tested
- test data is obtained to measure performance with respect to each requirement for each item in each disassembly operation
- test practices gather only useful test data
  - each test is designed to gather as much needed data as possible to
    - ♦ help designer redesign the item, if necessary
    - ♦ help design-team make decisions on disassembly level
  - tests are not redundant or useless
  - the entire test plan is feasible within cost, resources, facilities, and/or other constraints.

Once all requirements are identified, test data elements must be established that are necessary for validating each requirement. Test data elements are the specific data collected during testing which serve to assess the performance and specifications of the system/subsystem/component/ material. Test data elements are identified based on previous consideration of the block box model and the cause-effect diagram as well as prediction of system behavior.

The final results of the 'disassemble' step can be expressed by the AND/OR graph associated with the amount of textual documentation (e.g., attributes table with design constraints, QFD-relationship matrices, and other appropriate documentation format) in the following step. The resulting documentation is valuable for bringing together the relevant data which need to be analyzed for product recycling, product development, (re-) design, and (re-)production decision making.

Step 4: Analyze, Test and Document: The objective of this step is to establish the specifications (attributes) for the item in terms of its elements, including

- establish the design characteristics of the element by executing tests to determine performance characteristics (including life-span) and executing tests to determine the properties of its materials (including its possible process and potential environmental impact), as appropriate at this application of the process.
- determine possible recycling and/or redesign opportunities for each item and element.

Based on the disassembly and examination plans generated in step 3, this step includes the following subprocesses:

- test and examine the disassembled items
- develop a detailed functional structure of the product
- explore item-level physical attributes and physical principles
- draw detailed fishbone diagram of actual item/element

- put environmental label (such as collection, recycle, landfill/incineration) on each disassembled item/element.

In practice, items that may be reused, remanufactured, refurbished, or recovered should be determined through a test process for each item in each level before it is decomposed into elements. For example, if we determine item {2,3,4} at level 1 for reuse, then no further decomposition is required; otherwise, it is decomposed into lower level elements. All specifications of element and item are examined in the breakdown hierarchy. The QFD techniques employed in this step fulfill all product-related attributes after the disassembled item has been tested and examined. Element properties and operations with item properties and operations are correlated into the QFD/HoQ form. The activities of this step provide information that is recorded as attributes (design characteristics) in the QFD-system and the documentation system recommended for disassembly analysis and redesign activities in the following steps.

Step 5: Disassembly and Manufacturing Processes Analysis: For the same end-of-life products, the disassembly path may be different from one product to another, depending on the value-added of its specific disassembling process. Therefore, the first step in designing disassembly processes and systems is the establishment of a strategy for disassembling and recycling options. Within this step, the established distinct product-structure and AND/OR graph[3] (resulting from steps 3 and 4) is the first stage of the analysis process. The objective of this step is to establish all possible disassembling paths for the product and calculate their process performance, then determine a "best" path. In this step, the right tools or models are required to assess the value of the end-of-life product and the cost to generate an appropriate disassemble process with certain benefits. The aim is to develop an activities box of the product's life cycle for *life-cycle environmental analysis* and *life-cycle costs analysis*.

For cost-analysis effectiveness, the CBA model is used for economic analysis (or trade-offs analysis) in generation of disassembly sequences. In other words, the disassembly level (degree) based upon the foregoing considerations is a balance between all varieties of disassembly operations and items values that contribute leverage between costs and revenues to relevant activities, especially to recycling options, within the total product' life cycle.

Generally, to fulfill all possible recycling options, it is necessary to find methods:

- to generate all feasible disassembly operations,

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[3] According to Zussiman *et al.* [1994], there are at least three reasons make the AND/OR graph the most appropriate tool to represent all possible disassembly sequences (or a set of subsequent disassembly operations): (1) items, disassembly operations and their precedence relations are included in one representation. Based on the assessment of both disassembly operations and items values, the disassembly strategy may be identified. (2) AND/OR graphs allow the representation of all possible subsequent disassembly operations in one graph, easing the search and values assessment process. (3) if the effort for the disassembly of one part (item) of a product is influenced by prior disassembly of other parts (elements), this is reflected in the AND/OR graph by assigning different hierarchy to the disassembly operation. This allows an exact modeling of the effort for disassembly.

- to determine the execution of these sequences in the most efficient and economical way,
- to determine the optimal disassembly level (degree).

Determination of Disassembly Index for use in Redesign For Disassembly: Like DFE, Design for Disassembly (DFD) actually contains three fields:

- design of product for ease of disassembly and recycling.
- design of disassembly processes with respect to product-characteristics.
- design and implementation of the disassembly system.

With focus on design of product and disassembly processes simultaneously, activity in DFD can be classified into:

- design criteria formulation, to be applied by the design team during conceptual and detailed design.
- evaluation methods development for decision-analysis of alternative designs.

In the QFD-based IECDM process, we present a disassembly-evaluation-function for decision analysis. It is based on an index of DFD criteria, which is calculated in a QFD-driven way for each single part or subassembly to be removed, and is then evaluated for the whole assembly (product) as an average value. The idea beyond the disassembly-evaluation-function is also ranking the design alternatives with respect to product attributes based on the defined DFD criteria (requirements) expressed in phase I of a QFD/HOQ-matrix: product disassembly planning as illustrated in Figure F.6. Phase I is further broken down into five subphases: system, subsystem, components, parts, and materials disassembly/recycling planning (see Figure F.1). Then the disassembly-evaluation-index is defined as

$$DFDR_{product-design} = \frac{\sum_{i=1}^{N} DFDR_i}{N}$$

Where N is the total number of components (parts) being removed from the product, and

$$DFDR_i = \frac{\sum_{j=1}^{m} A_j}{\sum_{j=1}^{m} A_j^{max}}$$

Where A_j is the score of j^{th} DFD criteria. A_j^{max} is the maximum score of j^{th} DFD criteria. This disassembly-evaluation function approach needs to be further studied, but is beyond the scope of this report. However, a possible QFD/HoQ matrix for DFD is suggested in Figure F.6. It is noted that the engineering characteristics of component properties, process properties, assembly properties, and disassembly properties should be considered simultaneously because these engineering features are interdependent.

Figure F.6. A QFD/HoQ matrix for DFD (an example)

Determination of the Disassembly-Sequence and Disassembly Level: Disassembly is a process that is applied for the purpose of recycling and/or redesign of products. The aim of disassembly is to redesign the value added to items/elements and materials. as well as to protect the environment. In this context, the principal operations in 'disassembly' involve a number of subprocesses, such as:

- service and maintenance--repair
- disassembly--reuse
- dismantling--remanufacture
- recovering materials--recovery
- disposal

Each of these processes represents a different disassembly level (degree) which depends upon a number of economic considerations in terms of cost-benefit analysis. In other words, the 'optimal' disassembly problem may be described as an Optimal Disassembly Problem as:

: For a given existing product, find out

- a best sequence to disassemble a product to minimize costs committed by product disassembly operations, and
- an appropriate decomposition level to disassemble a product to maximize the profit gained by recycling items and recovering materials.

The objectives for an optimal disassembly sequence and an optimal disassembly depth may or may not conflict with this statement of a disassembly problem. Identification of the most cost-effective disassembly sequence and the disassembly level with the most benefits requires an appropriate analytical model. However, no mathematical programming model for optimization of the disassembly problem has yet been reported.

For the purpose of demonstration, let us consider the disassembly of the 'Tape driven horn'. The unit consists of the following details (Figure F.7): driver, tape, amplifier, and speaker. All possible disassembly alternatives are considered in the AND/OR graph (Figure F.7), where all possible disassembly sequences can be found. (The feasible disassembly sequences may be less than all the disassembly sequences shown.)

Generation of all possible disassembly sequences is the first step for disassembly analysis. Once the AND/OR disassembly graph has been generated, an appropriate model of disassembly analysis is required. In the context of RE, decisions should be taken at every disassembly level whether to continue with disassembling or with dismantling, or to send the discarded items/elements to the shredder. These decisions will affect the company's recycling policies (such as the recycling options discussed in Chapter 5) which, in turn, affect recycling-related costs and revenues.

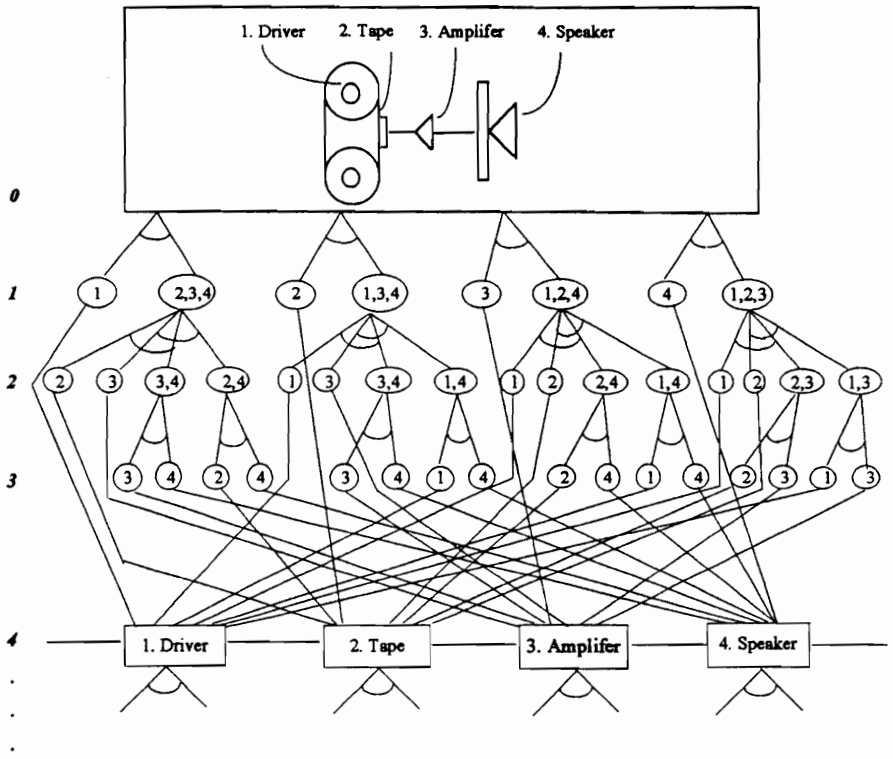


Figure F.7. AND/OR disassembly graph of the 'tape-driven horn.'

Step 6: Complete Documentation: The objective of the "complete documentation" step is to formalize the related information of the product being examined and disassembled. The document created by reverse engineering provides important information for redesign of the product and for generation of disassembly sequences. It is useful to prepare an exploded drawing of the item in terms of the elements and relevant attributes as well as disassembly sequences. It is also important to direct attention to any peculiar functions, operations, configurations, materials, or finishing methods.

Step 7: Product Redesign Approach with Mathematical Modeling Application: Redesign or performance upgrade is one objective of reverse engineering. In the context of green issues, however, materials substitution is thought to be much less likely to happen for the reasons of recycling than for broader economic or financial reasons. Therefore, Redesign-For-Environment becomes a good reason for doing the RE process, which can be achieved by going through the same design flow chart (see Figure 6.5) and design process steps (see Table 6.2) once the QFD-matrix is constructed.

- Identify Attributes from the RE Process and Customer Requirements: From the list of customer attributes, we select the design attributes that we will consider in the product redesign.
- Define Design Decision Variables and Parameters: The design-team identifies engineering characteristics that influence the customer's attributes. These engineering characteristics aid in

defining the design variables to be considered in redesign analysis. The relationship between decision variables and parameters is formulated by their correlation based on their physical principles.

- Construct Design Evaluation Function with Constraints: After the design variables and parameters are identified, by the QFD-optimization approach, as discussed in Appendix C.

F.4. Applying Value Engineering for (Re)design-For-Environment with QFD Applicatio

(Re)design-For-Environment is recognized as a value-added effort, and Value Engineering (VE) can be employed. In its most general from, value engineering is a method used in design reviews to improve the quality of a product. Traditionally, it has focused on cost reduction by assessing the functional value of different cost drivers in a product in order to assist the designer in finding better solutions. It is a four step method as:

(1) Establish hierarchical functional decomposition.

(2) Identify cost associated with function by benchmarketing functional sub-assemblies.

(3) Set new design goals based on the cost of the function.

(4) Redesign costing components while preserving product function.

Related to Reverse Engineering, VE is employed in RE for adding product value by redesign costly components. Related to environmental issues, as a matter of fact, environmental VE may have the four step method as traditional VE. The only difference is an additional first step where the designers choose the environmental cost measures, that will be considered in the Redesign-For-Environment efforts within RE process. Then the design team can search for alternatives that will likely reduce environmental impacts to receive the maximum benefit for a function.

Furthermore, the QFD process very nicely compliments VE and vise versa, especially for customer-oriented product design. QFD by no means replace VE although some may argue about its similarity. In QFD-process, engineers and designers are being pushed to think about who their customers are and what need the product to do for them. This is also a special opportunity for the value engineer to become involved. By becoming part of a QFD team, value engineers can introduce the VE techniques as a natural part of the quality process. Because QFD starts at the very beginning of the product life cycle, there is also a greater opportunity for involvement and a greater potential opportunity for significant cost prevention. Without doubt, VE techniques can be introduced into QFD-based IECDM for getting significant prevention of environmental costs, even in RE-IECDM.

F.5. Discussion

The Reverse Engineering Approach with IECDM application for disassembly evaluation and redesign-for-environment constitutes a useful framework for an environmentally-oriented product design. In the current form of RE-IECDM, the approach which focuses on process-steps development is somewhat judgmental. However, the current framework leads itself to a more systematic approach to problems related to disassembly and redesign of an existing product, for environmental reasons. The disassembly problem (optimal disassembly sequence and depth) is a critical issue for RE-IECDM implementation. Consequently, once the QFD/HoQ-relationship matrix is constructed, a QFD-based optimization approach can be employed for redesign-for-environment.

Appendix G: Glossary and Definition of Terms

Activity-Based Costing (ABC) *ABC* is a cost system where the consumption of activities performed is the basis for assessing the product cost. The consumption of activities may include energy and matter consumption when using the ABC method in DFE-relevant problems. Other terms related to ABC include:

Activity *Activity* is defined as gathered actions that have a logical connection. For example, the actions associated with setting up a machine can be treated as an activity.

Consumption intensity *Consumption intensity* is the unit-price of a cost driver.

Cost drivers *Cost drivers* are measures of the activities performed.

Cost of an activity An *activity cost* is the sum of all cost drivers associated with the activity times their consumption intensities.

Affinity Diagram/KJ method This tool gathers large amounts of language data (ideas, opinions, issues, etc.) and organizes them into groupings based on the natural relationship between the items. It is largely a creative rather than a logical process.

Analytic Hierarchy Process (AHP) *AHP* is a multiple-criteria decision-making method in which a complicated problem can be first analyzed as an orderly hierarchy structure, and then *rank*ed by its strengths. It is practical and adaptive, and has a wide range of applications in the decision-making process under uncertainty.

Arrow Diagram This tool is used to plan the most appropriate schedule for any task and to control the task effectively as it progresses. The *arrow diagram* is closely related to the CPM and PERT diagram methods. It is used when the task at hand is a familiar one with sub-tasks that are of a known duration.

By-product A useful product that is not the primary product being produced. In life-cycle analysis *by-products* are treated as co-products.

Closed-loop Recycling A recycling system in which waste from an industrial system is collected and reused in a way that contributes to the resource needs of that system.

Criteria, Attributes, Goals, and Objectives in MCDM The four 'terms' most used in MCDM methods are: criteria, goals, attributes, and objectives. There are no universal definitions of these terms. Some authors make distinctions in their usage while many use them interchangeably. Nevertheless, some distinctions can be made among these words in terms of their usage, as follows:

Criteria A criterion is a measure of effectiveness (e.g., cost, performance, quality). It is the basis for design evaluation. *Criteria* emerge as attributes (in MADM) or objectives (in MODM) in the actual design decision-making problem setting.

Goals (Targets) *Goals* are a priori values or levels (or factors or options) of aspiration. These are to be either achieved or not exceeded in design problem. They are often referred as constraints (explicated in MODM and implicated in MADM) because they are defined to limit and restrict the design alternative set.

Attributes Preference parameters, specifications, components, materials, factors, characteristics, and properties are all synonymous for different types of attributes bundling. An *attribute* should provide a means of evaluating the levels of an objective. Each alternative can be characterized by a number of attributes with levels. Design attributes are chosen by decision makers' or designers' conception of criteria, which are often constructed hierarchically to represent a specific system design alternative.

Objectives An *objective* is something (e.g., measure) to be pursued to its fullest (e.g., optimization). An objective generally indicates the improvement direction of change desired in the design decision-making process. Goals are more long-term--the final result; objectives relate to steps to get to a goal.

Demanufacturing and **Remanufacturing** *Demanufacturing* and *Remanufacturing* are the names of process-steps intended to enable both material recovering and product/item reuse. *Demanufacturing* characterizes the entire process involved in recycling, reuse, incineration, and/or disposal of a product after it has been taken back by a company. Remanufacturing deals with the refurbishment of partly worn products for their subsequent reuse (see **Remanufacturing** in this Appendix). Operationally, disassembly activities are pre-actions for demanufacturing and remanufacturing.

Design For Recycling (DFR) As for DFE practices, *DFR* is an aggregated effort including design for recycling, design for disassembly, design for refurbishment, design for remanufacturing, and other DFE matrices. DFR especially represents efforts of 3'R (reuse, remanufacture, recovery).

Design For Disposability As one of the DFE practices, design for disposability is used to assure that all non-recoverable materials and components can be safely and efficiently disposed of.

Design For Energy Recovery As one of the DFE practices, this effort extracts energy from waste materials through incineration or other processes.

Design For the Environment (DFE) *DFE* is a systematic approach to improving environmental performance of products and processes over their full life-cycle. DFE is defined as all efforts to include environmental criteria into product design: design for disassembly (DFD), design for recyclability

(DFR), efforts to include life-cycle analysis (LCA) in product development, efforts to map customer demand for environmental preference and environmental regulation into new products, or efforts to reduce corporate risk by designing pollution out of products and processes.

Design For Recyclability (DFR) As one of the DFE practices, the *DFR* concept is used to ensure both a high recycled content of products and a high degree of product recycling at end-of-life.

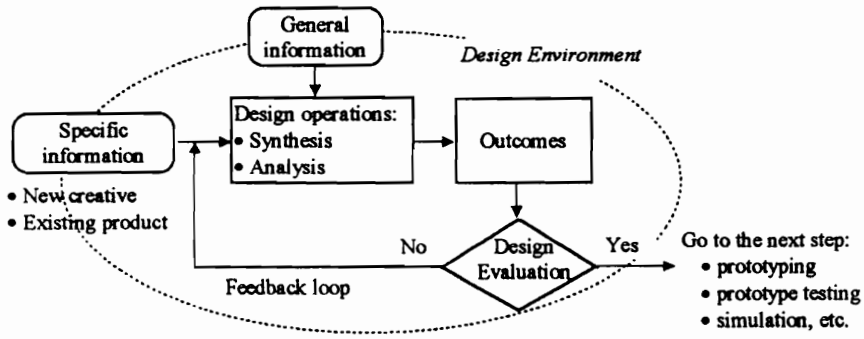
Design For Refurbishment As one of the DFE practices, *design for refurbishment* enables certain components of a product to be reclaimed, refurbished, and reused.

Design For Remanufacturing As one of the DFE practices, *design for remanufacturing* enables the recovery and reprocessing of used products (or components, or parts, or materials) and their recycling as inputs to the manufacture of new products.

Design For Separability or Disassembly (DFD) As one of the DFE practices, *DFD* principles and techniques are used to ensure that, at the end of its useful life, a product's components are cost-effectively extracted and sorted for recycling, reuse, or other means of disposal. In addition, a design that makes the unit easy to put together will also make it easy to take apart for servicing.

Design, Engineering, Engineering Design, and **Design Process**

Design, as a formal definition, establishes and defines solutions to and pertinent structures for problems not solved before, or new solutions to problems which have previously been solved in a different way. *Engineering* is defined as the application of science to the *solution of a problem* of society at a profit. Engineering is the profession in which a knowledge of the *mathematical and natural sciences* gained by study, experience, and practice is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind. *Engineering design* is the systematic, intelligent generation and evaluation of specifications for artifacts whose form and function achieve stated objectives and satisfy specified constraints. *Design Process*: Design is a sequential process; as such, it consists of many design operations (activities) for resulting solution of a problem. Three generic tasks that are repeatedly performed in the design process are expressed as a closed loop module as below:



Tow major categories of design operations are synthesis and analysis. *Synthesis* is the task of assembling a set of primitive design elements or partial designs into one or more configurations that clearly and obviously satisfy a few key objectives and constraints. Synthesis is often considered as the task most emblematic of the design process. It is concerned with assembling the elements into a workable whole. *Analysis* is the task of performing those calculations (or analyses) needed to assess the behavior of the current synthesis--or embodiment of the preliminary design. Analysis usually involves simplification of the real world through models. It is concerned with the separation of the problem into manageable parts. There is also an argument to be made that analysis is a task done early on in the design cycle since analytical thinking is required to clarify the client's requirements and lay out the specifications against which the design will be made and evaluated. The design operations produce a design outcome(s) that must be evaluated to decide whether it is adequate to meet the need. If so, the designer may go on to the next step. *Evaluation* is the task being done when we compare our analyses of the attributes and behavior of the current design to the stated design specifications and constraints to see if this synthesis is acceptable.

Durable Product The so-called 'durable' product, such as a machine, vehicle, or appliance that can be recovered for reduction of environmental impact.

Ecodesign and **Green Design** The term *ecodesign* indicates a design activity that aims at connecting what is 'technically possible' to what is 'ecologically necessary' in order to arouse socially and culturally acceptable new proposals resulting in green products. *Green design* aims at producing products of high quality with little environmental impact and less cost. Green design should incorporate environmental objectives while maintaining product performance, useful life, and functionality. OAT (Office of Technology Assessment, US) uses the phrase 'green design' to mean something qualitatively different: a design process in which environmental attributes are treated as design objectives or design opportunities, rather than as constraints. A key point is that green design incorporates environmental objectives with minimum loss to product performance, useful life, or functionality.

Eco-efficiency The term *eco-efficiency* is used to describe those corporations that produce ever more useful goods and services while continuously reducing resource consumption and pollution. It is defined as the ability of the managed entity to simultaneously meet cost, quality, and performance goals, reduce environmental impacts, and conserve valuable resources. With respect to this definition, an eco-efficient product (process) is a system that simultaneously meets eco-efficiency's requirements.

Efficiency and **Effectiveness** The long-term goal of the life-cycle ECDM approach is to provide efficient and effective decision support in environmentally sound industrial and product development.

Efficiency is a measure of swiftness. *Effectiveness*, on the other hand, is a measure of completeness and correctness. Efficiency and effectiveness are often in conflict.

Energy Use Reduction As one of the DFE practices, *energy use reduction* seeks to reduce the energy required to produce, transport, store, maintain, use, recycle, or dispose of the product and its packaging.

Engineering Design, Industrial Design, and **Concurrent Design** Historically, design has been devised into the fields of engineering design and industrial design. *Engineering design* primarily specifies a product's technical characteristics, while *industrial design* is principally concerned with the 'feel' of product, such as styling and ease of use (ergonomics). Most products embody in varying degrees the inputs of these two design disciplines. In the context of *concurrent design*, the term 'designers' or 'design team' refers to all design decision makers who participate in the early stages of product development, including a wide variety of disciplines: industrial designers, industrial ecologists, engineering designers, manufacturing engineers, as well as managers and marketing professionals.

Environmental Loading The release of pollutants to the environment, which should be measured throughout the life-cycle for environmental impact assessment.

Environmental Management The functional aspect of enterprise management that develops and implements environmental policies and strategies.

Environmental Quality The measurable attributes of a product or process that indicate its contribution to ecological health and integrity.

Environmental Performance The effectiveness of an enterprise in achieving its environmental objectives, potentially including reduced environmental impacts or improved environmental quality.

Environmental Release Emissions or waste discharged to the air, land, or water. Contaminants that cross a system boundary into the environment.

Green Products and **Green Product Design** *Green products* are those whose manufacture, use, and disposal place a reduced burden on the environment. *Green product design* is the design of products by applying environmental criteria that aim at prevention of the generation of waste and emissions and the minimization of their environmental impact, throughout the products/materials life cycle.

HOW A QFD term for a mechanism that fulfills a WHAT. In the first phase of QFD, HOWs are the first-level (system level) technical attributes of a product or service that explicitly address customer needs or wants (see **QFD**).

HOW MUCH A QFD term for the target value of a HOW (see **QFD**).

Interrelationship Digraph This tool takes a central idea, issue, or problem and maps out the logical or sequential links among related items. While still a very creative process, the *interrelationship digraph* begins to draw the logical connections that the KJ methods surfaces.

Impact Analysis Assesses the environmental impacts and risks associated with various activities. An *impact analysis* interprets data from a life cycle inventory by identifying the main impacts associated with inputs (i.e., energy and natural resource consumption) and outputs (i.e., waste releases associated with an actual or proposed action).

Improvement Analysis The component of a life-cycle assessment that is concerned with the evaluation of opportunities to effect reductions in environmental releases and resource use.

Industrial Ecology The design of eco-efficient industrial systems, involving one or more enterprises, that utilize or mimic the cyclical patterns of material and energy flow in natural ecosystems.

Inventory Analysis Identifies and quantifies all inputs and outputs associated with a product system including materials, energy, and residuals.

Life Cycle A sequence of consecutive and interlined stages associated with a product, process, facility, service, or enterprise system. With respect to a product, its *life cycle* starts from the extraction of natural resources to the final disposal of the product. The life-cycle concept is straightforward and is often termed a "cradle-to-grave" approach in industrial ecology.

Life Cycle Assessment or **Environmental Life-Cycle Analysis** A systematic set of procedures or methodology for compiling and examining the inputs and outputs of resources (e.g. materials and energy) and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle. In the complete methodology, LCA consists of four steps: initiation, inventory analysis, impact assessment, and improvement. LCAs are performed to evaluate the environmental burdens associated with a set of business processes, assess the impacts on the environment, and evaluate opportunities for improvement.

Life Cycle Cost Assessment (LCCA) *Life Cycle Cost Assessment* may be defined as a systematic process for evaluating the life-cycle economic and environmental costs of a product (or system) by identifying life-cycle cost items, assigning measures of value to those items, and evaluating options for reducing the total life-cycle cost and optimizing the use of scarce resources [Warren and Weitz, 1994].

Life Cycle Environmentally Conscious Design and Manufacturing An integrated, life cycle-oriented, system-oriented, and product/material-oriented approach for designing and manufacturing more ecologically (environmentally) and economically sustainable product systems. It couples the product development cycle used in business with the physical life cycle of a product. *Life cycle ECDM* integrates environmental requirements into the earliest stages of product and process design so total

impacts caused by the product and process systems can be reduced. In life cycle ECDM, environmental, performance, cost, cultural, and legal requirements are balanced. Concepts such as life-cycle design, life cycle costing, concurrent design, total quality management, design for environment, cross-disciplinary teams, and multi-attribute decision making are essential elements of the life cycle ECDM approach. The enhanced life cycle ECDM includes the issues of recycling and demanufacturing.

Life Extension As one of the DFE practices, *life extension* seeks to prolong the useful life of a product or its components/parts, thus resulting in reduction of the associated waste stream.

Logistics and **Reverse Logistics** *Logistics* is the process of planning, implementing, and controlling the efficient, effective flow and storage of goods, services, and related information from point of origin to point of consumption for the purpose of conforming to customer requirements. This definition broadly includes inbound, outbound, internal and external movements, and return of materials for environmental purposes. For environmental purpose practices, *reverse logistics* is also used as a broad term referring to the logistics management skills and activities involved in reducing, managing, and disposing of hazardous or non-hazardous waste from packaging and products. It includes reverse distribution which causes goods and information to flow in the opposite direction of normal logistics activities. Both logistics and reverse logistics are considered in the design of logistic support system for environmental purposes.

Metric *Metric* is a quantifiable measure of enterprise performance. Metric is a quantifiable measure of enterprise performance or product system performance.

Material Substitution As one of DFE practices, *material substitution* replaces product constituents with substitute materials that are superior in terms of increased recyclability, reduced energy content, or other environment-related metrics.

Matrix Data Analysis *Matrix data analysis* is a tool used to arrange data displayed in a diagram so that it can be more easily viewed and reveal the true strength of the relationship between variables.

Matrix Diagram This tool organizes large groups of characteristics, functions, and tasks in such a way that logical connecting points between each are graphically displayed. It also shows the importance of each connecting point relative to every other correlation.

Open-loop Recycling A recycling system in which a product made from one type of material is recycled into a different type of product. The product receiving recycled material itself may or may not be recycled.

Pre-consumer materials and **Post-consumer materials** *Pre-consumer materials* mean those materials generated during any step in the production of a product, that have been recovered from or otherwise

diverted from the solid waste stream for the purpose of recycling (in-process recycling), but does not include those scrap materials, virgin content of a material, or by-products generated from, and commonly reused within, an original manufacturing process. *Post-consumer materials* means those products or other materials generated by a business or consumer that have served their intended and use, and that have been recovered from or otherwise diverted from the solid waste stream for the purpose of recycling.

Pollution and **Waste** A broad definition of *pollution* encompasses both economic waste and environmental harm. Pollution changes the physical, chemical, and biological characteristics of our air, land, and water. Pollution causes harmful environmental impacts. Any by-product or unwanted residual produced by human activity is pollution. Residuals include all hazardous and non-hazardous substances generated or released to the air, water, or land. For producers in the economic system, *waste* is a nonproductive (non-value-added) stream of material or energy for which the cost of recovery, collection, and transportation increases. Waste generates pollution when released.

Pollution Prevention and **Clean Technology** *Pollution prevention* is any practice that reduces the amount of environmental and health impacts of any pollutant released into the environment prior to recycling, treatment, or disposal. Pollution prevention includes modifications of equipment and processes; reformulating or redesign of products and processes; substitution of raw materials; and improvements in housekeeping, maintenance, training, or inventory control. On the other hand, *clean technology* (or pollution preventive technology), the tool of pollution prevention, aims at product designs and manufacturing processes that use less raw materials, energy, and water; generates less or no wastes; and recycle waste as useful material in a closed system. It may alter existing manufacturing processes to reduce generation of wastes.

Process and **Industrial Process** *Process* is an operation made up of subsystems. Industrial process is an operation that transforms material, energy, and information inputs into outputs as part of an industrial production system.

Process Decision Program Chart (PDPC) *PDPC* is a method that maps out every conceivable event and contingency that can occur when moving from a problem statement to possible solutions. This tool is used to plan each possible event that needs to occur, when the problem or goal is an unfamiliar one.

Product Design and **Product Development** *Product design* is defined as conceiving and laying down the geometry, the material, and the processing techniques of a new product. Product design is a process of synthesis in which product attributes such as cost, performance, manufacturability, safety, and consumer appeal are considered together. *Product development* is defined as developing a company

activity for a new product. This entails the development of a design for a new product with the accompanying plans for manufacture, assembly, distribution, and sales. Product design is thus embedded in a more inclusive process called product development.

Product Life Cycle The life-cycle of a product system begins with the acquisition of raw materials and includes bulk material processing, engineering materials production, manufacture and assembly, use, retirement, and disposal of residuals produced in each stage.

Product-Realization Cycle (PRC) *PRC* is the product-development life cycle (system acquisition and utilization phases). It is the process of bringing a product into existence, from inception through development to customers.

Profitability and Profit *Profitability* is that assessed revenue minus the assessed costs associated with the creation of the revenue, while *profit* is that actual revenue minus actual costs.

Quality Function Deployment (QFD) A team-based, graphically oriented system used for translating customers' requirements into appropriate company requirements at each stage from research and product development to engineering and manufacturing to marketing/sales and distribution. *QFD* is a structured methodology for planning, communication, and decision-making. The overall purpose of QFD is to capture the 'voice of the customer' and use it to drive decisions related to the design of the product and process. In a generalized sense, this requires establishing sets of information.

WHATs A list representing what the customer wants.

WHYs A list of data that help us represent the value or importance to the customer of each of those WHATs.

HOWs A list of methods meeting the wants of the customer.

Relationships between WHATs and HOWs A set of relationships that show which items in the list of HOWs are part of feasible solution(s) to the customer WHATs. They also quantify the relative amount of contribution within a single WHAT.

The calculation of the relative-importance (prioritization) of doing each HOW uses all of this information and establishes:

HOW MUCHs Lists of data that represent the importance, magnitude, and target values of each HOW.

Reconditioning *Reconditioning* restores parts to a functional and/or satisfactory condition by surfacing, painting, etc.

Recovering *Recovering* takes component materials and processes them into the same material or degraded material.

Recycling and **Recycling rate** *Recycling* is the process by which materials otherwise destined for disposal are collected, reformed, reprocessed, or in-process reused into new products. Composting is a form of recycling. The EPA defines recycling as: "...the series of activities, including collection, separation, and processing, by which products or other materials are recovered from or otherwise diverted from the solid waste stream for use in the form of raw materials in the manufacture of new products other than fuel." In practice, the term recycling is often used for all activities that lead a product, parts of a product, or the constituent materials of a product into a new cycle(s) of usage. The principal operations in recycling are: collection, transport, separation, aggregation, reutilisation, including marketing. Here, recycling activities (options) include reuse, reconditioning, recovering, repair, and remanufacturing or their combinations. *Recycling rate* means the percentage by weight of a given product or material category that is recycled.

Recyclability In its narrowest sense, the term *recyclability* signifies the relative technical ease or feasibility of reintroducing a particular material, recovered from products that would otherwise enter the post-consumer waste stream, into the raw materials supply. Recyclability implies materials recovery as opposed to energy extraction. In a wider sense, however, 'recyclability' includes:

(a) Ease of recovery, or of separation from waste.

(b) Specification and acceptability of recovered products.

(c) Markets for recovered products.

(d) Disposal of residuals, left after recovery of valuables.

(e) Cost of recovery of valuables, and of disposal of residuals [Henstock, 1988].

Recyclability is a relative term because ease of recovery from a given product and the consequent profitability of the operation depend on a number of interdependent factors.

Recycling Policy (Options) An enterprise's overall aims and principles of action with respect to recycling to meet environmental regulations imposed by government, from which recycling objectives can be derived. *Recycling policy* is part of the environmental policy of an enterprise. Recycling policy affects the disassembly depth (level), which is generally determined by tradeoffs between efficiency and economic factors.

Recycled materials, Recyclable materials, and **Recycled content** *Recycled materials* mean pre-consumer materials and post-consumer materials, but does not include home scrap. *Recyclable materials* mean products or materials that can be recovered from or otherwise diverted from the solid waste stream and can be reused in economically valuable by-products for the purpose of recycling. *Recyclable materials*, after serving their original purpose, still have useful physical or chemical

properties and therefore can be recycled into new products. *Recycled content* means the portion of a material's or product's weight that is composed of pre-consumer and post-consumer materials.

Remanufacturing *Remanufacturing* restores a product to 'like-new' condition for the same purpose as during its original life-cycle, or reproduces it as a 'new' product for secondary purposes, by reusing, reconditioning, reassembling, and replacing parts, in which the geometrical form of components/parts is retained.

Repair *Repair* brings damaged components back to a functional condition (whereas remanufacturing brings a system to a 'like new' condition either of the original product or other type of product). The repair process often reuses good components/assemblies from returned products.

Requirements The functions, attributes, and constraints used to define and bound the solution space for a system (product and/or process) design and development. General categories of *requirements* include environmental, performance, cost, cultural, and legal.

Resource *Resource* is a natural or man-made good that has economic value. Renewable resource is a natural resource that can be replaced, regenerated, or otherwise restored once it has been used. Nonrenewable resource is a natural resource that cannot be replaced, regenerated, or otherwise restored once it has been used.

Retirement Stage The transitional life cycle stage between use and disposal. Resource recovery options are decided in this stage. Products and materials may be reused, remanufactured, recycled, or just disposed of after retirement.

Reuse A reuse activity (or process) uses good components from retired assemblies or uses good assemblies from retired products. *Reuse* is the use of a product or component part in its same form for the same use without remanufacturing. Reuse may be considered as a form of source reduction.

Reverse Distribution *Reverse distribution* is the process by which a company collects its used, damaged, or outdated products and/or packaging from end-users. Reverse distribution is a subset of reverse logistics.

Reverse Engineering *Reverse Engineering* (for hardware products) is the process of developing a set of specifications (attributes) for a complex hardware system by an orderly examination of specimens of that system. Reverse engineering may be viewed as a special case of systems engineering. The ultimate goal, generally, is to create a clone or a surrogate. The *clone* is considered to be an event reproduction of the original. The clone reproduction must exhibit exactly the same form, fit, function, and mechanism-of-operation as does the original item. The surrogate performs the same function as the original, but does not use the same mechanism-of-operation or necessarily look like the original [Rekoff, 1985].

Secondary Material *Secondary material* is recycled material that is used in place of primary or virgin material in manufacturing a product.

Secondary Packaging *Secondary packaging* is wrapping around the primary packaging or wrapping that joins together two or more primary packages for consumer sale.

Sustainable Development Industrial development that meets the needs of the present while sustaining the quality of the environment so that future generations may meet their own needs. It is a dynamic state that harmonizes economic activities with ecological processes.

System, System Engineering, and **Systems Engineering Process**

System is a set of interrelated components (or attributes) working together toward some common objectives. In the context of eco-systems, system is a dynamic, interconnected set of processes (including business processes, industrial processes, and material processes) that collectively perform an eco-balance function. *System Engineering* is the application of scientific and engineering efforts to transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, optimization, test, and evaluation; to integrate (incorporate) related technical parameters and ensure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; and to integrate reliability, maintainability, safety, survivability, human, and other such factors into an engineering effort to meet cost, schedule, and technical performance objectives.

System Engineering Process (SEP): System Engineering is a process, and as such, it can be devised into a set of steps. Since there are different views on what steps should be included in the SEP, we adopt the following SEP steps from Blanchard and Fabrycky [1990]:

(1) Conceptual system design consists of several stages: definition of requirements, preliminary system analysis, advance system planning, and conceptual design review;

(2) Preliminary system design consists of five stages: system functional analysis, allocation of requirements, trade-off and optimization, synthesis and definition, and system design review;

(3) Detailed design and development.

System Boundary Defines the extent of systems or activities. Boundaries delineate areas for design or analysis. The *system boundary* should be defined before environmental impact assessment or life cycle assessment.

System-oriented design As one of the ECDM practices, *system-oriented design* decreases the life-cycle cost or increases the life-cycle efficiency of the product in terms of resource usage or waste generation.

Taguchi's Philosophy and Loss Function Approach Taguchi's philosophy of robust design is aimed at reducing the loss due to variation of performance from the target value and is based on the quality loss function, single-to-noise ratio, optimization and experimental design methodology [Taguchi *et al.* 1989]. Taguchi states that the quality of a product is the loss imparted by the product to the society from the time the product is delivered. This viewpoint of quality relates quality to cost and loss in dollars, to manufacturer at the time of production and to the consumer and thus to the whole society as well as the environment. The quality activities must focus on the reduction of this loss. The quality evaluation system using loss functions evaluates the quality on a continuous basis, whether or not the characteristic is within or outside the specification limit. In fact, the loss function transfers the deviation of the quality characteristic from the target value to a monetary scale.

Toxic Use Reduction As one of the DFE practices, toxic use reduction seeks to reduce or eliminate the types and amounts of toxic chemicals incorporated into the product or used in its manufacturing process.

Tree Diagram/System Flow This tool systematically maps out the full range of paths and takes that needs to be accomplished in order to achieve a primary goal and every related sub-goal.

Useful Life Measures how long a system will operate safely and meet performance standards when maintained properly and not subject to stress beyond stated limits.

Voice Of Customer (VOC) VOC is a customer need, want, expectation, or concern. As input to QFD, VOC data consists of untranslated statements of customer values; these can be verbatim statements from customers, or unfiltered observations about customer behavior. In a generalized sense, VOC shows three general performance criteria: functional criteria, cost criteria, and environmental criteria.

Waste Source Reduction As one of the DFE practices, the *waste source reduction* techniques seek to reduce the mass of the product (or coproduct) or its packaging, thus reducing the resulting quantity of waste matter per product unit.

WHATs A QFD term for a statement of need or want. In the first phase of QFD, *WHATs* are the result of gathering VOC data. In subsequent phases of QFD, the needs of a product, process, or production facility are also thought of as WHATs. A WHAT is fulfilled by a HOW. (see **QFD**)

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