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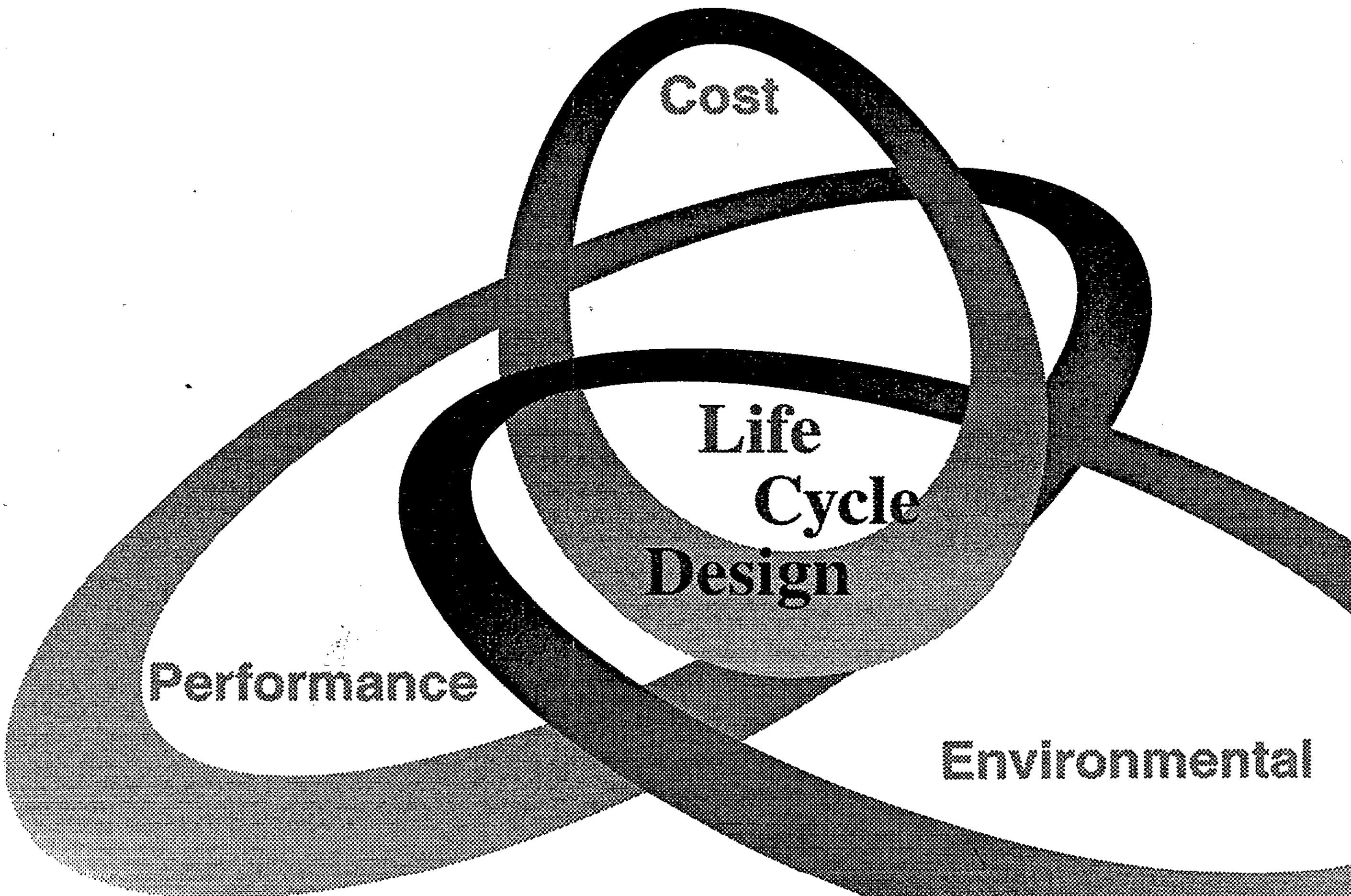
Life Cycle Design Framework and Demonstration Projects

Profiles of AT&T and AlliedSignal



CONTACT

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LIFE CYCLE DESIGN FRAMEWORK AND DEMONSTRATION PROJECTS

Profiles of AT&T and AlliedSignal

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I. NOTICE

The information in this document was funded wholly by the United States Environmental Protection Agency (EPA) under Cooperative Agreement #817570 to the University of Michigan. It has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document. This approval does not necessarily signify that the contents reflect the views and policies of the US EPA. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

II. FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet these mandates, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

III. PREFACE

This life cycle design project is part of the US Environmental Protection Agency's Pollution Prevention Research Program. Through such research EPA seeks to facilitate the development of product systems with reduced environmental burdens across all media and through each stage of the product life cycle. The life cycle design project was conducted in two phases: Phase I - preparation and publication of the *Life Cycle Design Guidance Manual* (EPA/600/R-92/226) and Phase II - completion of two life cycle design demonstration projects. This report covers Phase II demonstration projects with AT&T and AlliedSignal which tested the design framework discussed in the *Life Cycle Design Guidance Manual*, evaluated management practices that affect life cycle design, applied multicriteria requirements matrices, identified ways to improve the life cycle design process, and reported the findings of the demonstration projects.

Life cycle design is a proactive approach for integrating pollution prevention and resource conservation strategies into the development of more ecologically and economically sustainable products. The specific goal of life cycle design is to minimize the aggregate risks and impacts created by a product life cycle from raw materials acquisition through materials processing, manufacture and assembly, use and service, retirement, disposal, and the ultimate fate of residuals. This is a major challenge to design teams because many complex factors influence the design process, such as government regulations, market demand, public and scientific understanding of environmental risk, existing infrastructure, a firm's environmental management system, availability of data and tools for environmental analysis, the dynamic nature of a life cycle system, conflicts between classes of design criteria, and the diverse self interests of life cycle stakeholders.

Multicriteria requirements matrices were developed as a tool for systematically addressing these issues. These matrices were the focal point for both the AT&T and AlliedSignal Demonstration Projects. Balancing environmental, performance, cost, legal, and cultural requirements is essential for achieving successful designs. These requirements can best be identified and evaluated by a cross-functional design team with fully participating members. Accordingly, successful implementation of life cycle design will require changes in a firm's design and environmental management systems.

The life cycle design framework presented in this document is a refinement of the one originally proposed in the *Life Cycle Design Guidance Manual.* AT&T and AlliedSignal demonstration projects contributed substantially to our understanding of the practical application of life cycle design. We hope the insights gained from this process will encourage other firms to adopt new approaches for developing cleaner products and processes.

The research team of the National Pollution Prevention Center, based at the University of Michigan, welcomes your comments and suggestions. Please direct your comments to:

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IV. ABSTRACT

This document offers guidance and practical experience for integrating environmental considerations into product system development. Life cycle design seeks to minimize the environmental burden associated with a product's life cycle from raw materials acquisition through manufacturing, use, and end-of-life management.

The following key elements of the life cycle design framework are outlined: a firm's environmental management system, needs analysis and project initiation, specification of design requirements, selection and synthesis of design strategies for minimizing environmental burden, and evaluation of design alternatives using environmental analysis tools.

Life cycle design emphasizes integrating environmental requirements into the earliest phases of design and successfully balancing these requirements with all other necessary performance, cost, cultural, and legal criteria. As an extension of concurrent design, life cycle design addresses both product and process design across the full product life cycle.

Two demonstration projects with industry were conducted to test, evaluate, and refine the life cycle design framework presented in *Life Cycle Design Guidance Manual* (EPA/600/R-92/226), the predecessor to this report. Both AT&T Bell Labs and AlliedSignal, Filters and Spark Plugs applied this framework to the development of cleaner products. AT&T focused on achieving greater material and energy efficiency, improving recyclability, and using and releasing fewer toxic constituents in their design of a business telephone terminal. AlliedSignal developed design criteria to guide the improvement of future engine oil filters The AlliedSignal team considered a cartridge filter with a reusable housing and a single-use, spin-on design. Both AT&T and AlliedSignal concluded that multicriteria requirements matrices are a useful tool for organizing, identifying, and evaluating the complex set of life cycle issues affecting the design of a product system. Major accomplishments and difficulties in implementing life cycle design are highlighted for each project .

Research for this report covers the period from January 1992 to August 1994.

V. CONTENTS

VI. ACKNOWLEDGMENTS

We wish to thank both AlliedSignal and AT&T Bell Labs for testing the practical application of the life cycle design framework. At AlliedSignal, Gordon Jones, Director of Filter Engineering and Anthony Caronia, Vice-President of Engineering, were instrumental in championing life cycle design. In addition, we acknowledge Allen Wright, Gary Bilski, Bijan Kheradi, Ed Cote, Paul Manning, Russ Burke, Anthony D'Amico, Gerry Lamarre, Ken Conti, and Mike McCracken for their contributions to the enhancement of our framework.

At AT&T Bell Labs, Werner Glantschnig took the lead role in coordinating this project. We wish to acknowledge his valuable contributions to enhancing the life cycle design framework. In addition, we wish to thank GBCS (Global Business Communications Systems) designers Bill McCann (the physical designer for the 8403 terminal) and Jacob Sheinblat, and other members of the Green Project Realization Team. Furthermore, we would like to thank Janine Sekutowski and Neil Sbar at the Engineering Research Center, and Prat Kasbekar, Bob Martina, John Mikulak, Paul Stalets, Ted Snydal, Jim Strype, and Bill Zakowski from GBCS, for their support and cooperation.

We wish to recognize Jonathan Bulkley, Director of the National Pollution Prevention Center for his valuable contributions to this research and his assistance in reviewing this document. Bruce Vigon of Battelle and Kenneth R. Stone and Terri Hoagland of US EPA's Risk Reduction Engineering Lab assisted us by reviewing this document and providing helpful comments. At the University of Michigan, Erica Phipps assisted in reviewing and editing, and Dwayne Overmyer, Julie Grannis, and Michael Kania also provided input on graphic design.

1. INTRODUCTION

Life cycle design integrates environmental considerations into product development. To achieve this integration most effectively, practitioners of life cycle design should consider all stages of a product's life cycle from raw materials acquisition through manufacturing, use, and end-of-life management (retirement through disposal). In addition, development efforts should focus on the entire product system, which includes three components: product, process, and distribution.

Life cycle design emphasizes requirements which are developed through a team-oriented process involving as many stakeholders as possible. Understanding the relationship between environmental, performance, cost, cultural, and legal requirements of the product system is critical to successful design. Selecting strategies that satisfy all the various design criteria is a major challenge.

Life cycle design and related approaches, such as Design for Environment (DFE), are needed because of the inherent limitations of conventional industrial practices aimed at protecting the environment. Traditional pollution control and waste management programs do not prevent pollution from being generated. Companies are now realizing that simply striving to comply with ever more complex environmental regulations amounts to playing a costly and never-ending game of catchup. In response, industry leaders have begun to minimize pollution at the source through better design and manufacturing processes rather than relying on "end-of-pipe" controls and treatment.

Product takeback and recycling regulations proposed by several major industrialized countries provide additional impetus for improved design. Industry leaders planning for the future increasingly recognize that designing reusability, remanufacturability, and recyclability into products is a more cost effective and environmentally sound way to conduct business. Such proactive solutions are likely to be technically superior and also less costly than solutions developed by reacting to crises or new regulations.

Many innovative companies are beginning to implement life cycle design concepts and principles. A few of these companies have already initiated effective programs in life cycle design that have resulted in significant reductions in environmental burden and substantial cost savings to the company. Examples of industry programs that contain key elements of the life cycle design framework will be highlighted throughout this report.

DESCRIPTION OF THE REPORT

Purpose

The EPA Life Cycle Design Project developed the *Life Cycle Design Guidance Manual* (EPA 600/R-92/226) in Phase I, then applied and tested this design framework in two demonstration projects during Phase II. Companies contributing to the development of the guidance manual were invited to participate in a Phase 2 demonstration project.

The specific objectives of the demonstration projects included: evaluating the life cycle design guidance manual, applying multicriteria requirements matrices, exploring strategies for reducing environmental burden, and evaluating environmental management systems that support life cycle design. Feedback from the demonstration projects was used to improve the original manual (sections 1-4 of this document).

AT&T Bells Labs and AlliedSignal were selected for the demonstration projects based on a set of criteria that included: upper management commitment to applying elements of the *Life Cycle Design Guidance Manual*, substantially different product systems to demonstrate the range of life cycle design, significant participation of the product realization team, and willingness to share environmental information. Both companies were enhancing their environmental management systems and had already undertaken design initiatives to reduce environmental burdens at the time of the demonstration projects. The AT&T demonstration project applied the life cycle design framework to a business telephone terminal. The AlliedSignal demonstration project applied the life cycle design framework to an engine oil filter. Sections 5 and 6 of this report discuss demonstration project results. In summary, this report serves to:

- refine the life cycle design framework introduced in the *Life Cycle Design Guidance Manual*[1],
- show the relationship between the life cycle design framework and other major environmental design initiatives /tools,
- summarize key lessons learned from the demonstration projects, and
- provide a list of resources and glossary of terms related to life cycle design.

Because life cycle design is a dauntingly large, rapidly expanding subject, this report only attempts to highlight major principles and state-of-the-art approaches. Recognizing that no single design method has universal appeal, product realization teams should use the concepts described in the report as guidelines rather than prescriptions. Individual designers and design teams who recognize the benefits of pollution prevention are invited to adapt appropriate ideas and methods for their own specific applications.

The *Life Cycle Design Guidance Manual* serves as a useful reference document for a number of topics discussed in this report.

Audience

This manual is intended for the following decision makers:

- product designers
- industrial designers
- process design engineers
- packaging designers
- product development managers
- managers and staff in accounting; marketing; distribution; corporate strategy; environmental, health, and safety; law; purchasing; and service
- government officials who are active in pollution prevention

Content and Organization

Section 1. Introduction

The remainder of this section introduces the foundations of life cycle design and some of the major challenges that must be overcome to achieve successful LCD.

Section 2. Life Cycle Design Goals, System, Framework, and Principles

Presents the life cycle design framework which includes the product life cycle system, goals, principles, environmental management systems, and the development process.

Section 3. Life Cycle Management

The fundamentals of a corporate environmental management system are reviewed in section 3. Management plays a key role in the success of life cycle design by setting appropriate priorities, measures, and responsibilities.

Section 4. Life Cycle Development Process

This section describes an iterative development process that encompasses a needs analysis, requirements setting, design solution (including strategies), and implementation. Design evaluation tools are also reviewed.

Section 5. AT&T Demonstration Project

This chapter presents the AT&T demonstration project for designing a business telephone. It begins with an overview of AT&T's corporate environmental management system before discussing how multicriteria matrices were used to identify design requirements and resolve conflicts throughout the life cycle design process. The benefits gained as a result of the project are then outlined.

Section 6. AlliedSignal Demonstration Project

The results of the AlliedSignal demonstration project include an overview of AlliedSignal's corporate environmental management system, a list of design requirements identified by using multicriteria matrices, a discussion of two oil filter design alternatives, and the benefits gained and lessons learned in testing the life cycle design framework.

Additional References

Selected references for further information on the following topics are presented: corporate environmental management, life cycle design and Design for Environment, and life cycle assessment.

Glossary

FOUNDATIONS OF LIFE CYCLE DESIGN

Accomplishing pollution prevention by design is the antithesis of end-of-pipe remedial action. By integrating environmental requirements into the earliest stages of product development, adverse environmental impacts associated with the manufacture, use, and end-of-life management of a product may be reduced or eliminated. Life cycle design can also provide significant benefits such as enhanced resource efficiency, reduced liabilities, and enhanced competitiveness. Thus, life cycle design offers significant opportunities for achieving sustainable development. However, many organizational and operational changes within both society and companies must take place before environmentally improved design can be fully realized.

Life cycle design will usually be undertaken by teams that may include the following range of disciplines: industrial design, process engineering, product development management, accounting, purchasing, marketing, and specialists in ecosystem and human health, safety, and regulatory compliance. Product system development flows from a series of decisions made individually and collectively by design participants. These choices range from the selection of materials and manufacturing processes to decisions relating to the shape, form, and function of the product. Each choice shapes the overall environmental profile of the product system. At the same time, design decisions must lead to a product that meets its functional requirements and is competitive in the market place.

Existing knowledge and experience guide individual and group design decisions. Both new information and new approaches for synthesizing and evaluating this information are essential to achieve sustainable development through design.

CHALLENGES FACING LIFE CYCLE DESIGN

Product development teams face many challenges integrating environmental considerations into product system design. Successful life cycle design must address the following issues.

Pressure to reduce development time	How do we consider environmental issues when the time to conduct a detailed assessment may extend beyond the development cycle or the time-to-market needed to be competitive?
Expanding global economy and competitiveness	How can we meet different preferences, requirements, and regulations for an increasingly international marketplace?
Quantity and diversity of more stringent regulations	How is it possible to keep track of all environmental, health, and safety regulations at the local, state, national, and international level?
Shifting market demand for environmental improvements	Willingness to pay for environmental premiums is highly variable. Even so, green marketing campaigns are being used to gain competitive advantage. How can we balance customer desires for environmental improvements with affordability and convenience?

System boundaries	How far upstream or downstream in the product life cycle should a design effort encompass ? Should the environmental burdens associated with the equipment used to manufacture the product be accounted for?
Allocating burdens	How are impacts allocated between products and coproducts from the same process?
Data availability	How are environmental data accessed? Compared? Verified? What about the use of proprietary data?
Characterizing and assessing environmental impacts	How does the analyst aggregate or compare impact data?
Assigning priority to environmental problems	How do decision makers weigh disparate environmental impacts, such as kg of solid waste, joules of energy, one in a million risk of lung cancer, or loss of biodiversity?

These issues represent a small sampling of the difficult problems that must be overcome in life cycle design.

2. LIFE CYCLE DESIGN FRAMEWORK

The life cycle provides a logical framework for guiding the management and design of sustainable product systems because it systematically considers the full range of environmental consequences associated with a product. By focusing on the entire life cycle, designers and managers can prevent the shifting of impacts between media (air, water, land) and between stages of the life cycle. The life cycle design framework also encompasses information from multiple stakeholders whose involvement is critical to successful design improvement. The primary elements of the framework are:

- Product life cycle system
- Goals
- Principles
- Life cycle management systems
- Development process

The product life cycle system provides context for the goals of life cycle design. Principles to guide life cycle design combine the goals and system with the best traditional design methods. Life cycle management systems that adopt these general principles then enable and support the specific activities necessary for successful development.

PRODUCT LIFE CYCLE SYSTEM

A systems approach that considers the entire life cycle of a product is the foundation of life cycle design. All components of the product, including the product itself, processing, and distribution are also included in this system for every aspect of design. Successful life cycle design must then recognize how product systems are interconnected with others in the larger industrial web of activities.

Life Cycle Stages

Figure 2-1 presents a general flow diagram of the product life cycle organized into the following stages:

- raw material acquisition
- bulk and specialty processing
- manufacturing and assembly
- use and service
- retirement
- disposal

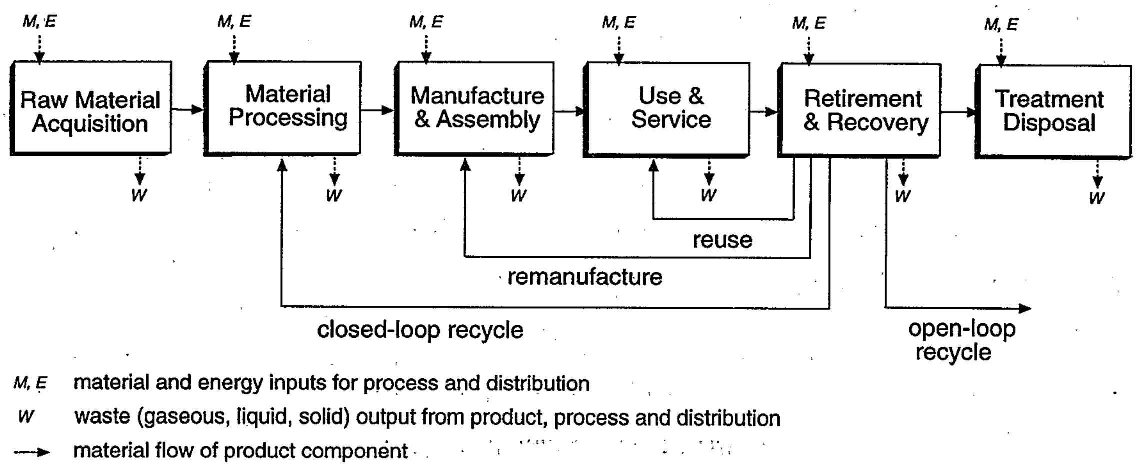


Figure 2-1. Product Life Cycle Stages

Raw materials acquisition includes mining nonrenewable material and harvesting biomass. These *materials* are *processed* into base materials by separation and purification steps. Examples include flour milling and converting bauxite to aluminum. Some base materials are combined through physical and chemical means into specialty materials. Examples include polymerization of ethylene into polyethylene pellets and the production of high-strength steel. Base and specialty materials are then *manufactured* through various fabrication steps, and parts are *assembled* into the final product.

Products sold to customers are *consumed* or *used* for one or more functions. Throughout their use, products and processing equipment may be *serviced* to repair defects or maintain performance. Users eventually decide to *retire* a product. After retirement, a product can be reused or remanufactured. Material and energy can also be recovered through recycling, composting, incineration, or pyrolysis. Materials can be recycled into the same product many times (closed loop) or used to form other products before eventual discard (open loop).

Some residuals generated in all stages are released directly into the environment. Emissions from automobiles, waste water discharges from processing facilities, and oil spills are examples of direct releases. Residuals may also undergo physical, chemical or biological *treatment.* Treatment processes are usually designed to reduce volume and toxicity of waste. The remaining residuals, including those resulting from treatment, are then typically *disposed* in landfills. The ultimate form that the residuals take depends on how they degrade after being released into the environment.

The life cycle system is complex due to its dynamic nature and its geographical scope. Activities within each stage of the life cycle change continuously, often independently of change in other stages. Life cycle stages are also widely distributed on a geographical basis, and environmental consequences occur on global, regional, and local levels.

Product System Components

The product system is defined by the material, energy, and information flows and conversions associated with the life cycle of a product. This system can be organized into three basic components in all life cycle stages: product, process, and distribution. As much as possible, life cycle design seeks to integrate these components.

Product

The product component consists of all materials constituting the final product. Included in this component are all the forms that these materials might take throughout the various life cycle stages. For example, the product component for a wooden baseball bat consists of the tree, stumpage, and unused branches from raw material acquisition; lumber and waste wood from milling; the bat, wood chips, and sawdust from manufacturing; and the broken bat discarded in a municipal solid waste landfill. If this waste is incinerated, gases, water vapor, and ash are produced.

The product component of a complex product such as an automobile consists of a wide range of materials and parts. These may be a mix of primary (virgin) and secondary (recycled) materials. The materials contained in new or used replacement parts are also included in the product component.

Process

Processing transforms materials and energy into a variety of intermediate and final products. The process component includes any direct and indirect material inputs used in making a product. Catalysts and solvents are examples of direct process materials that are not significantly incorporated into the final product. Plant and equipment are examples of indirect material inputs for processing. Resources consumed during research, development, testing, and product use are included in the process component.

In the *Life Cycle Design Guidance Manual*, management was considered a separate component. Experience gained in the demonstration projects (discussed in sections 5 and 6) resulted in a simplification of product system components to make it more intuitive. Management, including the entire information network that supports decision making, occurs throughout the process and distribution components in all life cycle stages. It is thus best considered an element of process and distribution rather than a separate component. Within a corporation, management responsibilities include financial management, personnel, purchasing, marketing, customer services, legal services, and training and education programs. These activities may generate substantial environmental burden and therefore should not be ignored.

Distribution

Distribution consists of packaging systems and transportation networks used to contain, protect, and transport products and process materials. Both packaging and transportation result in significant adverse environmental impacts. In 1990, containers and packaging accounted for 32.9% (64.4 million tons) of municipal solid waste generated in the US.[2] Rail, trucks, ships, airplanes, and pipelines constitute the major modes of transport; each consumes energy and causes environmental impacts. Material transfer devices such as pumps and valves, carts and wagons, and material handling equipment (forklifts, crib towers, etc.) are part of the distribution component, as are storage facilities such as tanks and warehouses.

Selling a product is also considered part of distribution. This includes both wholesale and retail activities.

Subcomponents of Process and Distribution

Both the process and distribution components of the product system share the following subcomponents:

- facility, plant, or offices
- unit operations, process steps, or procedures (including administrative services and office management)
- equipment and tools
- human resources (labor, managers)
- direct and indirect materialand energy inputs

These elements can have an important influence on product system development. For example, existing process equipment can constrain material options and make some improvements more difficult. In addition, facility siting, process design, and equipment selection may contribute significantly to a product's total environmental burden.

Figure 2-2 presents an example of product system elements across life cycle stages. The distribution component is shown between connecting life cycle stages to indicate that either transportation and/or packaging has been used to carry the product or process materials.

	Raw Material Extraction	Material Processing	Manufacturing	Use	Retirement/ Disposal
Product	Petroleum Natural gas	HDPE pellets Stabilizers, pigments	Cup	Cup	Cup or residuals from recycle, incineration
Process	Drilling equipment, labor, energy	Ethylene production, polymerization	Injection molding with SPI markings for recycling	Handling, filling, cleaning	Collect, process recycle, burn, or landfill
Distribution	Pipeline and tankers	Rail, barge, truck, containers	Transport, wholesale, retail, pkg	Trucks, containers	

Figure 2-2. Several Product System Elements for a Reusable Plastic Cup Over its Life Cycle

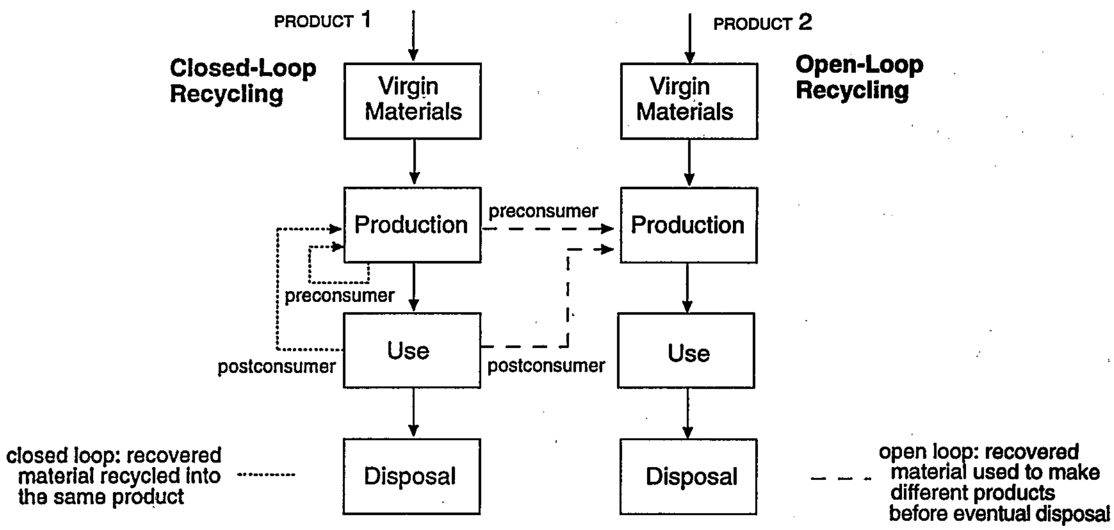


Figure 2-3. Product Systems Linked Through Recycling

Interconnected Product Systems

Each product system contains many product life cycles within it. The interconnections among these subsystems complicates analysis but also offers opportunities for reducing environmental impact. Different product systems are often connected through material exchange or common processes activities. **Figure 2-3** shows how product systems can be linked through recycling. An important objective of life cycle design is addressing how a product system fits into the larger industrial web of highly integrated activities.

In addition to the type of links shown in **Figure 2-3**, product systems may be linked within an interconnected system of multiple manufacturers. Organized networks or symbioses of facilities have been demonstrated to improve material use efficiency, reduce costs, and reduce environmental burdens

The town of Kalundborg, Denmark contains a well-recognized example of such a successful network. Kalundborg's industrial symbiosis consists of four companies: Asnæs Power Plant, Statoil Refinery, Novo Nordisk, and Gyproc, as shown in **Figure 2-4**. The eco-industrial network developed in Kalundborg includes the transfer of excess waste heat, process gasses, residual materials, water, and processed sludge among the participants, local farmers, and the municipal heating system. Kalundborg has benefited from reduced air emissions, water use and discharges, nonrenewable energy use, and chemical fertilizer application. In addition, participants benefit from the sale of waste materials, avoidance of disposal costs and capital improvements required by regulation, and local and international recognition for their actions.

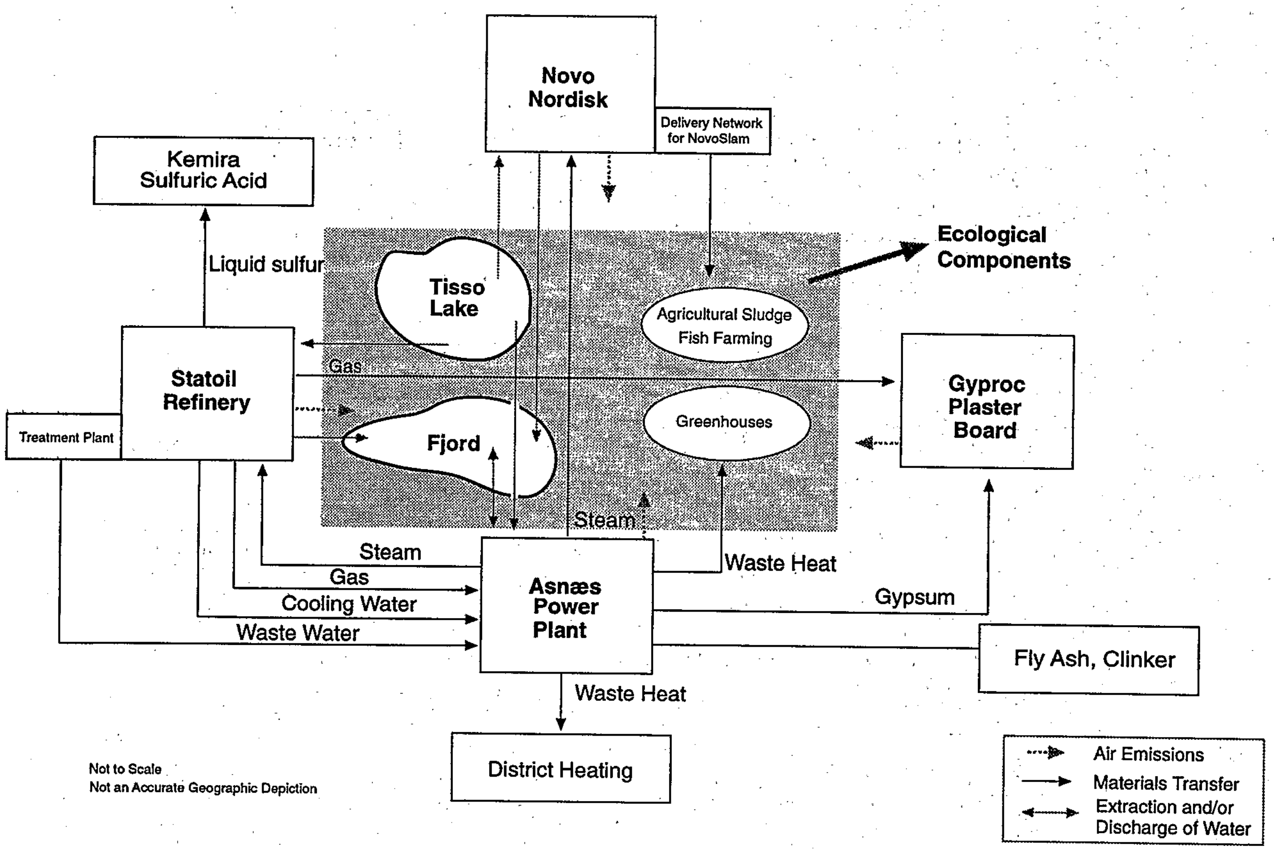


Figure 2-4. Kalundborg's Industrial Symbiosis

LIFE CYCLE DESIGN GOALS

Life cycle design seeks to reduce the total environmental burden from product system development and thus find sustainable solutions for significant societal needs.

Reduce Total Environmental Burden

The environmental goal of life cycle design is to minimize the aggregate life cycle environmental burden associated with product systems. Environmental burden can be classified into the following impact categories:

- resource depletion
- ecological and human health effects

These impacts are the result of resource use and environmental releases to air, water, and land. Conceptually, an environmental profile can be developed that characterizes the aggregate impacts for each life cycle stage and the cumulative impacts for the entire life cycle.

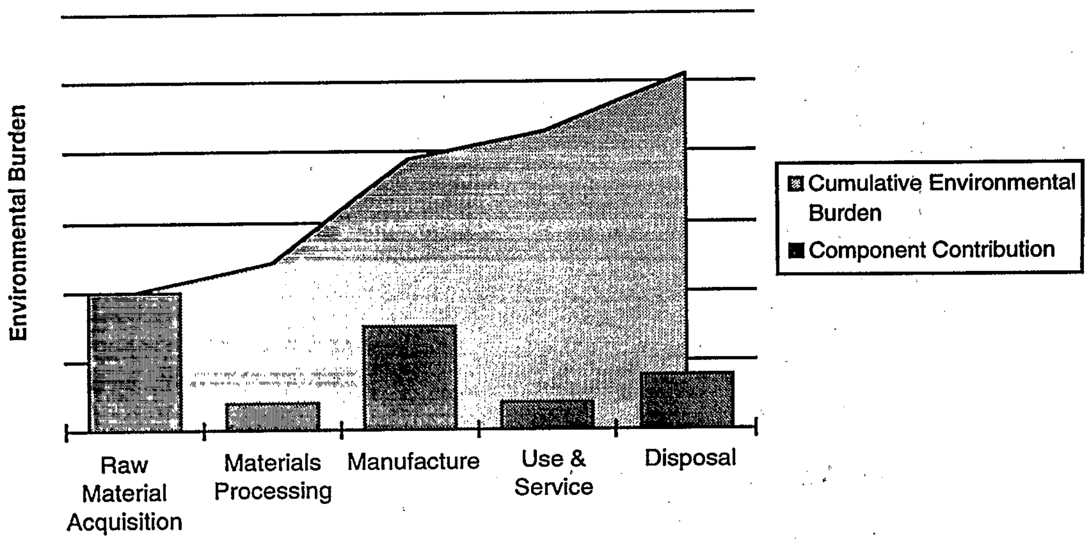


Figure 2-5. Environmental Burden in Hypothetical Units of a Product System

Although there are no universal methods for precisely characterizing and aggregating environmental burdens, **Figure 2-5** shows a hypothetical example of an environmental profile. As illustrated, impacts are generally not uniformly distributed across the life cycle. For example, the major environmental burdens associated with automobiles are caused by the consumption of petroleum and resulting air pollutant emissions during use. By contrast, environmental burdens resulting from furniture use are minimal, but significant impacts occur from manufacture and disposal of these products.

This figure also shows how burdens in all life cycle stages are aggregated to arrive at the full environmental consequences of a product system. It is important to recognize that human communities and ecosystems are also impacted by many product life cycle systems at once.

Achieve Sustainable Development

Sustainable development meets the needs of the present generation without compromising the ability of future generations to fulfill their needs.[3] Determining what constitutes significant societal need depends on collective value judgments and preferences, which are outside the scope of this report. Sustainable development can be furthered by life cycle design, but sustainability also requires evolving societal values, such as a willingness to forgo products or activities that create large environmental burdens.

Necessary elements for sustainability include: sustainable resource use (conserve resources, minimize depletion of non-renewable resources, use sustainable practices for managing renewable resources), pollution prevention, maintenance of ecosystem structure and function, and environmental equity. All of these elements are interrelated and highly complementary.

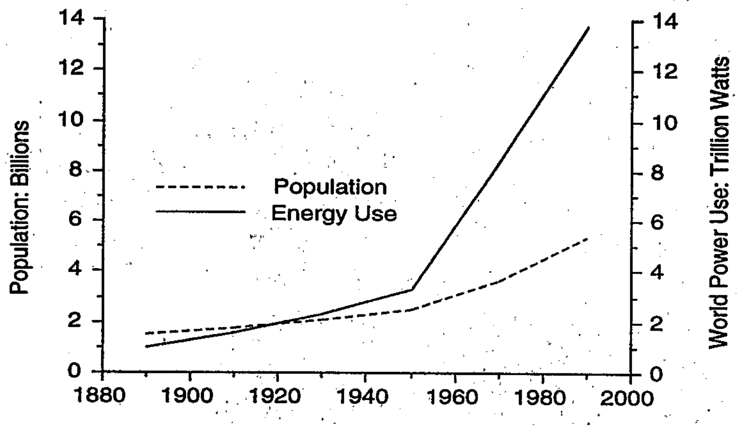


Figure 2-6. World Power Consumption and Population Growth [4]

Promote Sustainable Resource Use

There could be no product development or economic activity of any kind without available resources. Except for solar energy, the supply of resources is finite. Efficient designs conserve resources while also reducing impacts caused by material extraction and related activities.

Depletion of nonrenewable resources and overuse of otherwise renewable resources limit their availability to future generations. As **Figure 2-6** shows, world power consumption and population have recently grown at an exponential rate. If these trends continue, there will probably be insufficient resources to support human needs. Societies around the world will thus be unable to improve or maintain the quality of life for their citizens.

At present, one fifth of the world population consumes nearly 80% of fossil fuel and metal resources. Continuing this level of consumption in industrial nations while adopting it in developing countries is an unsustainable strategy.[5] Yet given recent history, impending resource depletion may not seem critical. In the past two hundred years, human activity in certain regions depleted economically exploitable reserves of several natural resources with critical applications at the time, such as certain woods for ship building, charcoal for steel making, and whale oil for lighting. When this happened, replacements were quickly found that usually proved both cheaper and more suitable for advancing industries. However, it would be unwise to assume that infinite abundance will be characteristic of the future. It may be true that widespread, critical shortages have not yet developed in the very brief history of intensive human resource use, but the amount and availability of resources are ultimately determined by geological and energetic constraints, not human ingenuity.

Promote Pollution Prevention

Pollution prevention focuses on reducing or preventing pollution at the source. It is a proactive approach that avoids the transfer of pollutants across media (air, water, land).

The US Environmental Protection Agency has adopted pollution prevention as a principal strategy for environmental protection. EPA's pollution prevention programs, such as the Source Reduction Review Program (SRRP), address multimedia risks and consider pollution prevention principles in rule-making. Pollution prevention offers numerous advantages over traditional end-of-pipe treatment mechanisms because it minimizes raw material losses, may eliminate the need for expensive pollution control equipment, and reduces long-term liabilities.

Protect Ecological and Human Health

Healthy, functioning ecosystems are essential for supporting life on earth. Recognizing that we depend on a properly functioning and healthy ecosystems for our ultimate survival, the EPA's Science Advisory Board determined that biodiversity and species loss are among the most severe risks to human health and the environment.

Specific human health risks occur through exposure to contaminants via inhalation, ingestion, and direct contact. Exposures can result in both acute and chronic health effects. Individuals are exposed to health risks in the workplace, at home, and during recreation. Life cycle design and other related approaches to preventing pollution seek to minimize or eliminate risks posed to workers, consumers, and the general public.

Promote Environmental Equity

The issue of environmental equity is related to sustainable development and is equally complex. A major challenge in sustainable development is achieving *intergenerational, intersocietal,* and *intrasocietal* environmental equity.

Intergenerational Equity	Meet current needs of society without compromising the ability of future generations to satisfy their needs.
Intersocietal Equity	Achieve more equal pattern of distribution between societies in developed and less developed countries.
Intrasocietal Equity	Address the disparity among socioeconomic groups within a country.

Depleting resources and polluting the planet in such a way that it enjoins future generations from access to reasonable comforts irresponsibly transfers problems to the future in exchange for short-term gain.

In addition to such intergenerational conflict, enormous intersocietal inequities in the distribution of resources and exposure to environmental degradation continue to exist between developed and less-developed countries.

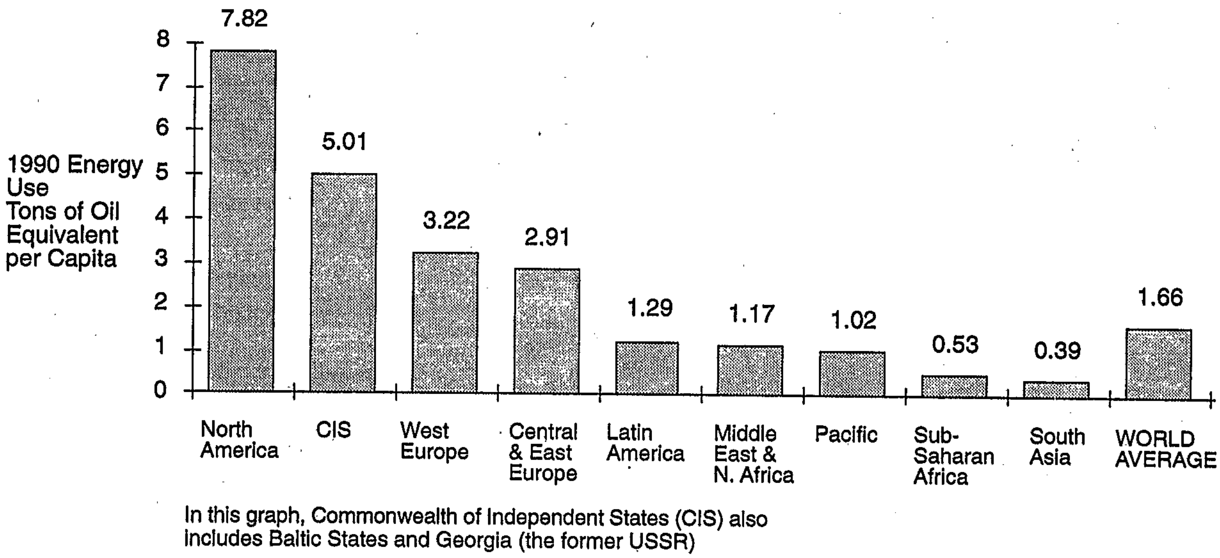
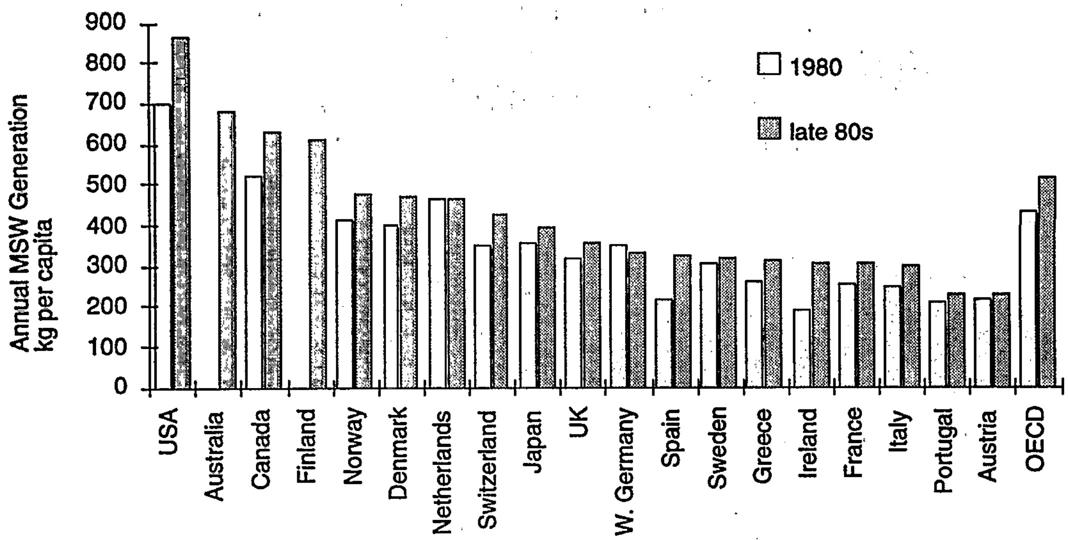


Figure 2-7. 1990 Energy Demand per Capita in Various World Regions[9]

Intrasocietal inequities occur when pollution and other impacts from production are unevenly distributed among different socioeconomic groups within countries. Studies show that low-income communities in the US are often exposed to higher health risks from industrial activities than are higher-income communities.[6, 7] Inconsistent regulations in the US also have led to different definitions of acceptable risk for workers and consumers.[8] In an effort to redress such disparities, President Clinton signed an Executive Order in 1993 requiring regulators to consider equity impacts during the rule development process.

Figures 2-7 and **2-8** show several aspects of environmental equity. **Figure 2-7** offers a clear example of intersocietal inequity by demonstrating how the developed portions of the world use substantially more energy than less-developed regions.



Figures 2-8. Annual Municipal Solid Waste Generation in Selected Countries (kg/capita)[10]

Both intergenerational and another facet of intersocietal environmental equity are implied in **Figure 2-8.** Here, only countries in the same general economic class are considered. Because waste production reflects both resource consumption and efficiency, this graph shows how different countries in the developed world vary in combined levels of consumption and resource efficiency. Nations that squander resources affect both future generations and their contemporaries in other nations who produce fewer environmental burdens by using resources less profligately.

LIFE CYCLE DESIGN PRINCIPLES

Principles for life cycle design are derived from the life cycle system outlook and the goals previously discussed. There are three main principles for guiding environmental improvement of product systems in life cycle design:

- Systems analysis of the product life cycle
- Multicriteria analysis for identifying and evaluating environmental, performance, cost, cultural, and legal requirements
- Multistakeholder participation and cross-functional teamwork throughout design

Use a Systems Approach

A systems approach is essential to achieving sustainable development goals. Understanding the interrelationships between societal needs, industrial systems that provide goods and services, political and regulatory systems, and the ecological systems impacted by human activities is a complex challenge.

Table 2-1. Organizational Hierarchies

Political	Social Organizations	Industrial Organizations	Industrial Systems	Ecological Systems
UNEP	World human population	ISO	Global human material & energy flows	Ecosphere
US (EPA, DOE)	Cultures	Trade associations	Sectors (e.g. transportation & health care)	Biosphere
State of Michigan (MDNR)	Communities	Corporation/ companies	Corporations & institutions	Biogeographic al region
Washtenaw County	Households	Divisions	Product systems	Biome landscape
City of Ann Arbor	Individuals/ consumers	Product develop-ment teams	Life cycle stages	Ecosystem
Individual Voter		Individuals	Unit steps	Organism

Table 2-1 shows organizational hierarchies for each of these systems. A table of hierarchies can be useful for examining interactions between systems and exploring how decisions and processes at different system levels influence higher and lower levels.

Life cycle design focuses on the product systems level in the industrial systems hierarchy. However, understanding the contribution of product systems to higher order levels (i.e., global flows of materials and energy, economic sectors, corporations) as well as the influence of individual subsystems (specific life cycle stages, unit operations), is crucial to effective life cycle design. Successfully reducing net environmental impacts from product systems while still meeting societal needs requires an awareness of the complex interactions that exist among different hierarchical levels and between the various organizational categories (e.g., economic, ecological, and sociological structures).

Metrics and other comparative methods of evaluation enable product designers to determine the advantages and disadvantages of design options. Comparisons across all stages of the product life cycle are necessary to accurately assess environmental burden and develop priorities for improvement.

Multicriteria Analysis

Life cycle design seeks to meet environmental objectives while also best satisfying cost, performance, cultural, and legal requirements. Specification of requirements is one of the most critical design functions. Requirements guide designers in translating needs and environmental objectives into successful designs. Environmental requirements should focus on minimizing natural resource consumption, energy consumption, waste generation, and human health risks as well as promoting the sustainability of ecosystems. The challenge is to apply design strategies that resolve conflicting requirements.

Multistakeholder Participation

Interdisciplinary participation is key to defining requirements that reflect the diverse needs of multiple stakeholders such as suppliers, manufacturers, consumers, resource recovery and waste managers, the public, and regulators. Within corporations, successful life cycle design requires the full participation of all members of a cross-functional development team.

LIFE CYCLE MANAGEMENT

Life cycle management includes all decisions and actions taken by multiple stakeholders which ultimately determine the environmental profile and sustainability of the product system. Each stakeholder has an important role in guiding improvement, as indicated in the following list.

Users and Public	Advance understanding and values through education Modify behavior and demand towards more sustainable lifestyles
Policymakers and Regulators	Develop policies to promote sustainable economies and ecological systems Apply new regulatory instruments or modify existing regulations Apply new economic instruments or modify existing ones
Suppliers, Manufacturers, End-Of-Life Managers	Research and develop more sustainable technologies Design cleaner products and processes Produce sustainable products Improve the effectiveness of environmental management systems
Investors/Shareholders	Support cleaner product system development
Service Industry	Maintain and repair products
Insurance Industry	Assess risk and cover losses

A major challenge for product manufacturers is coordinating the diverse interests of these stakeholder groups.

LIFE CYCLE DEVELOPMENT PROCESS

The development process varies widely depending on the type of product and company, the design management organization within a company, and many other factors. In general, however, most development processes, as shown in **Figure 2-9**, begin with a *needs analysis*, then proceed through formulating *requirements*, employing selected

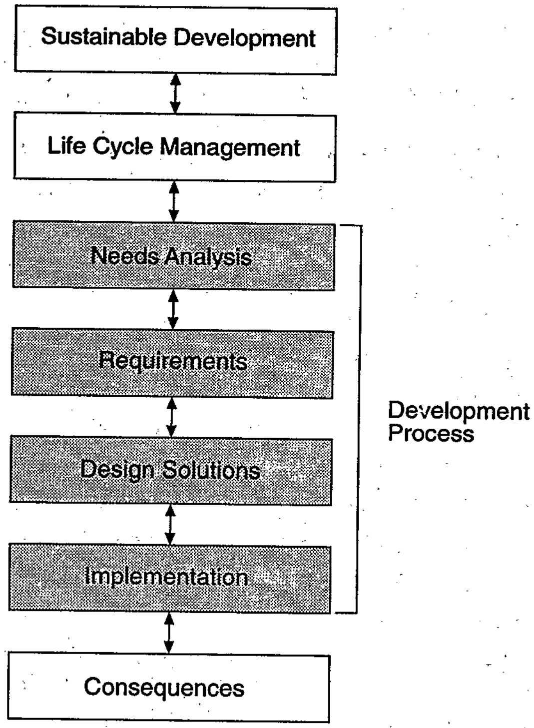


Figure 2-9. The Life Cycle Development Process

strategies, and performing *evaluations* to find *design solutions*. The design is then *implemented*, and various economic and environmental *consequences* result from production, use, and retirement of the product.

During the needs analysis or initiation phase, the purpose and scope of the project are defined, and customer needs are clearly identified. Needs are then expanded into a full set of design criteria including environmental requirements. Various strategies that act as a lens for focusing knowledge and new ideas into a feasible solution are then explored to meet these requirements. The development team continuously evaluates alternatives throughout the design process. Environmental analysis tools ranging from single environmental metrics to comprehensive life cycle assessments (LCA) may be used in addition to other analysis tools.

The development process is best characterized by an iterative process rather than a linear sequence of activities. Ideas, requirements, and solutions are continuously modified and refined until the detailed design is fixed or, in some instances, until the project is terminated or abandoned. Successful designs must ultimately balance environmental, performance, cost, cultural, and legal requirements.

Appropriate designs are then implemented. Product systems satisfy societal needs and result in environmental and other consequences which feed back into the process to influence future designs and guide continuous improvement.

3. LIFE CYCLE MANAGEMENT

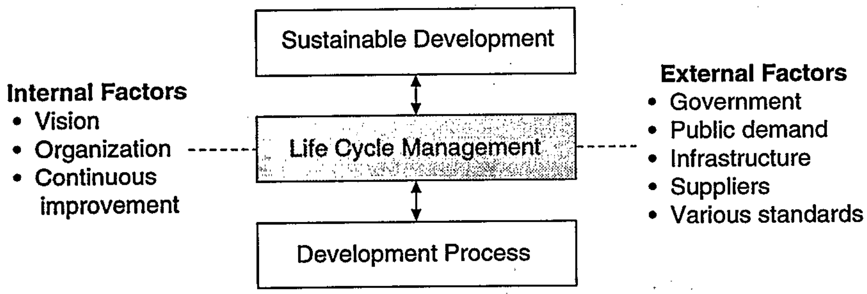


Figure 3-1. Internal and External Factors Influencing the Development Process

A range of internal and external factors influence the product development team's ability to effectively address environmental considerations through design. These factors, which are shown in **Figure 3-1**, form the context for the design process. Within a company, an environmental management system that includes goals and performance measures provides the organizational structure for implementing life cycle design. External factors that strongly influence life cycle management, but may be beyond the firm's immediate control, include government regulations and policy, infrastructure, and market demand. These external factors depend on the state of the economy, state of the environment, scientific understanding of environmental risks, and public perception of these risks.

INTERNAL FACTORS IN LIFE CYCLE MANAGEMENT

Environmental stewardship issues are increasingly addressed within corporations by formal environmental management systems.[11, 12] Ideally, the environmental management system is interwoven within the corporate structure and not treated as a separate function.[12]

An integral relationship between a company's design management structure and its environmental management system is essential for implementing life cycle design. Successful life cycle design projects require commitment from all employees and all levels of management. A corporation's environmental management system supports environmental improvement through a number of key components including its environmental policy and goals, performance measures, and a strategic plan. This system must also provide access to accurate information about environmental impacts. An effective environmental information system is critical to guiding the

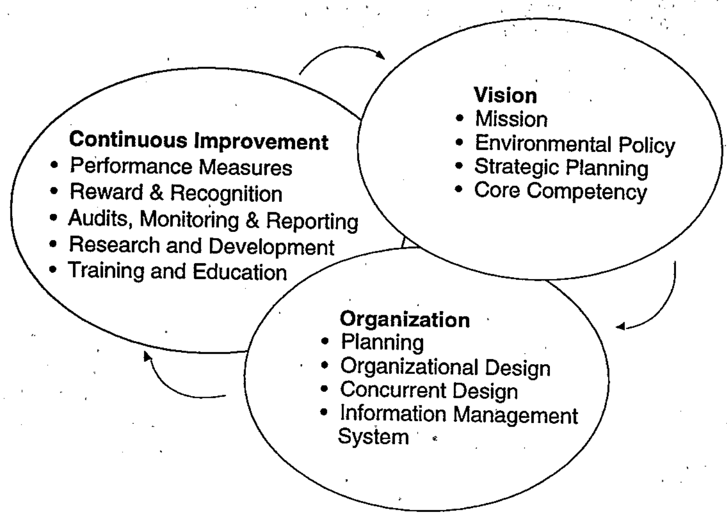


Figure 3-2. Internal Elements of Life Cycle Management adapted from [13]

design process in the direction of environmental improvement. Three main attributes of a well-designed environmental management system are: vision, organization, and continuous improvement.[13] **Figure 3-2** summarizes these issues.

Vision

Broadly defined, corporate vision includes four key attributes: mission statement, environmental policy, strategic planning, and focus on core competence. Each of these elements influences and supports life cycle design. When blended together in a focused program, they can lead to improved corporate environmental performance.

Mission Statement

A mission statement containing environmental principles helps communicate to internal and external stakeholders the importance of environmental issues and provides a context for evolving corporate cultures.[14] Statements that promote environmentally responsible practices and include sustainable development are an important component of setting vision for companies. Such mission statements demonstrate that top management is committed to protecting, preserving, and restoring the environment.

For example, a proposed mission statement from AT&T declares that:

> AT&T's vision is to be recognized by customers, employees, shareowners and communities worldwide as a responsible company which fully integrates life cycle environmental consequences into each of our business decisions and activities.
>
> Designing for the environment is a key in distinguishing our processes, products, and services.

Environmental Policy

Policies that support pollution prevention, resource conservation, and other life cycle principles foster life cycle design. However, such principles must be linked to guidelines and procedures at an operational level to be effective. Vague environmental policies may not result in much action on their own.

A well-known example of a corporate environmental policy was developed by 3M in 1975. This policy stated that 3M would prevent pollution at the source, develop products with minimal environmental effects, conserve resources, and assure that facilities and products meet all regulations while also assisting government agencies and others in their environmental activities. Recently, several companies have recognized the life cycle framework in their policy as shown in the following boxed statements.

The *Valdez Principles*, the *Global Environmental Management Initiative*, and the *Responsible Care* program developed by the Chemical Manufacturers Association provide examples of cooperative effort among companies and within industrial sectors to develop cohesive environmental policies. Major elements of the Valdez principles pledge companies to: protect the biosphere through safeguarding habitats and preventing pollution, conserve nonrenewable resources and make sustainable use of renewable resources, reduce waste and follow responsible disposal methods, reduce health risks to workers and the community, disclose incidents that cause environmental harm, and make public annual evaluations of progress toward implementing these principles.

Strategic Planning

Strategic planning requires that companies first recognize three important factors: their own internal capabilities, customer needs, and the competitive environment. After assessing current company performance against these criteria, strategic planning then focuses on where the company wants to go in the long term and how it can get there. This exercise positions companies for the future; it is essential for managing the complex and dynamic nature of the life cycle system.

XEROX ENVIRONMENTAL POLICY

Xerox Corporation is committed to the protection of the environment and the health and safety of its employees, customers and neighbors. This commitment is applied worldwide in developing new products and processes.

- Environmental health and safety concerns take priority over economic considerations.
- All Xerox operations must conduct themselves in a manner that safeguards health, protects the environment and conserves valuable materials and resources.
- Xerox is committed to the continual improvement of its performance in environmental protection and resource conservation.
- Xerox is committed to designing products for optimal recyclability and reusability. We are equally committed to exploring every opportunity to recycle or reuse waste materials generated by our operations.

Table 3-2. Time Scales of Events That Can Influence Design

- Business cycles on a macro and micro scale (e.g., recovery, inflation, recession and net income, cash flow, debt, equity)
- Product life cycle (R&D, production, termination, service)
- Useful life of the product
- Facility life
- Equipment life
- Process changes
- Cultural trends (fashion obsolescence)
- Regulatory change
- Technology cycles
- Environmental impacts

Effective planning can seem overwhelming given the different time scales affecting product system components. Shorter term and longer term environmental goals should be defined based on various time cycles. Understanding and coordinating time scales can be a key element in improved design.

For life cycle design to be effective, corporations must also make long-term investment decisions that assure corporate survival. Actions include:

- Identifying and planning reduction of a company's environmental impacts
- Discontinuing/phasing out product lines that have unacceptable environmental impacts
- Investing in research and development of low-impact technology
- Investing in improved facilities/equipment
- Recommending regulatory policies that assist life cycle design
- Educating and training employees in life cycle design

Management should develop short- and long-term environmental goals that are sufficiently detailed to guide design. Corporate goals, which often focus on in-house activities, should not lead to increased burdens in other life cycle stages. Examples of

GENERAL MOTORS ENVIRONMENTAL PRINCIPLES

As a responsible corporate citizen, General Motors is dedicated to protecting human health, natural resources and the global environment. This dedication reaches further than compliance with the law to encompass the integration of sound environmental practices into our business decisions.

The following environmental principles provide guidance to General Motors personnel worldwide in the conduct of their daily business practices.

1. We are committed to actions to restore and preserve the environment.
2. We are committed to reducing waste and pollutants, conserving resources and recycling materials at every stage of the product life cycle.
3. We will continue to participate actively in educating the public regarding environmental conservation.
4. We will continue to pursue vigorously the development and implementation of technologies for minimizing pollutant emissions.
5. We will continue to work with all governmental entities for the development of technically sound and financially responsible environmental laws and regulations.
6. We will continually assess the impact of our plants and products on the environment and the communities in which we live and operate with a goal of continuous improvement.

well-defined environmental goals include phasing out the use of specific chemicals under a specific timeline, reducing Toxic Release Inventory (TRI) chemicals by set targets, enhancing the energy efficiency of the product in use, and reducing packaging waste from suppliers to a specific target level. An example of corporate environmental goals is provided in Section 5, which profiles the AT&T Demonstration Project.

Core Competency

Effective strategy requires management to correctly assess the company's strengths, capabilities, and resources. If an environmentally responsible strategy is to succeed, the underlying technological capability and human skills or "core competence" of a corporation must be reconfigured to support that strategy.[15] Focus on core competence is also a commitment to guide product and process improvements by working across organizational boundaries.[15] Life cycle design initiatives thus benefit from corporate efforts to improve core competence.

Organization

Designing an organization that can successfully fulfill its vision requires effective planning processes and the appropriate organizational structure and responsibilities.

Planning

Corporate programs striving to improve environmental performance must integrate environmental issues into all planning processes. Investment, marketing, and research and development initiatives should include environmental considerations in addition to other business concerns. Effective planning depends on including all of the appropriate internal stakeholders. An organizational structure that supports all necessary communication and matches environmental goals with corporate culture enables successful planning.[11, 13]

Organizational Design

Environmental management systems should be buttressed by an appropriate organizational structure including an environmental officer at the highest level of the organization and management that supports cross-functional cooperation. Ideally, each unit of the organization has environmental responsibilities that cascade down to all levels of management and production. Organizational structure also provides accountability for environmental improvement and avenues for continuous feedback from employees and external sources. **Figure 3-3** shows the organizational structure for Xerox's environmental leadership program.

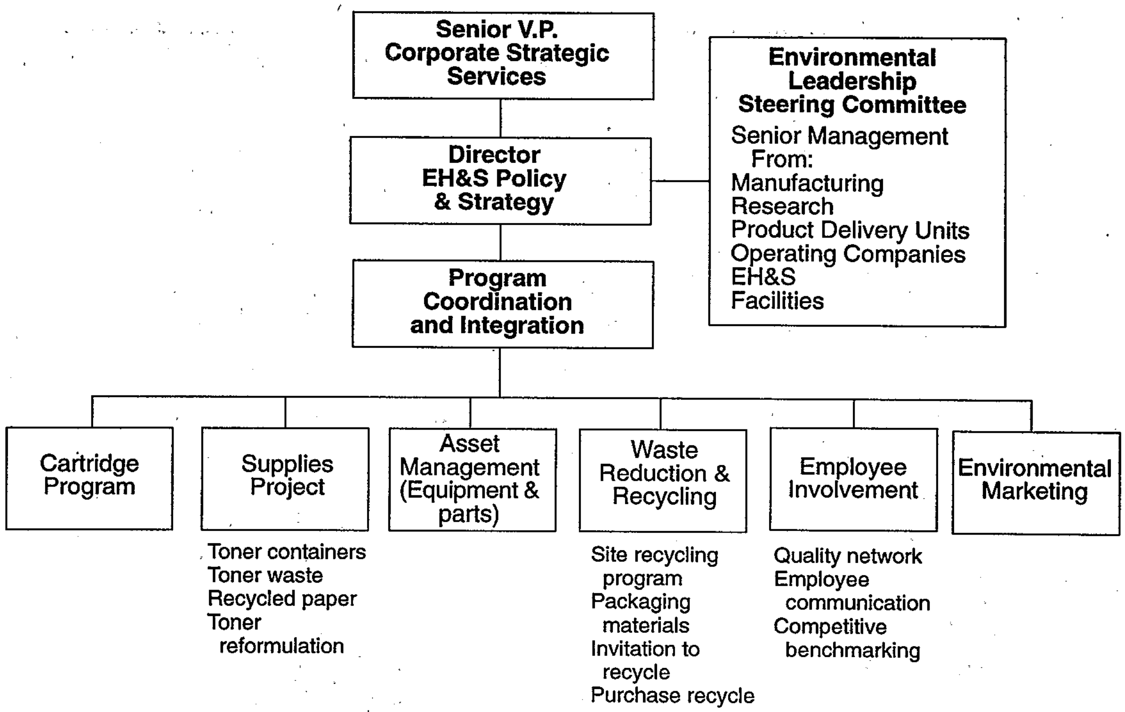


Figure 3-3. Xerox's Organization Chart

Concurrent Design and Cross Functional Teams

Traditionally, product and process design have been treated as two separate functions. This can be characterized by a linear design sequence: product design followed by process design. In the last two decades, much progress has been made through process-oriented pollution prevention and waste minimization approaches. Product-oriented approaches are also now gaining recognition. Concurrent design seeks to reduce environmental impacts associated with the entire product system by integrating product and process design.

Concurrent design is a logical extension of concurrent manufacturing, a procedure based on simultaneous design of product features and manufacturing processes. In contrast to projects that isolate design groups from each other, concurrent design brings participants together in a unified team. By having all actors responsible for separate stages or components of a product's life cycle participate in a project from the outset, problems that often develop between different disciplines can be reduced. Product quality can also be improved through such cooperation, while efficient teamwork helps reduce development time and lower costs.

Figure 3-4 depicts the various members of the design team that could participate in

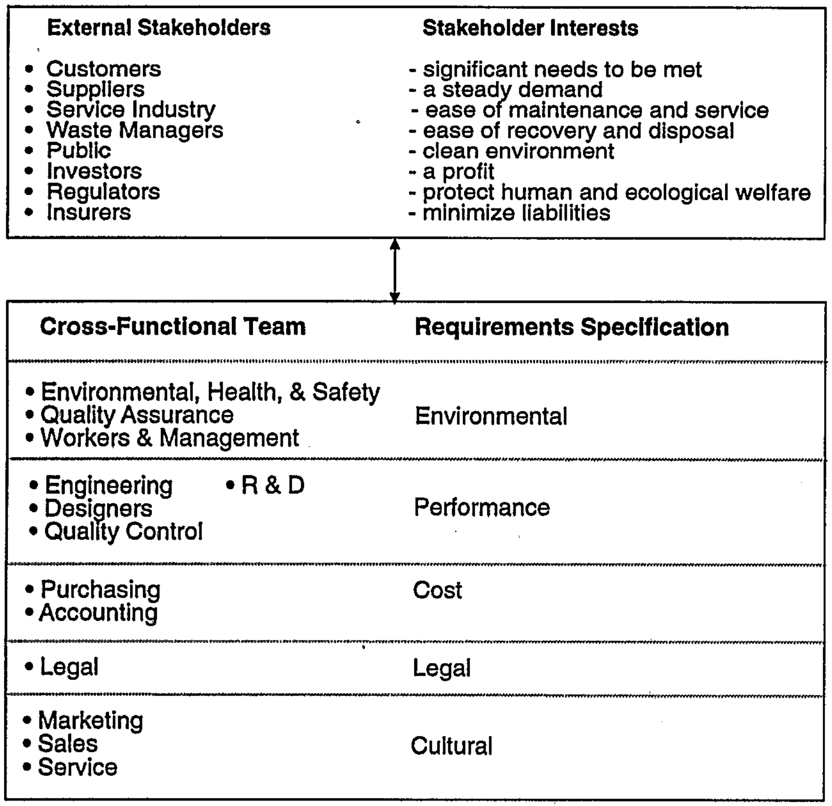


Figure 3-4. Cross-Functional Design Team Interacts with External Stakeholders to Develop Product System Requirements

product development and graphically shows how the cross-functional team translates the interests and needs of external stakeholders into product system requirements. The product system links these diverse groups together.

Information Management Systems

Collecting, analyzing, and reporting/disseminating information are functions of information management systems. Communications links that support environmental management systems are also part of an effective information system.

As a first step, material, energy, cost, performance, and legal/permitting data are collected from all life cycle stages of the product system. This information is then placed in a comprehensive, accessible information system and used for compliance reporting and continuous improvement analyses. Effective information management systems are capable of meeting all internal communications purposes and external reporting /permit requirements. Information management systems also provide a data bank that may be used to respond to public inquires or other external stakeholder questions. **Figure 3-5** illustrates how data may be collected from various sources and used for internal and external purposes.

A properly administered and updated information system supports life cycle design

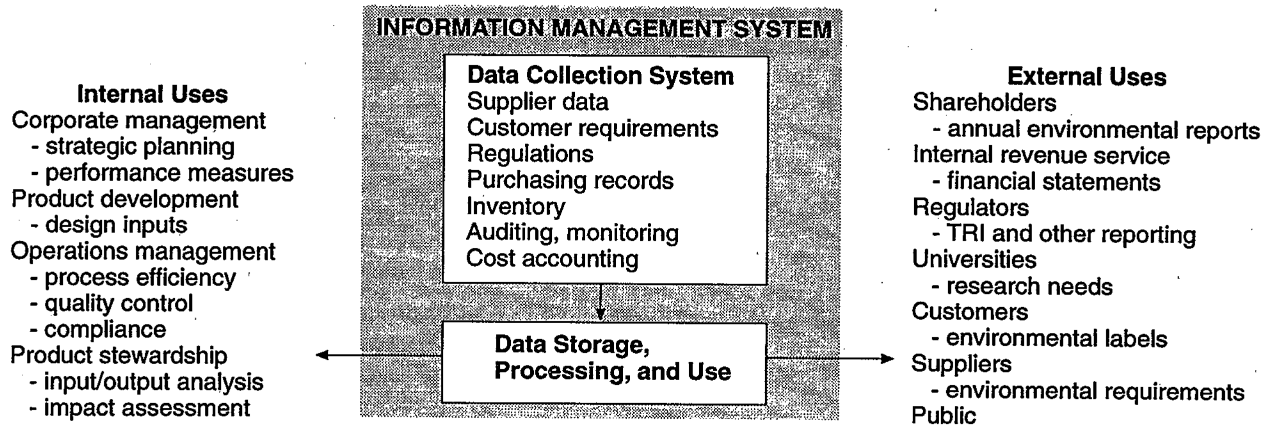


Figure 3-5. Internal and External Uses for an Information Management System

efforts by providing the data needed to analyze baseline conditions and determine which design strategies will minimize the environmental burden of the product system. An information system should also record results of the life cycle design process so that future improvement efforts may benefit from previous initiatives. Corporate communications efforts can take advantage of information management systems by using them to provide feedback on progress or problems to all levels of the organization.

In addition to internal communication, an information system facilitates communication of environmental results to external stakeholders including regulators and potential customers.

Marketing and product labeling provide opportunities to communicate environmental information to customers. Environmental marketing activities can be classified according to **Figure 3-6.** Examples of several ecologos are presented in **Figure 3-7.**

Award of these logos is based on various criteria ranging from a qualitative

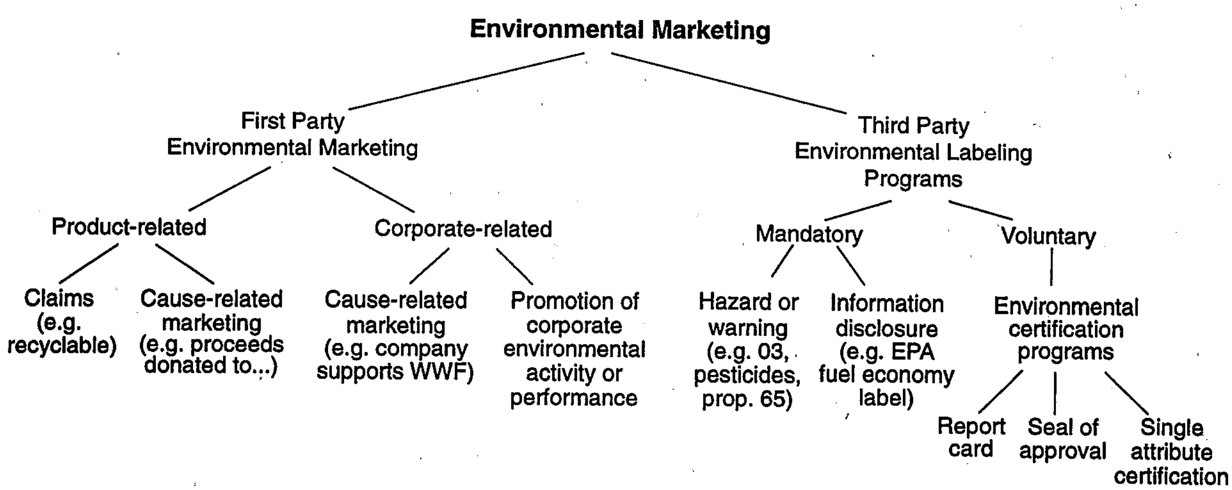


Figure 3-6. Environmental Marketing [16]

Figure 3-7. Ecologos

assessments to quantitative measures. Most are intended to help consumers make more informed purchasing decisions. Some logos attempt to reflect life cycle information, but cost and data limitations currently limit the efficacy of such efforts.

Unfortunately, some firms have responded to public concern for the environment with improper environmental advertising, prompting several State Attorneys General to file law suits against them.

In related action, the Federal Trade Commission (FTC) issued guidelines "to help reduce consumer confusion and prevent the false or misleading use of environmental terms such as "recyclable," "degradable," and "environmentally friendly" in the advertising and labeling of products in the marketplace." For example, the guidelines state, "In general, a product or package should not be marketed as recyclable unless it can be collected, separated, or otherwise recovered from the solid waste stream for use in the form of raw materials in the manufacture or assembly of a new product or package. Unqualified recyclable claims may be made if the entire product or package, excluding incidental components, is recyclable."

Continuous Improvement

Total Quality Management (TQM) is widely recognized as an effective strategy for improving corporate performance. The basic elements of TQM are as follows:[17-22]

- Primacy of the customer
- Measurement systems that provide continuous feedback
- More extensive use of external information (benchmarking)
- A focus on processes rather than departments or events
- Strong emphasis on training
- Extensive use of teams
- Suggestions systems designed to promote continuous improvement
- A robust program of recognition and reward
- CEO commitment and involvement

Environmental issues are increasingly seen as an integral component of continuous improvement in both the corporate and environmental fields. This has lead to a movement called Total Quality Environmental Management (TQEM). TQEM extends traditional quality tenets to the management of corporate environmental matters as well as those of process efficiency and product performance.

TQEM can help lay the groundwork for implementing life cycle design. By including the environment as a customer, TQEM focuses company attention on continuously improving environmental performance. A discussion of several aspects of corporate environment improvement programs that are critical to life cycle design follows.

Performance Measures: Environmental Metrics

The progress of design projects should be clearly assessed with appropriate measures to help members of the design team achieve environmental goals. Consistent measures of impact reduction in all phases of design provide valuable information for design analysis and decision making. It is important to establish measures that cover resource efficiency, waste generation in all media, ecosystem sustainability, and human health.

Companies can measure progress toward stated goals in several ways. In each case, life cycle design is likely to be more successful when environmental aspects are part of a firm's incentive and reward system.

Reward & Recognition

Even though life cycle design can cut costs, increase performance, and lead to greater profitability, it may still be necessary to include discrete measures of environmental responsibility when assessing an employee's performance. If companies claim to follow sound environmental policies, but never reward and promote employees for reducing adverse environmental impacts, managers and workers will naturally focus on other areas of the business.

Auditing, Compliance Monitoring & Reporting, and Emergency Preparedness

Effective environmental management system require auditing, compliance monitoring and reporting systems to fulfill regulatory mandates. Audit teams should include individuals with environmental credentials and expertise in pollution prevention. Compliance monitoring and reporting is usually undertaken as often as necessary to meet regulatory or permit mandates. However, all companies, even those not involved in regulated activities, may want to track significant materials so that evaluations may be made on their use and disposal as well. Assessment of nonregulated materials should be driven by strategic planning and policy.

Emergency preparedness systems must also exist to control accidents. Emergency preparedness protocols should follow guidelines at least as stringent as those set by the Occupational Safety and Health Administration. Companies may find that reducing accidental risks provides monetary benefit as well as maintaining and improving staff morale.

Research and Development

To help assure that current and future environmental needs are translated into appropriate designs, priorities for global, regional, and local environmental problems developed by the scientific community and the general public should be used to guide product improvement. Research and technology development can then identify new approaches for reducing adverse environmental impacts, while the state of the environment provides a context for design.

Thus corporate research and development properly includes pollution prevention projects such as source reduction, materials/energy reuse, and materials/energy recycling. Investigating methods to reduce environmental burden throughout the entire product life cycle is also part of effective research and development. Companies that participate in industrial technology consortiums, research sponsored by trade associations, and government assisted or public-private collaboration position themselves to gain many potential benefits. Knowledge gained from these activities may yield improved product performance, reduced costs, and reduced pollution.

Training & Education

An effective environmental improvement program also includes training and education programs. Environmental science, policy, and strategy may not be familiar to employees. Education and training helps employees understand the relationship between environmental quality and their own work, and may foster interest in proactive efforts. Training should provide guidance for corporate compliance and pollution prevention programs as well as innovative initiatives such as life cycle design, life cycle inventory analysis, and full-cost accounting. Motorola recently instituted a corporate-wide educational program on environmental awareness for all employees.[23]

EXTERNAL FACTORS IN LIFE CYCLE MANAGEMENT

A corporate environmental program capable of furthering life cycle design must also deal with myriad external factors including government policy and regulations, market demand, infrastructure, and supplier relationships. The success of life cycle design depends on how well corporations communicate their expectations and objectives to these multiple stakeholders. The following section summarizes the key challenges facing corporate environmental leaders in managing external concerns and advancing life cycle design.

Government

Government plays an important role in promoting life cycle design through both regulatory and voluntary programs. The US Congress Office of Technology Assessment (OTA) recently conducted a thorough study of policy options for promoting green product design.[24] Although existing market incentives and environmental regulations have been somewhat effective in promoting sustainable practices, OTA concluded that Congress can foster further progress in this area by: supporting research, providing information for consumers, developing policies that internalize environmental costs, and harmonizing various programs.

Government policies and regulations have become increasingly stringent over the past two decades and will continue in this direction. Companies must make investment decisions under a great deal of uncertainty because it is difficult to predict the regulatory landscape of the future. Companies should make good-faith efforts with regulators to develop and test the most effective regulatory strategies.

Clearly the greatest role government now plays in promoting sustainability is regulating environmental protection. The EPA Pollution Prevention Policy and recent voluntary programs represent significant new approaches to achieving environmental protection. It remains to be seen whether regulations can be rewritten to promote the life cycle design approach for reducing environmental burdens. The EPA Source Reduction Review Project (SRRP) and the new Common Sense Program represent advancements in this direction.

Other countries are pursuing a variety of strategies to promote life cycle design. In Germany, a packaging ordinance, several ecolabeling programs, and various proposed waste ordinances promote extended producer responsibility and thus foster corporate action to reduce environmental impacts associated with products.

Public Demand

Manufacturers must be aware of rising levels of concern for the environment among consumers. Market demand for environmentally responsible products or the boycott of harmful products has forced companies to consider the environment as a core business issue. Product design strategies that reduce environmental impacts as well as costs will provide the greatest potential for manufacturers to meet rising consumer expectations. However, companies may have to implement environmental programs even if no cost advantages are gained merely to stay competitive. Innovative companies may find that adopting life cycle design gains them an advantages in the marketplace.

VOLUNTARY INITIATIVES IN POLLUTION PREVENTION BY THE FEDERAL GOVERNMENT

- 33/50 program
- Green Lights
- Energy Star Computers
- Energy Star Buildings
- Corporate Environmental Leadership Program
- Golden Carrot Award
- Natural Gas Star
- Building Air Quality Alliance
- Waste Wi$e
- WAVE (Water Alliances for Voluntary Efficiency)
- Mobility Partners
- Design for the Environment (DFE) program

Infrastructure

Companies must deal with infrastructure factors that impede environmental efforts, such as inadequate networks to support reuse and recycling. For example, companies may find that the necessary collection, handling, and sorting facilities for recycling are inadequate or not economically viable without public support. In such cases, it may be prohibitively expensive for companies to develop the needed infrastructure on their own. Moreover, secondary markets for some recycled materials are volatile, increasing the risk of investing in a recycling or recovery program.

Supplier Relationships

Life cycle design requires companies to take a systems view of all their operations including upstream and downstream impacts. Manufacturers need to understand the impacts of their products at each stage of the life cycle. Supplier management is a critical component of external environmental management. Corporations should evaluate their suppliers' environmental performance to determine if there are liability risks in conducting business with them or if there are means by which the company may encourage or require the supplier to achieve improved environmental performance. Often opportunities identified in the design process require supplier participation. Effective and open communication with suppliers or substantial influence over supplier activities may be instrumental in reducing the environmental burden of many product systems.

THE COMMON SENSE INITIATIVE

The Common Sense Initiative is designed to achieve greater and more cost effective environmental protection by focusing on regulations for an entire industry rather than on individual pollutants. A team of government officials, national environmental organizations, and industry partners will focus on six areas: review environmental regulations for opportunities to get better environmental results at less cost, promote pollution prevention as a standard business practice and a central ethic of environmental protection, make reporting of environmental information easier, strengthen environmental enforcement, improve the permitting process, and raise incentives for industry to find innovative technologies to solve pollution problems. Subcommittees are currently operating for the following six sectors: auto manufacturing, computers and electronics, iron and steel, metal finishing, petroleum refining, and printing.

National/International Standards

Companies must develop programs to meet national or international standards in order to remain viable competitors in the marketplace. A number of organizations have introduced, or are in the process of developing, standards for implementing environmental management systems or for conducting life cycle analysis including: the International Standards Organization (ISO), the British Standards Association, the Canadian Standards Association, National Sanitation Foundation, the Society for Environmental Toxicology and Chemistry, and the American National Standards Institute, among others.

The following box contains a summary of the subcommittee structure and related topics being addressed by the International Standards Organization.

ISO TC 207 ON ENVIRONMENTAL MANAGEMENT
***SECRETARIAT:* Canada (CSA for SCC)**
TAG Administrator: USA (ASTM)

SC 1 Environmental Management Systems (EMS)
Secretariat: United Kingdom
US TAG: ASQC
Scope: Establish standards for activities to set environmental policy, objectives, and responsibilities and to implement them through planning, measures of effectiveness and control of environmental impact.

SC 2 Environmental Auditing
Secretariat: Netherlands
US TAG: ASQC
Scope: Establish standards for measuring organizational compliance with an environmental management system and for establishing the policies, directives and goals expressed by organizational policy.

SC 3 Environmental Labeling
Secretariat: Australia
US TAG: ASTM
Scope: Develop standard terminology, definitions, symbols, test methods, test summary, reporting standards, etc.

SC 4 Environmental Performance Evaluation (EPE)
Secretariat: USA
US TAG: ASTM
Scope: Guidance for evaluating environmental effects of products and services and the effect of business operations on the environment.

SC 5 Life-Cycle Analysis (LCA)
Secretariat: France
US TAG: ASTM
Scope: Standardized programs for analyzing environmental impacts of products, processes and services during their life cycle, including the production and use of raw materials, manufacturing practices, distribution methods and options related to disposal or recycling.

SC 6 Terms and Definitions
Secretariat: Norway
US TAG: ASTM
Scope: To standardize terminology and coordinate the use of standards with other committee within ISO.

WG Environmental Aspects in Product Standards (EAPS)
Secretariat: Germany
US TAG: ASTM
Scope To develop guidance for use by other technical committees for including environmental elements in existing or forthcoming product standards.

4. LIFE CYCLE DEVELOPMENT PROCESS

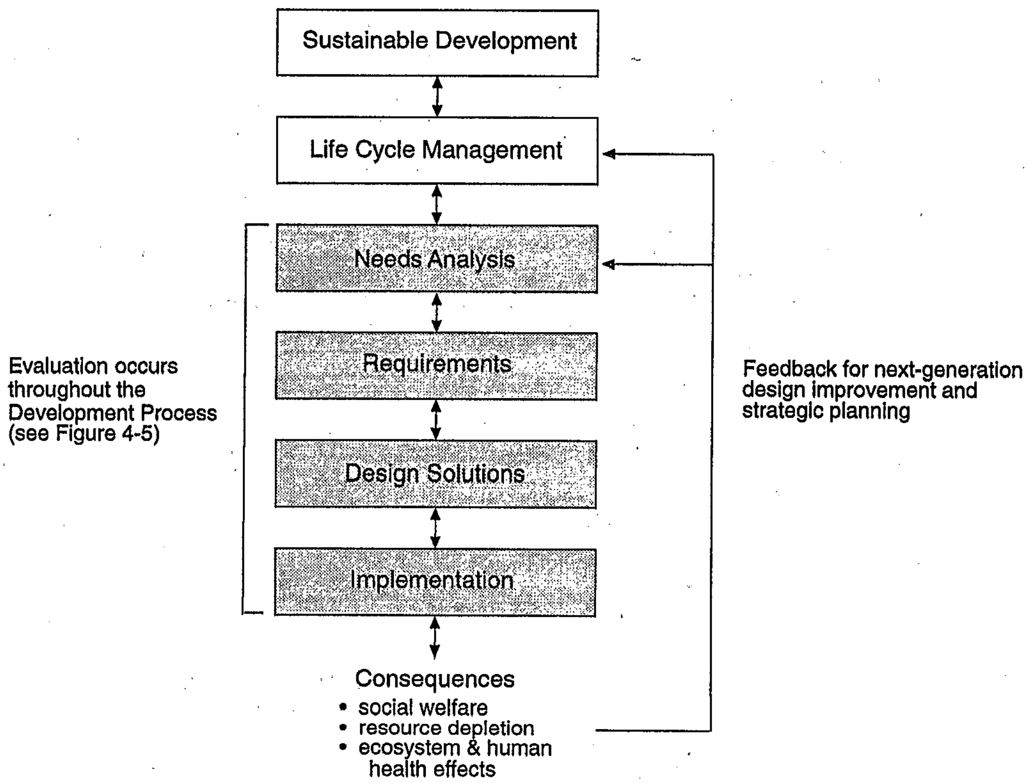


Figure 4-1. Life Cycle Development Process

The life cycle development process, which occurs in the context of sustainable development and life cycle management, is shown in **Figure 4-1**. Design begins with a needs analysis, then includes specification of requirements, selection and synthesis of strategies, evaluation, and final choice of a solution, as introduced in section 2. The design team seeks a solution that satisfies the full set of design requirements while minimizing environmental burden. At this point, an environmental profile for the product system can be estimated.

Implementation of the design solution requires material and energy inputs ,throughout all life cycle stages and results in outputs of products, coproducts, and waste. Environmental consequences of these inputs and outputs include positive and negative social welfare effects, resource depletion, and ecological and human health effects. The actual environmental burden resulting from design implementation then feeds back into the process to guide future design improvements.

Product development is a dynamic, extremely complex process. Each of the steps from the needs analysis through implementation undergo continuous change. **Figure 4-1** shows the iterative nature and feedback mechanisms of the development process.

NEEDS ANALYSIS AND PROJECT INITIATION

A product design project should first clearly identify customers and their needs, then focus on meeting those needs. Ideas for design projects come from many sources, such as customer focus groups and research and development efforts. Environmental assessment of existing products may also uncover opportunities for design improvements that target major impacts for reduction or elimination.

Identify Significant Needs

Life cycle development projects should focus on filling significant customer and societal needs in a sustainable manner. Avoiding confusion between trivial desires and basic needs is a major challenge of life cycle design. Unless life cycle principles such as sustainable development shape the needs analysis, design projects may not create low-impact products. By including environmental criteria in the set of customer requirements that must be satisfied, designers are motivated to focus on environmental improvement.

Product development managers should first recognize that environmental impacts can be substantially reduced by ending production of environmentally damaging product lines for which lower-impact alternatives are available. In the short term, this may conflict with corporate economic goals.

Define Project Scope and Purpose

Set System Boundaries

Setting system boundaries requires determining which stages of the product life cycle will be emphasized by the design team as well as setting appropriate spatial and temporal scales. In choosing an appropriate system boundary, the development team should initially consider the full life cycle from raw material acquisition to the ultimate fate of residuals. Beginning with the most comprehensive system, design and analysis can focus on the:

- full life cycle,
- part of the life cycle, or
- individual stages or activities.

Choice of the full life cycle system provides the greatest opportunities for overall adverse impact reduction.

In some cases, the development team may confine analysis to a part of the life cycle consisting of several stages or even a single stage. Stages can be omitted if they are static or not affected by a new design. As long as designers working on a more limited scale are aware of potential upstream and downstream impacts, environmental goals can still be reached. Even so, a more restricted scope will reduce possibilities for design improvement.

After life cycle endpoints are decided, the project team should define how analysis will proceed. Depth of analysis determines how far back indirect inputs and outputs will be traced. Materials, energy, and labor are generally traced in a first level analysis. A second level analysis accounts for facilities and equipment needed to produce items on the first level.

The basis for analysis should be *equivalent use*, defined as the delivery of equal amounts of product or service. This allows alternate designs to be accurately compared.

Spatial and temporal boundaries must also be determined prior to system evaluation. The time frame or conditions under which data were gathered should be clearly identified. Often performance of industrial systems varies over time, so it is best to gather data that reflect the appropriate range of possibilities. Presenting worst- and best-case scenarios or using well-considered averages helps avoid distortions caused by gathering data under unusual conditions.

In regard to spatial conditions, the design team must recognize that the same activity may have quite different impacts in different places. For example, water use in arid regions has a greater resource depletion impact than in areas where water is abundant.

Establish Schedule and Allocate Budget

After a project has been well defined and deemed worth pursuing, a project time line and budget should be proposed. Life cycle design requires funds for environmental analysis of designs. Managers should recognize that budget increases for proper environmental analysis can pay future dividends in avoided costs and added benefits that outweigh the initial investment. However, the choice of analysis tools may be limited by reasonable financial considerations. For example, most small firms can not yet afford the substantial cost of a comprehensive life cycle assessment.

Baseline and Benchmark Environmental Performance

Evaluating *baseline* conditions of manufacture, use/service, and end-of-life management helps life cycle designers gain an understanding of the environmental profile of an existing or future product system. *Benchmarking* activities properly target design improvements by gathering information about the best products that fulfill similar customer needs. While companies have programs that compare their product performance and cost against the competition, environmental criteria are generally more difficult to benchmark due to lack of information, insufficient scientific understanding, and limited availability of resources.

Baseline Analysis

The purpose of a baseline analysis is to understand the environmental profile of the existing product system. Baseline analysis of existing products may indicate opportunities for improving a product system's environmental performance.[25, 26]

Baseline analysis may consist of a life cycle inventory analysis, audit team reports, or monitoring and reporting data. In all cases, process flow diagrams are useful for synthesizing data. Baseline analysis can be used to help the design team formulate both general design goals and detailed design requirements. Section 6 describes how AlliedSignal's life cycle design team conducted a baseline analysis of an existing product.

The following sources of environmental data for baseline analysis can be helpful in evaluating internal environmental performance:

- life cycle inventory
- purchasing and accounting records
- monitoring reports
- quality assurance and quality control
- legal department
- audit reports
- compliance records
- community relations activities

Benchmarking

Benchmarking is the practice of comparing programs or processes with the intent of establishing reference points for continuous improvement. Because benchmarking activities have been widely practiced by industry, many sources of information on methodologies exist. However, corporations may not have experience in benchmarking competitor's environmental performance or practices.

Life cycle assessment is one means of performing a comprehensive comparative analysis. LCA inventories have been used for comparing products such as polyethylene and paper grocery sacks or hard surface and mix-your-own cleaning systems.[27, 28] However, this tool has several limitations, not the least of which is that LCA activities are influenced by the availability of company resources. Regardless of methods chosen, the following basic guidelines apply to benchmarking:[25]

- Plan and determine goals and scope of benchmarking study
- Collect preliminary data
- Select "best-in-class"
- Ascertain data on best-in-class
- Review and assess data in teams
- Develop implementation plan
- Assess program performance continuously

Sources of data useful for benchmarking the environmental performance of existing product lines include:

- clearinghouses
- published surveys
- published consulting reports and corporate magazines
- workshops, conferences, and roundtables
- EPA programs e.g., 33/50, Green Lights, DFE
- government reports and task force papers
- annual reports and SEC filings
- periodicals and journals
- global environmental management initiative
- state and local regulatory agencies
- census data
- interviews with academia and industry

In addition to these sources, companies can apply reverse engineering analysis to competitors' products. This approach offers specific information about material composition and other aspects of design, such as performance and assembly details. Baselining and benchmarking may reveal significant vulnerabilities associated with environmental risks or liability, performance standards, cost, or cultural issues such as brand-name recognition or image. An equally important aspect of these exercises is indicating opportunities for improvement in environmental and other design criteria.

Identify Opportunities and Vulnerabilities

In this phase of the life cycle development process, current and future design goals are stated explicitly. Design goals must be compatible with a company's overall strategic direction. Elements of strategy that have to be addressed when identifying design goals include corporate goals, consumer markets, the competition, image, and other fundamental business criteria.

Table 4-1. Systematic Evaluation of Overall Product Design Strategy (with examples)

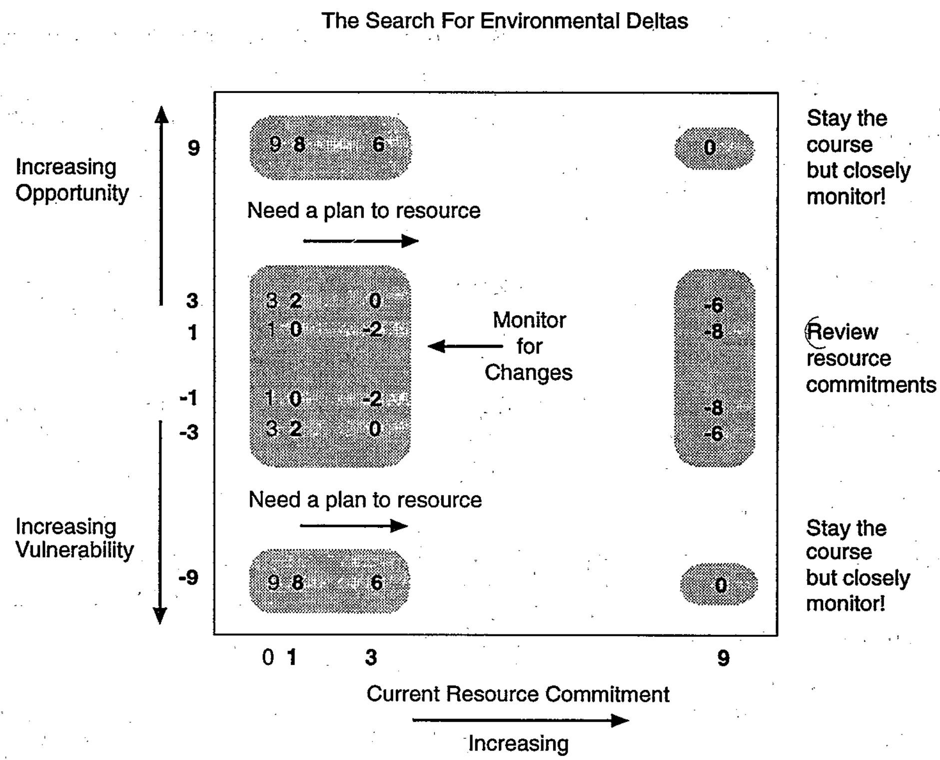
Benchmark "Best-In-Class"	Baseline Existing Product Line	Current Design Goals	Future Design Goals
Analysis of Competitor Position	Current Operations	Opportunities for Incremental Improvement	Strategic Goals & Direction
Environmental programs, performance, and technology	Results of environmental profile	Reduce TRI emissions by 20% Improve resource efficiency of product	Abandon current product and introduce improved design
Performance rating including product test results and substitute products	Performance rating including product test results and consumer feedback	Attain highest product rating in class	Improve performance and maintain superiority
Financial comparison including economies of scale, government subsidy, excess cash, fixed costs	Cost per unit output, labor and materials	Hold product at current cost	Reduce life cycle cost to users
Legal advantage from government or patents and liabilities	Legal liabilities	Meet or exceed existing regulatory requirements	Influence regulations and policy to promote sustainable products
Cultural advantage including consumer preference or brand name recognition	Market niche or cultural advantages	Expand into multicultural market	Market environmental claims; capture global market share

The results of the design team's baseline analysis and benchmarking activities can serve as a basis for developing a short- and long-term goal horizon. **Table 4-1** presents a format for integrating baseline and benchmarking information with current and future design goals. Examples of opportunities and vulnerabilities for product improvement are indicated as well.

The goals established during the needs analysis serve as guides to setting performance requirements and weighting product design requirements.

Dow Chemical Company has developed a matrix tool for assessing environmental opportunities and vulnerabilities across the major life cycle stages of the product system. Opportunities and vulnerabilities are assessed for the following core environmental issues: safety, human health, residual substances, ozone depletion, air quality, climate change, resource depletion, soil contamination, waste accumulation, and water contamination. Corporate resource commitments may then be changed to more closely match the assessed opportunities and vulnerabilities.

Figure 4-2 shows a tool that Dow has developed to prioritize resource allocation for environmental improvement. Areas that represent the greatest environmental deltas (i.e.,



Courtesy of Scott Noesen, Dow Chemical Company

Figure 4-2. Dow Opportunities and Vulnerabilities Matrix

high opportunity or vulnerability and low current resource allocation, or low opportunity or vulnerability and high current resource allocation) are targeted for change.

REQUIREMENTS

After establishing project goals, life cycle designers must identify and weight product system requirements. Life cycle design requires that the product realization team identify explicit criteria for environmental performance at the same time that specifications are set for performance, cost, legal, and cultural requirements. Product realization teams also need to weight the importance of all design requirements. Carefully assigning priority to various design requirements helps resolve conflicts at the earliest stages of design and defines the solution space for later efforts.

Formulating requirements may well be the most critical phase of design.[29] Requirements define the expected outcome and thus are crucial for translating needs and environmental goals into an effective design solutions. Design usually proceeds more efficiently when the solution is clearly bounded by well-considered requirements. In later phases of design, alternatives are evaluated on how well they meet requirements.

Incorporating environmental requirements into the earliest stage of design can reduce the need for later corrective action. Pollution control, liability, and remedial action costs can be greatly reduced by developing environmental requirements that address the full life cycle at the outset of a project. Life cycle design also seeks to integrate environmental requirements with traditional performance, cost, cultural, and legal requirements. All requirements must be properly balanced in a successful product. An environmentally preferable product that fails in the marketplace benefits no one.

Regardless of the project's nature, the expected design outcome should not be overly restrictive nor should it be too broad. Requirements defined too narrowly eliminate potentially attractive designs from the solution space. On the other hand, vague requirements (such as those arising from corporate environmental policies that are too broad to provide specific guidance), lead to misunderstandings between potential customers and designers while making the search process inefficient.

The majority of product system costs are fixed in the design stage. Activities through the requirements phase typically account for 10-15% of total product development costs, yet decisions made at this point can determine 50- 70% of costs for the entire project.[30, 31]

Requirements matrices, design checklists, and other methods are available to assist the design team in establishing requirements. Requirements can also be established by formal procedures such as Quality Function Deployment (QFD).

Checklists

Checklists are usually a series of questions formulated to help designers be systematic and thorough when addressing design topics. Environmental design checklists that accommodate quantitative, qualitative, and inferential information in different design stages have been offered for consideration. As an example, AT&T developed proprietary checklists for Design for Environment (DFE) that are similar to the familiar Design for Manufacturability (DFM) checklists. In the AT&T model, a Toxic Substance Inventory checklist is used to identify whether a product contains a select group of toxic metals.

The Canadian Standards Association is currently developing a Design for the Environment standard which includes checklists of critical environmental core principles. A series of yes/no questions are being proposed for each major life cycle stage: raw materials acquisition, manufacturing, use, and waste management.

Checklists are not difficult to use but they must be compiled carefully to avoid placing excessive demands on designers' time. Generic checklists can also interfere with creativity if designers rely on them exclusively to address environmental issues, thereby failing to focus on the issues that are most important to their specific project.

Matrices

Matrices allow product development teams to study the interactions between life cycle requirements. **Figure 4-3** shows a multilayer matrix for developing requirements. The matrix for each type of requirement contains columns that represent life cycle stages.

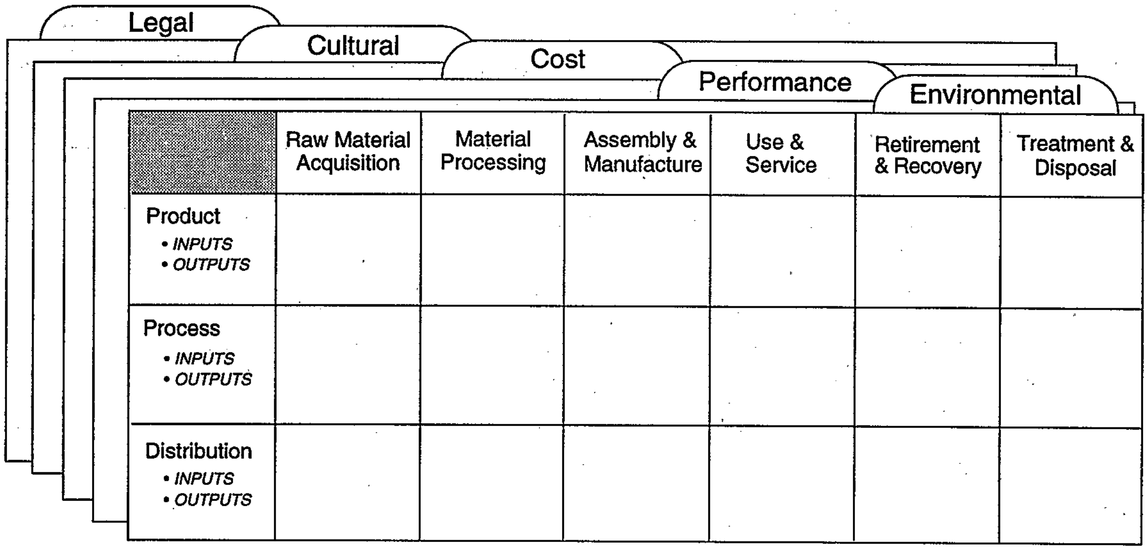


Figure 4-3. Conceptual Multilayer Matrix for Developing Requirements

Rows of each matrix are formed by the product system components described in Section 2: product, process, and distribution. Each row can be subdivided into inputs and outputs. Elements can then be described and tracked in as much detail as necessary. **Table 4-2** shows how each row in the environmental matrix can be expanded to provide more detail for developing requirements.

Table 4-2. Example of Subdivided Rows for Environmental Requirements Matrix.

	Product	Process	Distribution
Inputs			
Materials	Content of final product	Direct: process materials Indirect: *1st level (equipment and facilities, office supplies,)* *2nd level (capital and resources to produce 1st level)*	Packaging Transportation *Direct (e.g., oil & brake fluid)* *Indirect (e.g., vehicles and garages)* Office supplies Equipment and facilities
Energy	Embodied energy	Process energy (direct and indirect)	Embodied in packaging Consumed by transportation (Btu/ton-mile) Consumed as power for administrative services, etc.
Human Resources		Labor (workers, managers) Users, consumers	Labor (workers, managers)
Outputs			
	Products Coproducts Residuals	Residuals Generated energy	Residuals

The requirements matrices shown in **Figure 4-3** are strictly conceptual. Practical matrices can be formed for each class of requirements by further subdividing the rows and columns of the conceptual matrix. For example, the manufacturing stage could be subdivided into suppliers and the original equipment manufacturer. The distribution component of this stage might also include receiving, shipping, and wholesale activities. Retail sale of the final product might best fit in the distribution component of the use phase.

There are no absolute rules for organizing matrices. Information may be classified according to quantitative/qualitative, present/future, and must/want requirements. Development teams should choose a format that is appropriate for their project. Sections 5 and 6 describe the application of requirements matrices for the AT&T and AlliedSignal Demonstration Projects.

Following is a discussion of the environmental, performance, cost, legal, and cultural requirements that constitute the matrices.

Environmental Requirements

Environmental requirements should be developed to minimize:

- the use of natural resources (particularly nonrenewables)
- energy consumption
- waste generation
- health and safety risks
- ecological degradation

By translating these goals into clear functions, environmental requirements help identify and constrain environmental impacts and health risks.

Table 4-3 lists issues that can help development teams define environmental requirements. This manual cannot provide detailed guidance on environmental requirements for each business or industry. Although the lists in **Table 4-3** are not complete, they introduce many important topics. Depending on the project, teams may express these requirements quantitatively or qualitatively. For example, it might be useful to state a requirement that limits solid waste generation for the entire product life cycle to a specific weight.

In addition to criteria uncovered through needs analysis or benchmarking, government policies can also be used to set requirements. For example, the Integrated Solid Waste Management Plan developed by the EPA in 1989 targets municipal solid waste disposal for a 25% reduction by 1995.[2] Other initiatives, such as the EPA's 33/50 program are aimed at reducing toxic emissions. It may benefit companies to develop requirements that match the goals of these voluntary programs.

It can also be wise to set environmental requirements that exceed current government regulations. Such requirements may have been identified while investigating opportunities and vulnerabilities early on in the needs analysis. Designs based on such

Table 4-3. Issues to Consider When Developing Environmental Requirements

Materials and Energy			
Amount	*Character*	*Resource Base*	*Impacts Caused By Extraction and Use*
Type	Virgin	Location	Material /energy use
Renewable	Reused/recycled	- local vs. other	Residuals
Nonrenewable	Reusable/ recyclable	Scarcity	Ecosystem health
		Quality	Human health
		Management/ restoration practices	
Residuals			
Type	*Characterization*	*Environmental Fate*	
Solid waste	Nonhazardous	Containment	Treatment/disposal impacts
Air emissions	- constituents, amount	Bioaccumulation	
Waterborne	Hazardous, Radioactive	Degradability	
	- constituents, amount, concentration, toxicity	Mobility/transport	
Ecological Health			
Ecosystem Stressors	*Impact Categories*	*Impacts*	*Scale*
Physical	Diversity	System structure and function	Local
Biological	Sustainability, resilience to stressors	Sensitive species	Regional
Chemical			Global
Human Health and Safety			
Population at Risk	*Exposure Routes*	*Toxic Character*	*Accidents*
Workers	Inhalation, skin contact, ingestion	Acute effects	Type & frequency
Users		Chronic effects	*Nuisance Effects*
Community	Duration & frequency	Morbidity /mortality	Noise & odors

proactive requirements offer many benefits. Major modifications dictated by regulation can be costly and time consuming. In addition, such changes may not be consistent with a firm's own development cycles, creating even more problems that could have been avoided.

Performance Requirements

Performance requirements define the functions of the product system. Functional requirements range from size tolerances of parts to time and motion specifications for equipment. Performance requirements for an automobile include fuel economy, maximum driving range, acceleration and braking capabilities, handling characteristics, passenger and storage capacity, and ability to protect passengers in a collision. Environmental requirements are closely linked to and often constrained by performance requirements.

Performance is limited by the following technical factors:.

- thermodynamic limits (e.g., first and second laws of thermodynamics)
- best available technology
- best affordable technology

Practical performance limits are usually defined by best available technology or best affordable technology. Absolute limits to performance are determined by thermodynamics or the laws of nature. Noting the technical limits on product system performance provides designers with a frame of reference for comparison.

Other limits on performance must also be considered. In many cases, process design is constrained by existing facilities and equipment. This constraint affects many aspects of process performance. It can also limit product performance by restricting the range of possible materials and features. In such cases, the success of a major design project may depend on upgrading or investing in new technology.

Designers should also be aware that customer behavior and social trends affect real and perceived product performance. Innovative technology might increase performance and reduce impacts, but possible gains can be erased by increased consumption. For example, automobile manufacturers doubled average fleet fuel economy over the last twenty years, yet gasoline consumption in the US remains nearly the same because more vehicles are being driven more miles.

Although better performance may not always result in environmental gain, poor performance usually produces more impacts. Inadequate products are retired quickly in favor of more capable ones. Development programs that fail to produce products with superior performance can therefore contribute to excess waste generation and resource use.

Cost Requirements

Meeting all performance and environmental requirements does not ensure project success. Regardless of how environmentally responsible a product may be, many customers will choose another if it cannot be offered at a competitive price. In some cases, a premium can be charged for significantly superior environmental or functional performance, but such premiums are usually limited.

Modified accounting systems that better reflect environmental costs and benefits are important to life cycle design. With more complete accounting, many low-impact designs may show financial advantages. Methods of life cycle accounting that can help companies make better design decisions are discussed later in this section.

Cost requirements should guide designers in adding value to the product system. These requirements can be most useful when they include a time frame (such as total user costs from purchase until final retirement) and clearly stated life cycle boundaries. Parties who will accrue these costs, such as suppliers, manufacturers, and customers should also be identified.

Cost requirements need to reflect market possibilities. Value can be conveyed to customers through estimates of a product's total cost over its expected useful life. Total customer costs include purchase price, consumables, service, and retirement costs,

Table 4-4. Example of General Cost Requirements over Product Life Cycle

Life Cycle Stages	Stakeholders	
	Manufacturers	*Consumers*
Raw Materials/Supply	Minimize unit cost of materials or parts	
Manufacturing	Minimize unit cost of production - waste management costs - cost of packaging Administrative	
Use	Product and environmental liability	Purchase price Operating cost - energy - maintenance - repair
Service	Minimize warranty costs	
End-Of-Life Management	Environmental liabilities	Disposal cost

although it does not address full environmental costs. By providing an estimate of total user costs over the product's useful life, quality products may be judged on more than least first cost, which addresses only the initial purchase price or financing charges. **Table 4-4** lists some cost requirements over the product life cycle.

Cultural Requirements

Cultural requirements define the shape, form, color, texture, and image that a product projects. Material selection, product finish, colors, and size are guided by consumer preferences. In order to be successful, a product must meet the cultural requirements of customers.

Decisions concerning physical attributes and style have direct environmental consequences. However, because customers usually do not know about the full environmental consequences of their preferences, creating pleasing, environmentally superior products is a major design challenge. Successful cultural requirements enable the design itself to promote an awareness of how it reduces impacts.

Cultural requirements may overlap with other types of requirements. Convenience is usually considered part of performance, but it is strongly influenced by culture. In some cultures, convenience is elevated above many other functions. Cultural factors may therefore determine whether demand for perceived convenience and environmental requirements conflict.

Legal Requirements

Local, state, and federal environmental, health, and safety regulations are mandatory requirements. Violation of these requirements leads to fines, revoked permits, criminal prosecution, and other penalties. Both companies and individuals within a firm can be held responsible for violating statutes. Firms may also be liable for punitive damages.

Paying attention to legal requirements is clearly an important part of design requirements. Environmental professionals, health and safety staff, legal advisors, and government regulators can identify legal issues for life cycle design. Local, state, federal , and international regulations that apply to the product system provide a framework for legal requirements. Legal and quasilegal requirements include:

- international regulations
- national regulations (US)
- state and local regulations
- voluntary standards

Federal regulations are administered and enforced by agencies such as the Environmental Protection Agency (EPA), Food and Drug Administration (FDA), and the Consumer Product Safety Commission (CPSC). In addition to such federal authorities, many other political jurisdictions enforce environmental regulations. For example, some cities have imposed bans on certain materials and products. Regulations also vary dramatically among countries. The take back legislation in Germany is beginning to draw more attention to end-of-life issues in product design.

Whenever possible, legal requirements should consider the implications of pending and proposed regulations that are likely to be enacted. Such forward thinking can prevent costly problems during manufacture or use while providing a competitive advantage.

Assigning Priority to Requirements

Ranking and Weighting

Ranking and weighting design requirements helps distinguish between critical and merely desirable requirements. After assigning requirements a weighted value, they should be ranked and separated into several groups. An example of a useful classification scheme follows: after[29]

- Must requirements are conditions that designs have to meet. No design is acceptable unless it satisfies all of these must requirements.
- Want requirements are less important, but still desirable traits. Want requirements help designers seek the best solution, not just the first alternative that satisfies mandatory conditions. These criteria play a critical role in customer acceptance and perceptions of quality.

- Ancillary functions are low-ranked in terms of relative importance. Designers should be aware that such desires exist, but ancillary functions can only be expressed in design when they do not compromise more critical functions.

Once must requirements are set, want and ancillary requirements can be assigned priority. There are no simple rules for weighting requirements. Assigning priority to requirements is always a difficult task, because different classes of requirements are stated and measured in different units. Judgments based on the values and experience of the design team must be used to arrive at priorities.

The process of making tradeoffs between types of requirements is familiar to every designer. Asking *How important is this function to the design?* or *What is this function worth (to society, customers, suppliers, etc.)?* is a necessary exercise in every successful development project.

Organizing Requirements

Various approaches can be taken to organize requirements. The must versus want distinction can be a useful guide. The following list provides some additional methods for organizing requirements in each component of the matrix.

Must	Compliance with existing environmental laws
Want	Beyond Compliance
Qualitative	Reduce the use of toxic constituents
Quantitative	Specify a 25% reduction in the use of lead
Present	Current regulations
Future	Future regulations (promulgated phase-out of CFC or take back legislation)
General Criteria	Component recyclable
Environmental Metric	Energy efficiency and energy used per unit of operation

Resolving Conflicts

Development teams can expect conflicts between requirements. If conflicts between must requirements can not be resolved, there is no solution space for design. When a solution space exists but it is so restricted that little choice is possible, must requirements may have been defined too narrowly. The absence of conflicts usually indicates that requirements are defined too loosely. This produces cavernous solution spaces in which virtually any alternative seems desirable. Under such conditions, there is no practical method of choosing the best design.

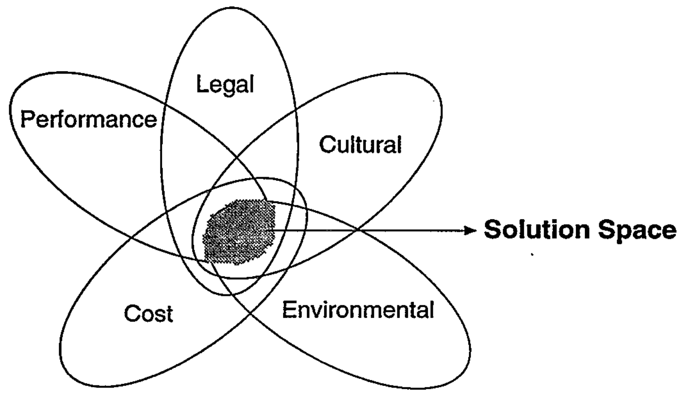


Figure 4-4. Design Solution Space

In all of these cases, design teams need to redefine or assign new priorities to requirements. If careful study still reveals no solution space or a very restricted one, the project should be abandoned. It is also risky to proceed with overly broad requirements. Only projects with practical, well-considered requirements should be pursued. Successful requirements usually result from resolving conflicts and developing new priorities that more accurately reflect customer needs.

DESIGN SOLUTION

Needs analysis and requirements specification provide the ideas, objectives, and criteria that eventually define the design solution space which then shapes the development process from the conceptual design phase through detailed design. The solution space is the intersection of potential design solutions that meet all key environmental, performance, cost, legal, and cultural requirements. **Figure 4-4** illustrates this point graphically. The space in the diagram that each criteria overlaps is the solution space. At this point in development, designers select and synthesize strategies that fulfill the multicriteria design requirements defining the solution space.

Design Strategies

Selecting and synthesizing design strategies for meeting the full spectrum of requirements is a major challenge of life cycle design. Presented by themselves, strategies may seem to define the goals of a design project. Although it may be tempting to pursue an intriguing strategy for reducing environmental impacts at the outset of a project, deciding on a course of action before the destination is known can be an invitation to disaster. Strategies flow from requirements, not the reverse.

Table 4-5. Summary of Design Strategies

General Categories	Specific Strategies
Product Life Extension	Extend useful life Increase durability Ensure adaptability Increase reliability Expand service options Simplify maintenance Facilitate repairability Enable remanufacture of products Accommodate reuse of product
Material Life Extension	Develop recycling infrastructure Examine recycling pathways Use recyclable materials
Material Selection	Use substitute materials Devise reformulations
Reduced Material Intensiveness	Conserve resources
Process Management	Substitute better processes Increase process energy efficiency Increase process material efficiency Improve process control Control inventory and material handling Plan facilities to reduce impacts Ensure proper treatment and disposal
Efficient Distribution	Optimize transportation systems Reduce packaging Use alternative packaging materials
Improved Management Practices	Use office materials and equipment efficiently Phase out high-impact products Choose environmentally responsible suppliers or contractors Encourage eco-labeling and advertise environmental claims

General strategies for fulfilling environmental requirements are shown in **Table 4-5.** An explanation of each strategy is provided in the *Life Cycle Design Guidance Manual* published by EPA. Most of these strategies reach across product system boundaries; life extension, for example, can be applied to various elements in all three product system components.

In most cases, a single strategy will not be best for meeting all environmental requirements. Recycling illustrates this point. Many designers, policymakers, and consumers believe recycling is the best solution for a wide range of environmental problems. Yet, even though recycling can conserve virgin materials and divert discarded material from landfills, it also causes other impacts and thus may not always be the best way to minimize waste and conserve resources.

Single strategies are unlikely to improve environmental performance in all life cycle stages; they are even less likely to satisfy the full set of cost, legal, performance, and cultural requirements. Appropriate strategies need to satisfy the entire set of design requirements shown in **Figure 4-3**, thus promoting integration of environmental requirements into design. For example, essential product performance must be preserved when design teams choose a strategy for reducing environmental impacts. If performance is so degraded that the product fails in the marketplace, the benefits of environmentally responsible design are only illusory.

In most cases, successful development teams adopt a range of strategies to meet design requirements. As an example, design responses to an initiative such as extended producer responsibility [32, 33] are likely to include waste reduction, reuse, recycling, and aspects of product life extension.

EVALUATION

Analysis and evaluation are required throughout the product development process. If environmental requirements for the product system are well specified, design alternatives can be checked directly against these requirements. Tools for design evaluation range from comprehensive analysis tools such as life cycle assessment (LCA) to the use of single environmental metrics. In each case, design solutions are evaluated with respect to the full spectrum of requirements.

Figure 4-5 shows different applications of environmental evaluation tools throughout the development process. Note that the actual environmental burden associated with a product system may differ from the environmental profile estimated during design. Such variation is likely in a dynamic system.

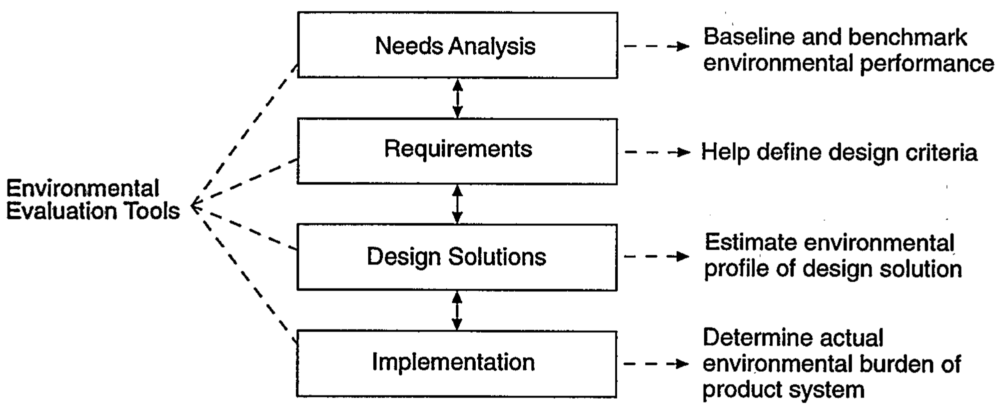


Figure 4-5. Environmental Evaluation In the Development Process

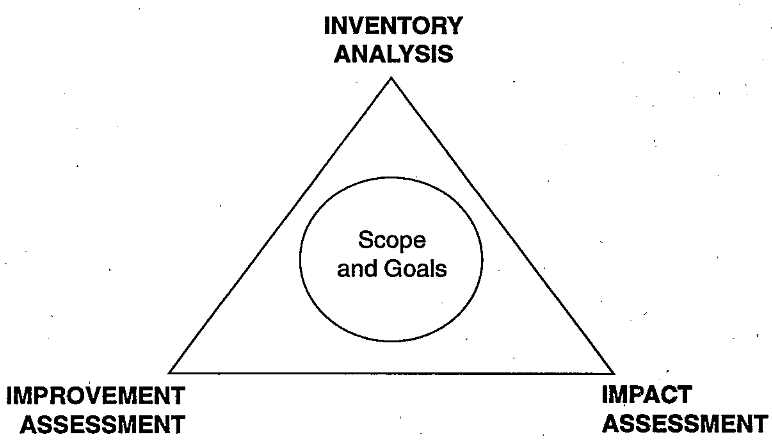


Figure 4-6. LCA Framework[34]

LCA and Its Application to Design

Methodology

Life cycle assessment consists of several techniques for identifying and evaluating the adverse environmental effects associated with a product system.[34-39] The most widely recognized framework for LCA, shown in **Figure 4-6**, consists of inventory analysis, impact assessment, and improvement assessment components.

At present, inventory analysis is the most established methodology of LCA. The following steps for performing a life cycle inventory are described in EPA's Life Cycle Assessment: Inventory Guidelines and Principles[37]:

- Define the purpose and scope of the inventory
- Devise an inventory checklist
- Institute a peer review process
- Gather data
- Develop stand-alone data
- Construct a computational model
- Present the results
- Interpret and communicate the results

For an inventory analysis, a process flow diagram is constructed and material and energy inputs and outputs for the product system are identified and quantified.[37] A template for constructing a detailed flow diagram for each life cycle subsystem is

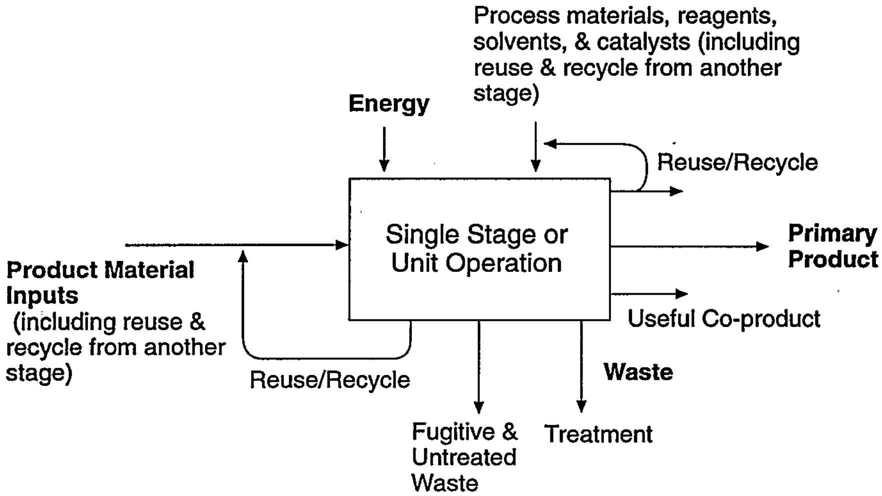


Figure 4-7. Template for Flow Diagram of Life Cycle Subsystem

shown in **Figure 4-7.** This template can be used to conduct an input/output analysis for each substage.

The impact assessment component of the LCA framework, which is still under development, applies quantitative and qualitative techniques to characterize and assess the environmental effects associated with inventory items. EPA and the Society of Environmental Toxicologists and Chemists (SETAC) have classified the impact assessment into three steps: classification, characterization, and valuation. The impact assessment conceptual framework taken from the EPA Impact Assessment Guidelines [40] is shown in **Figure 4-8.**

Impacts are usually classified as resource depletion, human health and safety effects, ecological degradation, and other social welfare effects relating to environmental

DESIGN EVALUATION TOOLS

Life Cycle Assessment
- EPA/SETAC Framework (inventory analysis, impact and improvement assessment)
- DFEIS in matrix (Allenby)
- EPS system (Federation of Swedish Industries)

General Environmental Metrics
- Resource Productivity Index (Sony)
- Waste/unit product

Specific Metrics
- Energy consumed in use stage per unit product
- Percent recycled content; weight of recyclable components/weight of product

Cost Assessment
- Life cycle costing
- Environmental accounting

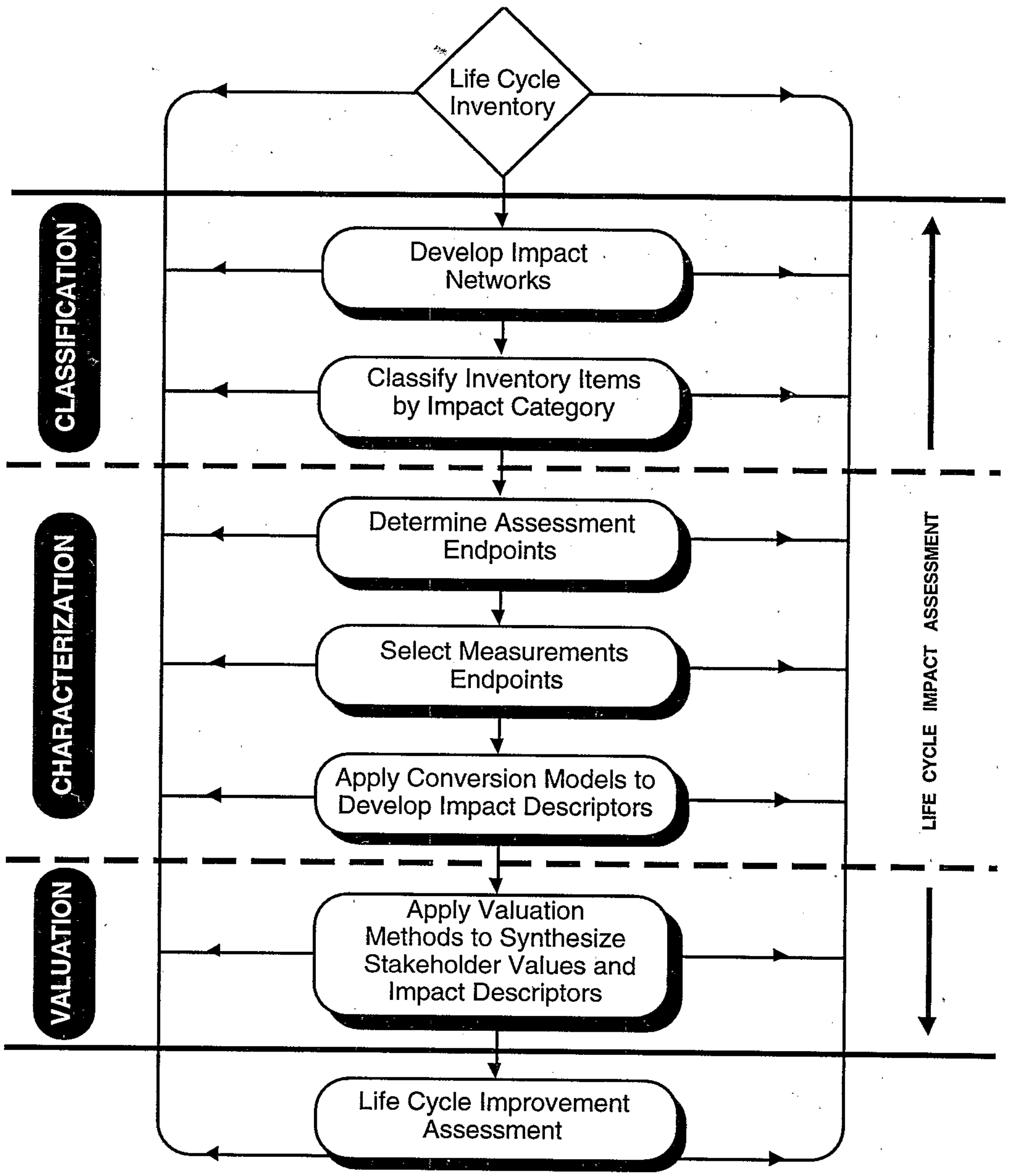


Figure 4-8. Impact Assessment Conceptual Framework[40]

disturbances. In the classification stage, impact networks (linkages between release and environmental impacts) are developed and endpoints for each inventory item are determined.

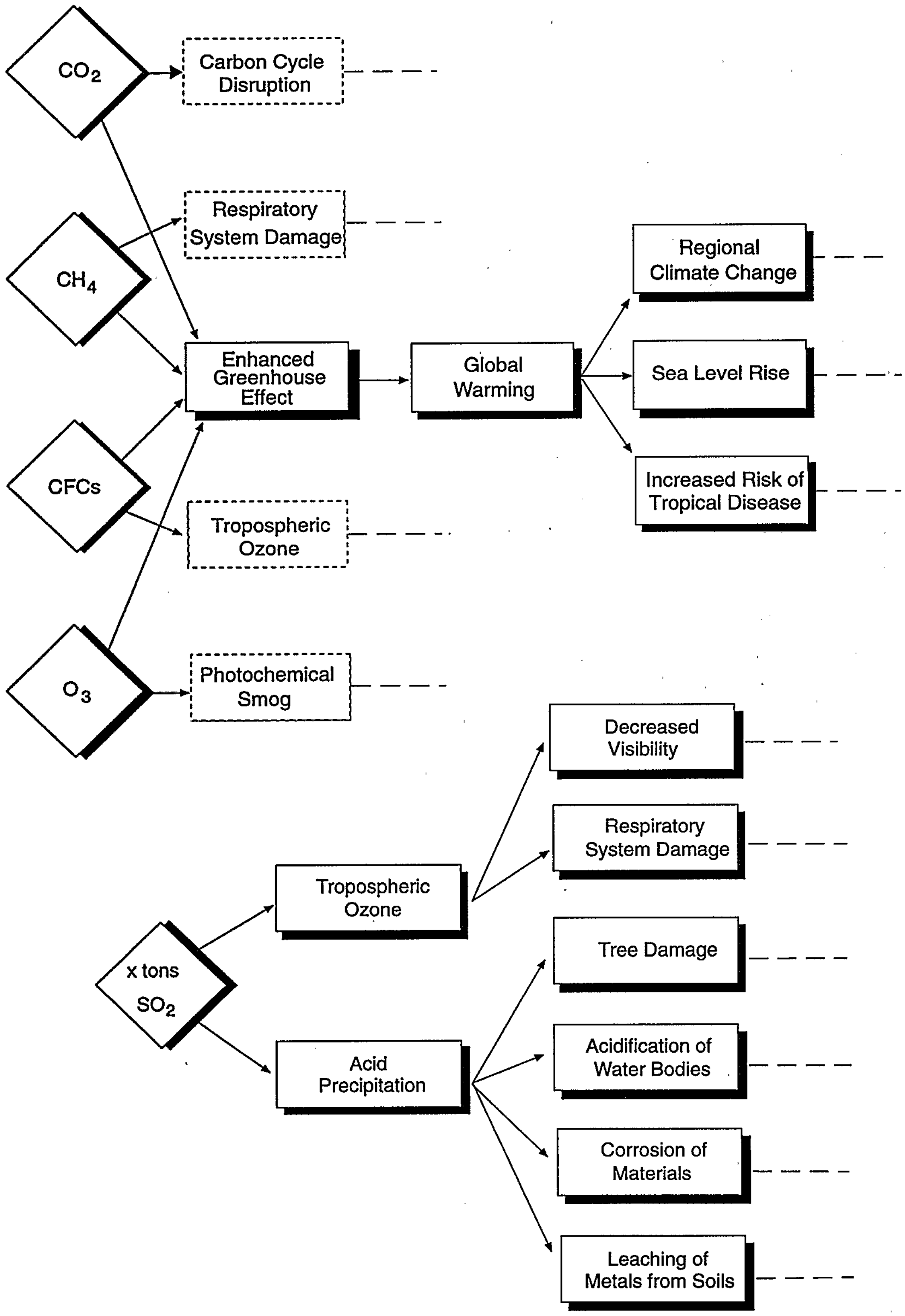


Figure 4-9. Impact Network Examples[40]

An example of an impact network is provided in **Figure 4-9**. A wide range of models can be used to characterize impacts such pollutant transport, exposure assessment, and risk assessment models.

Improvement analysis uses life cycle inventory and/or impact assessment methods to identify opportunities for reducing environmental burdens. This component is under development; there are no widely accepted practices for performing improvement analysis at present.

Other efforts have also focused on developing streamlined tools that are not as rigorous as LCA (e.g. Canadian Standards Association).

LCA and more streamlined approaches can potentially be applied in the needs analysis, requirements specification, and evaluation of conceptual through detailed design phases. Specific uses of LCA are summarized below.

Needs Analysis	Project definition: use streamlined LCA for initial project screening; use improvement analysis to identify opportunities for reducing environmental burdens (e.g., target major impacts). Baseline environmental profile: conduct LCA on the existing product system to establish a baseline for comparative analysis.
Specifying Requirements	Use LCA information for the existing product system to guide improvement of new designs.
Evaluating Design Alternatives	Conceptual design: use streamlined LCA techniques to formulate and evaluate design concepts; at this stage the system is not sufficiently defined to conduct a full-scale LCA. Detailed design: full-scale LCA is possible at this stage, but the design is fixed and opportunities for improvement are limited.

Difficulties

General difficulties and limitations of the LCA methodology are characterized in the following list.[41]

Goal Definition and Scoping	Costs to conduct an LCA may be prohibitive to small firms; time required to conduct LCA may exceed product development constraints especially for short development cycles; temporal and spatial dimensions of a dynamic product system are difficult to address; definition of functional units for comparison of design alternatives can be problematic; allocation methods used in defining system boundaries have inherent weaknesses; complex products (e.g., automobiles) require overwhelming resources to analyze.
Data Collection	Data availability and access can be limiting (e.g., proprietary data); data quality including bias, accuracy, precision, and completeness are often not well addressed.
Data Evaluation	Sophisticated models and model parameters for evaluating resource depletion and human and ecosystem health may not be available or their ability to represent the product system may be grossly inaccurate. Simpler models may be more available, but they can also be less representative or accurate. Uncertainty analyses of the results are often not conducted.
Information Transfer	Design decision makers often lack knowledge about environmental effects, and aggregation and simplification techniques may distort results. Synthesis of environmental effect categories is limited because they are incommensurable.

In principle, LCA represents the most accurate tool for design evaluation in life cycle design and DFE. Many methodological problems, however, currently limit LCA's applicability to design.[41] Costs to conduct a LCA can be prohibitive, especially to small firms, and time requirements may not be compatible with short development cycles.[42, 43] Although significant progress has been made towards standardizing life cycle inventory analysis,[34-38] results can still vary significantly.[44, 45] Such discrepancies can be attributed to differences in system boundaries, rules for allocation of inputs and outputs between product systems, and data availability and quality issues. LCA also generally lacks uncertainty analysis of results.

Incommensurable data presents another major challenge to LCA and other environmental analysis tools. The problem of evaluating environmental data remains inherently complicated when impacts are expressed in different measuring units (e.g., kilojoules, cancer risks, or kilograms of solid waste). Furthermore, different conversion models for translating inventory items into impacts are required for each impact. These models vary widely in complexity and uncertainty. For example, risk assessment and fate and transport models are required to evaluate human and ecosystem health effects associated with toxic emissions. Model sophistication dictates whether additional data beyond inventory results is needed for proper evaluation. Simplified approaches for impact assessment, such as the "critical volume or mass" method [39] have fundamental

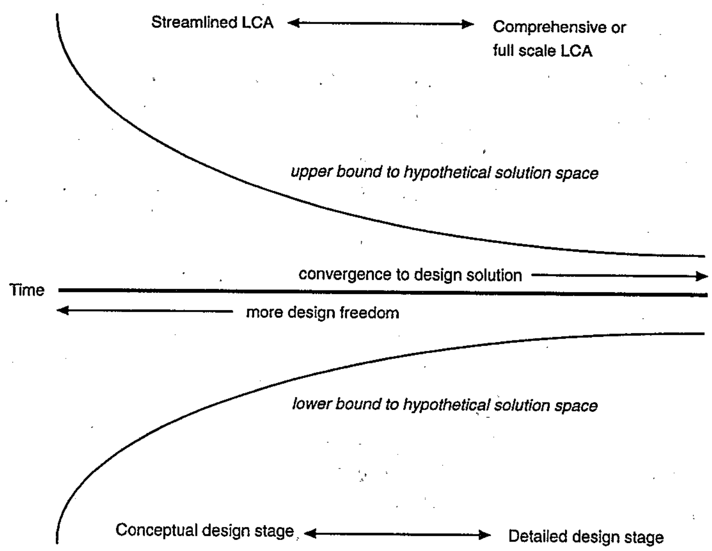


Figure 4-10. Design Solution Space as Function of Time[41]

limitations. These general models are usually much less accurate than more elaborate site-specific assessment models, but full assessment based on site-specific models is not presently feasible.

Other simple conversion models, such as those translating emissions of various gases into a single number estimating global warming potential or ozone depleting potential, are available for assessing global impacts.[46, 47]

Even if much better assessment tools existed, LCA has inherent limitations in design, because the complete set of life cycle environmental effects associated with a product system can not be evaluated until the design has been specified in detail. But at this stage, the opportunities for design change become drastically limited. This condition is represented graphically in **Figure 4-10**.

In the conceptual design phase, the design solution space is wide, whereas in detailed design, the solution space narrows. Thus the feasibility of a comprehensive LCA is inversely related to the opportunity to influence product system design. In addition to these limitations, many of the secondary and tertiary inventory items of a life cycle system that are often neglected in an LCA, such as facilities and equipment, are significant forces that greatly affect product development.

Case Examples of LCA Use in Design

Although numerous life cycle inventories have been conducted for a variety of products,[45] only a small fraction have been used for product development. Proctor and Gamble is one company that has used life cycle inventory studies to guide environmental improvement for several products.[48] One of their case studies on hard surface cleaners revealed that heating water resulted in a significant percentage of total energy use and air emissions related to cleaning.[28] Based on this information, opportunities for reducing impacts were identified which include designing cold water and no-rinse formulas and educating consumers to use cold water.

The Product Ecology Project, a collaboration between European industry and academia, is another example where life cycle inventory and a valuation procedure are used to support product development.[49] For this project, the Environmental Priority Strategies (EPS system) in product design is used to evaluate the environmental impact of design alternatives using a single metric based on environmental load units. An inventory is conducted using the LCA Inventory Tool developed by Chalmers Industriteknik, and valuation is based on a willingness-to-pay model that accounts for biodiversity, human health, production, resources, and aesthetic values. This system enables the designer to easily compare alternatives, but the reliability of the outcome is heavily dependent on the valuation procedure.

LCA Computer Software Tools

LCA software tools and computerized databases may make it easier to apply LCA in design.[37] Examples of early attempts in this area include: SimaPro, developed by the Centre of Environmental Science (CML), Leiden University, Netherlands; LCA Inventory Tool, developed by Chalmers Industriteknik in Göteborg, Sweden, PIA, developed by the Institute for Applied Environmental Economics (TME) in the Hague, Netherlands (available from the Dutch Ministry for Environment and Informatics (BMI)); and PEMS, developed by Pira International in the UK. These tools can shorten analysis time when exploring design alternatives, particularly in simulation studies, but data availability and quality are still limiting factors. In addition to these tools, a general guide to LCA for European businesses has been compiled that provides background and a list of sources for further information.[50]

Other Design Evaluation Approaches

Environmental Indicators and Metrics

In contrast to a comprehensive life cycle assessment, environmental performance indicators or metrics can be used to evaluate design alternatives. Navin-Chandra [51] introduced the following set of environmental indicators: percent recycled, degradability, useful life, junk value, separability, life cycle cost, potential recyclability, possible recyclability, useful life and utilization, total and net emissions, and total hazardous fugitives. Many of these indicators can be calculated relatively easily; the last two, however, require life cycle inventory data to compute.

Watanabe [52] proposes a Resource Productivity measure for evaluating "industrial performance compatible with environmental preservation." Resource productivity is a dimensionless parameter defined as:

$$\text{Resource Productivity} = \frac{(\text{Economic value added}) \times (\text{Product lifetime})}{(\text{Material consumed-Material recycled}) + (\text{Energy consumed for production, recycling}) + (\text{Lifetime energy used})}$$

where the individual terms in the denominator are expressed in monetary units. Longer product life, increased material recycling, and less material and energy consumption all contribute to a higher resource productivity. Watanabe has applied this metric in evaluating three rechargeable battery alternatives.

While resource productivity incorporates many environmental concerns, it is not comprehensive because costs associated with toxic emissions and human and ecosystem health are ignored. In addition, the value added component of the numerator includes other factors besides environmental considerations. Despite these limitations, this metric is relatively simple to evaluate and it accounts for resource depletion, which correlates with many other environmental impacts.

Another design evaluation approach is to develop general classes of environmental criteria and then attempt to measure specific aspects of the criteria with a variety of metrics. This produces data that can be used to evaluate the design against environmental requirements. Some environmental metrics, such as those measuring efficiency, can also serve as metrics for assessing performance and cost requirements. Examples of both environmental criteria and metrics are shown in **Table 4-6.**

Table 4-6. Examples of Environmental Metrics

Criteria	Metrics
Energy	Efficiency in use (energy consumed/unit of use) Production energy efficiency (energy consumed/unit product)
Materials	Material efficiency (mass of material in part/mass of material required for fabrication) Water use efficiency (water/unit of product) Recycling - recycled content (mass of recycled material/mass of product) - recyclability (mass of material in product actually recycled at projected retirement/total product mass)
Energy	Cumulative, all media (kg waste/unit product) Ozone depleting potential (ODP) Global warming potential (GWP) kg of volatile organic compounds (VOCs)/unit product

Matrix Approaches

DFE methods developed by Allenby [53, 54] use a semiquantitative matrix approach for evaluating life cycle environmental impacts. A graphic scoring system weighs environmental effects based on available quantitative information for each life cycle stage. In addition to an environmental matrix and toxicology/exposure matrix, manufacturing and social/political matrices are used to address both technical and non-technical aspects of design alternatives.

Computer Tools

ReStar is a design analysis tool for evaluating recovery operations such as recycling and disassembly.[55] A computer algorithm determines an optimal recovery plan based on tradeoffs between recovery costs and the value of secondary materials or parts.

Cost Analysis

Cost analysis for product development is often the most influential tool guiding decision making. Key issues of environmental accounting are:

- Measuring environmental costs
- Allocating environmental costs to specific cost centers
- Internalizing environmental costs

Life cycle costs can be analyzed from the perspective of three stakeholder groups: manufacturers or producers, consumers, and society at large. Definitions for some accounting and capital budgeting terms relevant to life cycle design are shown below.[57]

Accounting

Full Cost Accounting	A method of managerial cost accounting that allocates both direct and indirect environmental costs to a product, product line, process, service, or activity. Not everyone uses this term the same way. Some include only costs that affect the firm's bottom line, while others include the full range of costs throughout the life cycle, some of which do not have any indirect or direct effect on a firm's bottom line.
Life Cycle Costing	In the environmental field, this has come to mean all costs associated with a product system throughout its life cycle, from materials acquisition to disposal. Where possible, social costs are quantified; if this is not possible, they are addressed qualitatively. Traditionally applied in military and engineering to mean estimating costs from acquisition of a system to disposal. This does not usually incorporate costs further upstream than purchase.

Capital Budgeting

Total Cost Assessment	Long-term, comprehensive financial analysis of the full range of internal (i.e. private) costs and savings of an investment. This tool evaluates potential investments in terms of private costs, excluding social considerations. It does include contingent liability costs.

For life cycle design to be effective, environmental costs need to be allocated accurately to product centers. Environmental costs are commonly treated as overhead. Methods such as activity based costing (ABC) may be useful in properly assigning product costs in many situations, resulting in improved decision making.[57, 58] Properly allocating environmental costs can be one of the most powerful motivators for addressing environmental issues in design.

Unfortunately, the current market system does not fully account for environmental costs, so prices for goods and services do not reflect total costs or benefits. A design that minimizes environmental burden may thus appear less attractive in terms of cost than an environmentally inferior alternative.

The most significant unrealized costs in design are externalities, such as those resulting from pollution, which are borne by outside parties (society) not involved in the original transaction (between manufacturers and customers). Corporations choosing to reduce emissions and internalize the associated costs can find themselves at a competitive disadvantage unless their competitors do so as well.[59] Despite this problem, manufacturers can benefit from pursuing design initiatives which produce tangible savings through material conservation, or reduction in waste management and liability costs.

A number of resources are available to identify full environmental costs.[60, 61] In the EPA Pollution Prevention Benefits Manual, costs are divided into four categories: usual costs, hidden regulatory costs, liability costs, and less tangible costs. Usual costs are standard capital and operating expenses and revenues for the product system, while hidden costs represent environmental costs related to regulation (e.g., permitting, reporting, monitoring). Costs due to noncompliance and future liabilities for forced cleanup, personal injury, and property damage as well as intangible costs/benefits such as effects on corporate image are difficult to estimate. In any case, methods for evaluating and internalizing externalities are limited.

From a consumer's perspective, life cycle costing is a useful tool for making product selection decisions. In traditional use, life cycle costs consist of the initial purchase price plus operating costs for consumables (e.g. fuel, electricity, lubricants), servicing not covered under warranty, and possible disposal costs.[62] Providing estimates of life cycle cost can be a useful marketing strategy for environmentally sound products.

The most comprehensive definition of life cycle costs is the sum of all internal and external costs associated with a product system throughout its entire life cycle.[56, 63] At present, government regulation and related economic policy instruments appear to be the only effective methods of addressing environmental costs to society.

Presenting Design Evaluation Results

Life cycle design teams rely on existing, in-house design evaluation protocols. Life cycle design seeks to expand these protocols to include methods that systematically evaluate the environmental performance of a design solution. Although several factors complicate the comparison of alternatives, such as different units of measurement and

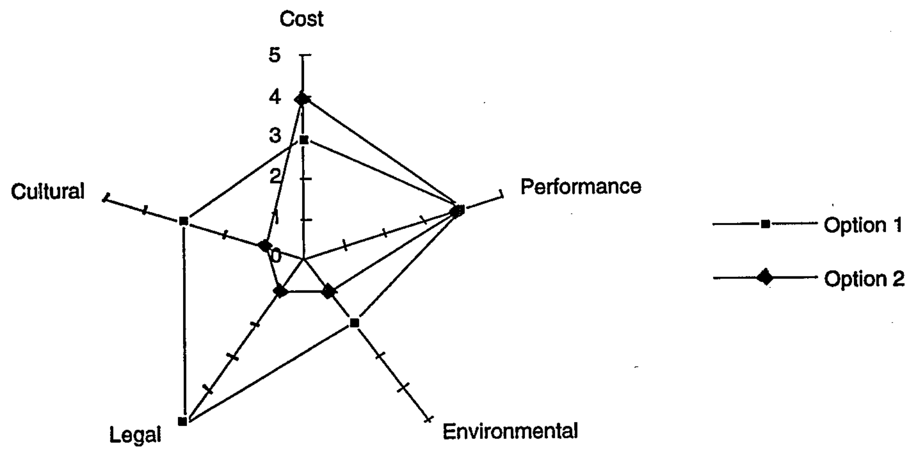


Figure 4-11. Assessing Two Hypothetical Design Options

uncertain health or ecological impacts, product realization teams need some mechanism for comparing each design option. Effective evaluation tools document a particular design's ability to meet a varied set of design requirements and elicit more feedback regarding the potential tradeoffs or conflicts arising from design alternatives.

Figure 4-11 presents a simple graphic method for showing how well two design alternatives satisfy requirements. Results in this form can be used for further review by all members of the life cycle design team.

The axes of the Requirements Profile are on a scale of 0-5, representing the ability of the design to meet the stated requirements. Rankings in each requirements class are determined by the design team. The challenge in using this type of simplified decision making tool is to establish a method for accurately assigning numerical scores.

IMPLEMENTATION

After formal approval, designs are implemented. Implementation includes production and distribution of the product along with marketing and labeling. Building or planning infrastructure and recommending policy changes to regulators is also a part of implementation.

Product development is a continuous process that does not end at this point. Existing products, even if newly implemented, should be viewed as the starting point for new initiatives.

5. AT&T DEMONSTRATION PROJECT

The AT&T Life Cycle Design Demonstration Project explored the feasibility of applying the life cycle design framework. This demonstration project focused on integrating environmental issues into the design of a business telephone terminal.

Like all manufactured products, telephone terminals contribute environmental burdens throughout their life cycle. These burdens range from health hazards caused by toxic constituents such as lead solder to impacts associated with the end-of-life management of various product components. Reducing the environmental burden associated with this or any other electronic product represents a significant challenge to corporate management, designers, and other participants in product development. Some of these challenges are technical in nature, such as those posed by the complexity of the product and the wide array of materials required, some of which are hazardous. Others have more to do with external forces acting on the product realization process. For example, there are safety standards and regulatory requirements the product must comply with and market expectations it must live up to.

In practice life cycle design can denote a very comprehensive analytical exercise, or it can imply something more modest. Clearly, if one approaches a "green concept telephone" as a unique experimental concept that explores unconventional green design goals without regard to cost or marketability, then a very diverse set of issues can be considered. But if the life cycle design approach is applied to a marketable and competitive product that is on a strict development and introduction schedule, then obviously one must operate in a much more constrained environment. In such cases, design objectives are necessarily more modest.

Having chosen a next-generation business telephone terminal as the product, it became clear that a comprehensive life cycle analysis was not going to be feasible for this project. Instead, AT&T's goal was to address some of the practical issues of life cycle design as they exist in a present-day corporate setting.

In addition, the participants in this joint project had their own more specific objectives. As the authors of the Life Cycle Design Guidance Manual, the University of Michigan researchers were interested in evaluating the applicability and utility of their life cycle design framework. The AT&T participants, on the other hand, wanted to explore how certain life cycle design methodologies, such as using multicriteria requirements matrices, might enhance and expand their own Design for Environment (DFE) processes. In addition, the AT&T team wanted to explore and document to what extent AT&T was already positioned to address various product life cycle issues, given the multitude of its environmental programs. Furthermore, the AT&T team wanted to study how the delivery of these programs might be improved and better coordinated.

This profile was written jointly by Dr. Werner Glantschnig, the Life Cycle Design Demonstration Project coordinator at AT&T Bell Labs Engineering Research Center, and the research group at the University of Michigan.

PROJECT ORIGIN AND BACKGROUND

Origin of the Life Cycle Design Project

AT&T's participation in the demonstration phase of the Life Cycle Design Project came about for three reasons. First, the principle investigators, Greg Keoleian (University of Michigan) and Werner Glantschnig (Bell Laboratories) had interacted previously, which paved the way for initial discussions about a possible collaboration. Second, AT&T had already embarked on a "green product initiative". The goal of this initiative was to baseline the "greenness" of a recent AT&T product, namely the 8503 Integrated Services Digital Network (ISDN) terminal, and to explore opportunities for improvements in the environmental design of future generation telephone terminals. Finally, the Global Business Communication Systems (GBCS) product line management team, which had been involved in the 8503 baseline study, was supportive of this joint project as well. Questionnaires returned by present and potential customers attending a Special Interest Group session on "green products" at a Definity® Users Group Forum in October 1991 indicated that customers were quite aware of environmental issues and that environmental concerns might start to influence purchasing decisions. Thus, product-line management saw merit in supporting a project that would explore green product and life cycle design issues.

While the goals of the original AT&T green product realization project were not as comprehensive as those proposed for the life cycle design study, there were sufficient similarities between the existing AT&T initiative and the project proposed by the University of Michigan researchers to justify building on the AT&T project. The present Life Cycle Demonstration Project represents the consolidation of these two initiatives.

Formation of the Cross Functional Team

Rather than forming a new team, the project team originally assembled for AT&T's Green Product Realization initiative remained intact and become involved in the joint AT&T/EPA/University of Michigan Life Cycle Design Demonstration Project. Not only had this team already become familiar with many environmental issues as they pertain to the product life cycle of a typical telephone, but it was also a well balanced and highly interdisciplinary team. The business unit responsible for the 8403 terminal, AT&T GBCS, was represented by members of product-line management, marketing, design, and product engineering. For purposes of this project, representatives from Corporate Environmental and Safety Engineering and the environmental research team at Bell Laboratories joined the business unit team. The Green Product Realization Group at AT&T Bell Labs Engineering Research Center in Princeton, New Jersey assumed responsibility for coordinating the Life Cycle Design Demonstration Project on the AT&T side.

Selection of the 8403 Terminal

The initial goal of the AT&T team in embarking on its green product initiative was to baseline the "greenness" of the 8503 terminal. The purpose of this step was to determine to what extent environmental concerns were already being addressed either through design or, at product end-of-life, via the activities of AT&T service and reclamation centers. An additional goal was to identify ways in which the life-time impact of a telephone product could be further reduced. At the time of the conclusion of the 8503 terminal study (December 1991), the 8403 DCP (Digital Communications Protocol) voice terminal was still on the drawing board. Thus, this terminal seemed to be a good candidate for the AT&T/EPA/University of Michigan life cycle design study. Furthermore, the 8403 terminal was to be designed by the same physical design group which was involved in the 8503 green baseline study. Finally, the design, manufacturing, and product introduction schedule for the 8403 fit well with the time line for the Life Cycle Design Project. For these reasons the product team decided to select the 8403 terminal as a vehicle for the life cycle design study.

Description of the 8403 Digital Communications Protocol (DCP) Terminal

The 8403 terminal is a digital voice terminal designed to work with the AT&T DEFINITY® large business communications system. The DEFINITY® System supports a large range of applications and features including call center applications, networking capabilities, system management, and desktop and voice processing solutions. The combination of voice, data, and conferencing capabilities available to every DEFINITY® System user depends, among other things, on the terminal he or she uses. The DEFINITY® System supports communication protocols such as ISDN, Digital, and Analog; AT&T offers a line of terminals compatible with each protocol.

The 8403 is a 3-line digital voice terminal. The features of this 24-button set, pictured in **Figure 5-1**, include:

- 2- and 4-wire connectivity
- international portability
- a one way speaker for hands-free listening
- 3 call appearance or flexible feature buttons, (two with LED)
- 12 additional features via dialpad
- message waiting indicator
- 8 personalized ringing styles
- push button mute feature
- digital volume control rocker
- textured, scratch-resistant, finish
- adjunct jack for headset or speakerphone

Figure 5-1. 8403 Terminal

The 8403 terminal is a more feature rich and versatile replacement for the 7401 Digital Voice Terminal which was introduced in 1982. Specific environmental design features which differentiate the 8403 from the 7401 will be discussed later.

ENVIRONMENTAL MANAGEMENT SYSTEM

An effective environmental management system is required to establish a successful environmental design program. Following a brief business description, several key elements of AT&T's environmental management system are discussed below, including environmental policies and goals, and organizational structure and responsibility.

It should be noted that discussions of the organizational structure and the Design for Environment (DFE) program that follow describe the state of affairs in early 1993 when the life cycle project began. Several changes to organizational structure and the DFE program have been made since. These modifications are the result of lessons learned with early green design projects, the corporation's realization that the introduction of an effective DFE program required a more forceful and better organized approach, and ongoing efforts to better align certain corporate resources with the needs of AT&T's business units. One example is the appointment of a chief environmental officer by each business unit.

If the accomplishments of the AT&T/EPA/University of Michigan Life Cycle Design Project seem modest, this in no small part due to applied life cycle design being such a novel concept when the project began that sufficient support for it within the corporation was still missing.

AT&T Business Description

AT&T provides domestic and international information movement and management services and products, as well as leasing and financial services. In 1993 59% of AT&T's business resulted from telecommunications services, 27% from sales of products, 10% from rentals and other services, and 4% from financial services and leasing. The company provides long-distance communications services throughout the US and internationally. AT&T manufactures a range of customer equipment, data communications and computer products, switching and transmission equipment, and components for high-technology products and systems. The Bell Laboratories of AT&T design and develop new products and carry out fundamental research.

AT&T Environmental Policy

In order for a corporation to make progress in its environmental performance, clearly articulated environmental goals are necessary. Historically, AT&T's environmental programs were shaped by US environmental laws and regulations and by its unique position prior to 1984 as the monopoly supplier of telephone equipment and services. Much changed in the 1980s. Not only did divestiture start a telecommunications revolution that has had a significant impact on AT&T's manufacturing businesses and product development strategies, but environmentalism became a mainstream movement. Industry realized that the old end-of-pipe approach to pollution control had its limits. Pollution control did little to prevent the creation of pollution and waste, and it had become exorbitantly expensive. While pollution control legislation and the resulting industrial pollution control practices had resulted in significant improvements, it had also become clear that in order to reach the next level of industrial environmental stewardship, new approaches were needed.

Some of the changes in environmental thinking that have evolved during the past decade are reflected in AT&T's original environmental policy statement. This statement was developed as a result of the corporation and its senior management becoming aware of the need to articulate a broad policy which would set the stage for specific action on environmental issues. This policy statement, as signed on 14 November 1988 by Robert E. Allen, CEO and Chairman of the Board, reads as follows:

AT&T Environmental Policy

AT&T is committed to the protection of human health and environment in all areas where it conducts operations. Implementation of this policy is a primary management objective and the responsibility of every AT&T employee.

Guidelines:

- Comply with all applicable laws governing environmental protection.
- Support and contribute to the development of reasonable, cost-effective environmental laws and regulations.
- Evaluate on a continuing basis AT&T's compliance with applicable laws and regulations in all its operations.
- Encourage the use of non-polluting technologies and waste minimization in the design of products and processes.
- Include environmental considerations among the criteria by which projects, products, processes, and purchases are evaluated.
- Develop in our employees an awareness of environmental responsibilities and encourage their adherence to sound environmental practices.

New Proposed Environmental Policy Statement

While AT&T has made great progress with its pollution prevention and waste minimization initiatives, management recognized that in order to reach the next level of environmental performance, a broader and more holistic approach to environmental stewardship needs to be developed and implemented. Accordingly, the following revised policy statement outlining more ambitious environmental goals has been developed, though not yet formally adopted.

Proposed AT&T Environmental Policy

AT&T is committed to fully integrating life cycle environmental consequences into our design, development, manufacturing, marketing and sales activities worldwide. Implementation of this policy is a primary management objective and the responsibility of every AT&T employee.

Guidelines:

- Utilize Design for Environment principles to design, develop, manufacture and market products and services worldwide with environmentally preferable life cycle properties.
- Promote achievement of environmental excellence by designing every new generation of product, process, and service to be environmentally preferable to the one it replaces.
- Determine the environmental impacts of products, processes and services on an individual basis to prioritize the order in which they can be effectively addressed within technological and economic constraints.
- To the extent that proven and efficient technology allows, eliminate or reduce production of waste; seek economic uses of materials which would otherwise become wastes; where it is produced, eliminate or reduce discharge of waste.

- Design, develop and market products and services worldwide which support our customers in their efforts to reduce or eliminate harmful environmental impacts of their activities.
- Integrate applicable life cycle environmental considerations into each of our business decisions and planning activities, including acquisition/ divestiture activity, and into the measurement standards applied to management performance.
- Work with suppliers, customers, governments, the scientific community, educational institutions, public interest groups and the general public worldwide to develop and promote environmental management policies and environmental standards based on life cycle, system-based principles.

As compared to the original policy statement, the proposed statement is more specific, with greater emphasis on forward-looking and preemptive approaches. A central goal is the avoidance of environmental impacts through sound design, planning, and management practices. Note that terms such as Design for Environment and life cycle are explicitly stated. This reflects the corporation's belief that Design for Environment or life cycle design practices are crucial in enhancing and solidifying AT&T's competitiveness and position in the vanguard of environmentally-conscious, global businesses.

Corporate Environmental Goals

While broad policies put in place by top management are certainly steps in the right direction, policies with no measurable and time-bound goals are often not very effective. Accordingly, at the 1990 Annual Shareholders Meeting, Chairman Allen announced the following aggressive environment and safety goals for AT&T:

- CFC phaseout
  - 50% reduction by 1991
  - 100% reduction by 1994
- Total toxic air emissions
  - 50% reduction by 1993
  - 95% reduction by 1995
  - striving for 100% reductions by 2000.
- Decrease total manufacturing process waste disposed by 25% by 1994
- Paper use and recycling
  - increase the recycling of paper 35% by 1994
  - decrease paper use 15% by 1994

These environmental policy and associated goals have been very effective. By the end of 1992, all of the goals had been either met or surpassed, with the exception of the goal on paper use. At the conclusion of 1992, paper use had decreased by 10%.

Corporate Resources

When the Life Cycle Design Project began, the following organizations within AT&T concerned themselves in a major way with environmentally related activities:

- Corporate Environment and Safety Engineering
- Environmental Health, Environmental Management & Safety (EHEM&S) organization of Bell Laboratories (responsible for activities of Bell Laboratories only)
- Environmental Technologies Department of the Engineering Research Center
- Environmental and safety engineering groups at all AT&T manufacturing locations

With the exception of the Environmental Technologies Department, which is involved in research and technology development, all of these entities have historically helped AT&T achieve compliance with environmental and safety regulations in all its operations.

In the past, these organizations performed their duties without interacting much with the product realization community. However, if effective life cycle design is ever to become a reality, processes for better information exchange and interaction between design and environmental and safety engineering organizations will have to be developed. This is going to be a major challenge. The incorporation of environmental thinking into product development inevitably adds a layer of complexity to the product realization process. This runs counter to the desire to simplify and shorten product development cycles.

In discussing organizational resources, the focus shall be on the two entities primarily concerned with environmental issues as they affect AT&T business units: the Corporate Environment and Safety Engineering Center (E&SEC) located in Basking Ridge, New Jersey, and the Environmental Technologies Department of the Engineering Research Center (ERC) in Princeton, New Jersey. Both organizations belong to AT&T's Global Manufacturing and Engineering (GM&E) organization and as such constitute corporate-wide resources.

Corporate Environment and Safety Engineering Center

The Environment and Safety Engineering Center (E&SEC) develops the environmental and safety policies of AT&T and serves all AT&T business units and divisions. It is also the main corporate entity concerned with compliance and regulatory affairs. Its mission is to:

- Ensure that all business units, country units, and divisions are in compliance with environmental and safety laws and regulations
- Establish environmental and safety direction through the development and worldwide deployment of policies, standards, and goals

- Maintain a worldwide environmental and safety center of excellence for interpreting current regulations and anticipating future requirements, providing technical support and delivering a range of environmental and safety services
- Manage certain environmental liabilities
- Protect and enhance AT&T's brand image worldwide

A fundamental objective of E&SEC is to foster the development of a corporate culture in which environmental protection and safety are central to all aspects of business.

ERC's Environmental Technologies Department

The Engineering Research Center (ERC), a Bell Laboratories entity, was originally chartered in 1952 to conduct manufacturing and process research and development. Most of the Center's work is still in support of AT&T's major manufacturing businesses such as AT&T Network Systems, AT&T Microelectronics, and the Communication Products group. Now subdivided into three Centers of Excellence, each with its own customer-focused roadmap, ERC's mission is to develop critical processes and tools that will provide AT&T's manufacturing organizations with a sustained competitive edge.

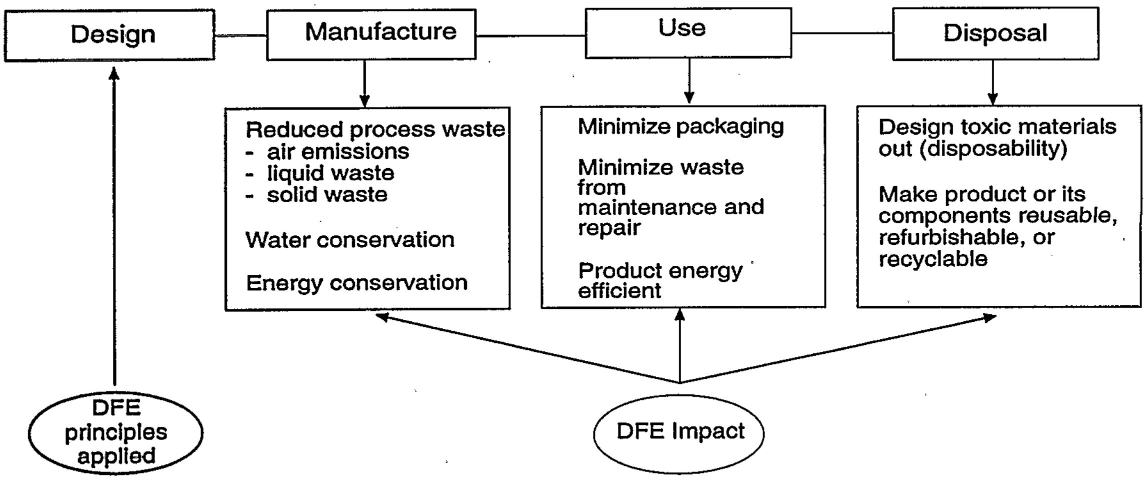
The Environmental Technologies Department's mission is to provide technologies for minimizing the environmental impact of products throughout their entire life cycle. Current research and development programs focus on Green Product Realization and Manufacturing Pollution Prevention. Each of these two project areas consists of the following portfolio of subprojects:

- Green Product Realization
  - Design for Environment
  - Pb-free interconnect
  - Product take-back and recycling
- Manufacturing Pollution Prevention
  - Systems methodology for waste minimization
  - Solvent replacement and effluent management
  - Environmental monitoring and reporting

Clearly, all these activities support the goal of minimizing the aggregate environmental impact of designing, manufacturing, and marketing products. Design for Environment is the most forward-looking approach, and the one most akin to life cycle design. For this reason, the Design for Environment program being developed by the Green Product Realization group of the Environmental Technologies Department will be singled out and described in the next section.

Design for Environment

DFE is a design philosophy and practice whose goal is to minimize the environmental impact of the manufacture, use, and eventual disposal of products without



While design for environment principles and tools are applied during the design stage, the intended impact is felt during subsequent product life stages.

Figure 5-2. Conceptual Diagram of DFE

compromising essential product functions, and, ideally, without significantly affecting the life cycle cost of the product in a negative way. The goal of DFE is to apply methods of concurrent engineering in order to solve some of the environmental problems typically associated with manufacturing. At AT&T Bell Laboratories DFE is considered a part of "Design for X" or DFX, AT&T's approach to concurrent engineering. The "X" in DFX can stand for manufacturability, testability, serviceability, or any other downstream concern. Environmental concern is just the latest component to be added for consideration early in the product realization process. **Figure 5-2** shows a conceptual diagram of DFE.

Since virtually no current product developers are environmental design experts, they need to be provided with DFE tools and training that will enable them to consider the environmental ramifications of their designs and make informed design choices. To meet this need, researchers in the Environmental Technologies Department are currently making a major effort to develop DFE guidelines, checklists, and the "Green Index" scoring system.

DFE Guidelines and Checklists

The primary purpose of guidelines and checklists is to help designers practice DFE. The more aids like guidelines and checklists present and explain green design in an easily understandable and useful form, the more useful and effective they will be. Ideally, guidelines should list specific design choices relevant to accomplishing a certain objective, such as minimizing the lead content of a printed wiring board. Furthermore, the guidelines should not just outline choices but also rank them in terms of preference. This helps designers make unfamiliar environmental tradeoff decisions.

DFE checklists are typically appended to major guideline segments. The model for DFE checklists are various Design for Manufacturability (DFM) checklists that are widely used by AT&T Bell Laboratory designers today. By reviewing a checklist item by item, a designer can quickly ascertain whether he or she has taken the most important environmental design issues into consideration. Furthermore, the checklists offer a means of organizing information for design reviews. Some checklists can also serve to document the incorporation of green design features in the product system.

Green Index Scoring System

The "Green Index" scoring system is an AT&T proprietary, software-based design tool which enables designers to compute an environmental figure of merit for a product and/or its major components. This tool evaluates a select group of criteria including reusability, recyclability, and toxicity to gage environmental merit. This scoring system is one of several DFE tools being developed by AT&T.

The inspiration for the Green Index came from a quantitative "design for simplicity" assessment method by Watson et. al.[64], which itself was inspired by "design efficiency" or "design for assembly" scoring systems as proposed by Boothroyd and Dewhurst [65] among others. Rather than having the designer make judgments as to the desirability of a certain design feature, a computer program provides a greenness score based on factors such as material variety, whether or not parts are marked with symbols identifying their material, percent weight of recyclable to total materials, and many others.

The Green Index rating system mentioned above is not based on life cycle analysis but rather on a common-sense analysis of empirical data and the operating experience of AT&T factories, service centers, and product reclamation and recycling operations. Thus the rating scheme is highly subjective. If it is consistently applied, however, the scoring system allows one to track progress in green design from one product generation to the next. Much work remains to be done, both in terms of refining and testing the system and making it more user friendly. As concerns the latter, a better graphical user interface as well as the capability to import design data are the most needed improvements. Because of its current limitations, the Green Index system is not yet of much use to practicing designers. However, it is a vehicle for exploring approaches to rating the environmental merit of products, and it constitutes a kernel around which more sophisticated and useful tools can be constructed in the future.

PROJECT DESCRIPTION

In exploring the integration of environmental issues into the development of the 8403 terminal, the project team pursued a dual-track approach. It tried to both follow the life cycle design framework, and use elements of AT&T's DFE program. This dual-track approach is possible because life cycle design and DFE are not mutually exclusive. On the contrary, there is a significant overlap between DFE and life cycle design.

Life cycle design is the most comprehensive approach for incorporating environmental thinking into product development. According to the framework proposed in the Life Cycle Design Guidance Manual, the identification and specification of requirements using a multicriteria matrix is a crucial step in the initial phases of a life cycle design project. The multicriteria matrix system affords a unique way of presenting a diverse set of design requirements organized by product life cycle stages. In order to explore the usefulness of this matrix system and its relevance to a real design environment, the project team decided to make the development of design requirements using this matrix system a major task of the joint AT&T/EPA/University of Michigan Life Cycle Design Project.

Needs Analysis

Any product development process necessarily starts with identifying market and customer needs. Beyond that, clearly defined boundaries for other needs, such as those of the environment, and requirement analysis must be established.

Setting System Boundaries

The product life cycle starts with raw material extraction and bulk material processing. However, the project team narrowed the system boundaries by excluding the raw material acquisition and bulk and virgin engineered material processing stages from detailed analysis. Good data and information about the impacts associated with these life cycle stages are not readily obtainable at this point. Certainly they are not available in a form that is useful for helping designers make sound material choices. The project team also decided not to consider the management component of the product system, which includes administrative services, in depth. To be consistent with the modified product system organization presented in this report, the University of Michigan researchers folded the limited management criteria developed for this project into the process and distribution components for each class of requirements.

Baseline Analysis

A good first step in embarking on a life cycle design project is to conduct a baseline analysis of an existing, similar product. This helps establish to what extent environmental concerns are already being taken into account and what further improvements might be possible. The baseline analysis, which was performed on the 8503 ISDN terminal as part of the Green Product Realization initiative mentioned previously, consisted of both a conventional analysis of the environmental impacts associated with the 8503 terminal and the application of an early version of the "Green Index" system to obtain a "green" score for this product. The conventional part of the analysis included establishing an inventory of all materials and parts used for the product, as well as all waste streams and emissions created as part of its manufacture.

Customer Focus Groups

AT&T periodically organizes customer focus groups to survey attitudes about preferable products and product features. Recently AT&T has begun to study customer attitudes about environmentally-conscious products. In one survey, the participants were first introduced to AT&T's environmental program. This served as a basis for discussing issues such as whether customers considered environmental attributes when purchasing products, were willing to pay more for environmentally-preferable products, found the concept of using refurbished or remanufactured components acceptable, would be willing to participate in recycling programs, and would accept documentation printed on recycled paper. While current and potential customers appeared to support these concepts, their willingness to pay for environmental premiums was rather limited. In this focus group survey, only slightly more than half of 17 participants were willing to pay somewhat (no more than 5%) more for an environmentally-preferred product.

This is in line with the results of other green marketing surveys. While most people consider themselves environmentalists, few are willing to pay a premium for environmentally superior products. However, the perceived environmental merit of a product is increasingly becoming a differentiator when people make purchasing decisions. Thus, to the extent that a product's environmental profile can be improved without appreciably increasing its cost, this should be done.

Establishing Design Requirements

Requirements Matrices

A major focus of the AT&T demonstration project was identifying design requirements with multicriteria matrices consisting of environmental, performance, cost, cultural, and legal requirements. Design requirements, of course, have always existed. Traditionally, designers focused primarily on performance and cost requirements, although for many products cultural and legal requirements are important as well. The multicriteria matrices used in this project provide a novel tool for including specific environmental requirements in design, organizing all other requirements, and facilitating discussion of how to make design tradeoffs..

Matrix dimensions are defined by product system components and life cycle stages. The conceptual matrix proposed in the Life Cycle Design Guidance Manual can be organized using different formats. For this project, life cycle stages under consideration were consolidated into manufacturing, use, and end-of-life management.

A set of matrices containing environmental, performance, legal, cost, and cultural requirements for telephone terminals are presented in **Tables 5-1** through **5-5**. Many of the environmental and legal requirements apply to telephone products in general. On the other hand, some performance, cost, and cultural requirements are specific to the 8403.

The matrices shown in **Tables 5-1** through **5-5** were compiled using information contributed by members of our multidisciplinary project team during seven "green product realization" meetings at Bell Laboratories in Holmdel, New Jersey. (Project participants from outside New Jersey were teleconferenced into those meetings). Clearly, a variety of competencies are required to develop such a breadth of requirements. This is why multidisciplinary teams are crucial to life cycle design projects.

The environmental requirements presented in **Table 5-1** amount, for the most part, to "want" requirements. In other words, unlike legal requirements, they are not statutory. (Design requirements having their origin in environmental regulations are included in the legal requirement matrix). They represent things an environmentally-conscious company should do to go beyond mere compliance.

Many of the requirements in **Table 5-1** follow from the basic "reduce-reuse-recycle" philosophy. Others are based on AT&T's corporate environmental goals for manufacturing and office management. As discussed earlier, these goals set quantitative targets for reductions in CFC emissions, toxic air emissions, process wastes, and paper consumption, as well as increased use of recycled paper. Still other requirements specify mechanisms that, according to our current understanding, facilitate the reuse of parts/components and the recycling of materials such as plastic housings. Not all environmental requirements listed in **Table 5-1** can be met today.

Table 5-1. Environmental Requirements

Product		
Manufacture - Use recyclable materials - Maximize onsite recycling of molding scrap - Use recycled materials to the extent possible - Choose ODS free components - Eliminate the use of toxic materials (e.g., Pb) - Minimize defective products	*Use/Service* - Extend useful life through modular design with sufficient forward and backward capability	*End-of-Life Management* - Reuse parts - Standardize parts to facilitate remanufacture - Product components recyclable (after consumer use) - Open-loop recycling into fiber cables, spools and reels - Easy to disassemble: no rivets, glues, ultrasonic welding, and minimal use of composites - Components easy to sort by marking and minimal use of materials
Process		
Manufacture - Minimize process wastes including air emissions, liquid effluents and hazardous and nonhazardous solid wastes - Minimize resource consumption - Minimize power consumption - Meet corporate environmental goals of CFC phaseout, reduced toxic air emissions, decreased process waste disposal, reduced paper use, and increased paper recycling - Use greener processes R&D: ERC developing environmental technology; also use design guidelines, checklists, DFE tools, Green Index - Purchasing records to monitor ODS; encourage suppliers to discontinue ODS use	*Use/Service* - Energy efficient operation (operate on line power only) - Manual printed on recycled paper	*End-of Life-Management* - Service or reconditioning operations should minimize use of solvents
Distribution		
Manufacture - Minimize supplier packaging • non hazardous - Packaging containing recycled material (postconsumer content specified) - Reusable trays for parts in factory	*Use/Service* - Minimize product packaging • use Electronic Packaging Guidelines • non hazardous - Optimize number of phones per package - Specify packaging containing recycled material (post-consumer content specified) - Use recycled paper for manual (list environmental features)	*End-of-Life Management* - Recyclable packaging

Table 5-2. Performance Requirements

Product		
Manufacture - Avoid discoloration of housing by specifying maximum blend of recycled plastics with virgin resins	*Use/Service* - Compatible with AT&T Definity Communications Systems (both current and earlier) - International portability - Digital voice technology - 3-line operation - Ensure reliable components and subsystems - Ensure structural integrity - Environmental conditions; Temperature: 40-120° F Humidity: 5-95% noncondens.	*End-of-Life Management* - Maximize component reuse - Maximize material recycling of components that are not reused
Process		
Manufacture - Identify requirements related to following programs: • Maximum product yield • Just-in-time manufacture • TQM • Statistical quality control • Manufacturing cells (production layout) • Ergonomics - New product engineering requirements - Concurrent design requirements	*Use/Service* - NE SOC - Business performance functional criteria - Fatigue testing - Electrical testing - Systems engineering specs - Ergonomics - Manual should contain information on installation and appropriate use	*End-of-Life Management* - Minimize repair cost (mostly labor) - Maximize material recycling of components not reused: • easy disassembly, i.e. no face plate cement • clean with water to remove contaminants which cause porous molds • touch-up paint is a problem for recycling
Distribution		
Manufacture - Inventory control requirements - Just-in-time manufacturing requirements	*Use/Service* - Product packaging must protect product surface appearance	*End-of-Life Management* - Minimum variety of materials used in packaging (e.g. attempt to eliminate cellophane wrap)

The performance requirements shown in **Table 5-2** focus on product functions and features, reliability of the electrical system, physical and operating integrity of the product under different conditions, and other efficiency and quality measures. Many of these requirements can also to be found in AT&T internal product standards. However, requirements spelling out features and functions typically get established anew for each product generation based on input from customers and market research.

Table 5-3. Legal Requirements

Manufacture	Use/Service	End-of-Life Management
Product		
- US Regulations/Product Safety Standards • Clean Air Act Amendments: CFC labeling requirement (April 15, 1993) • Underwriter Laboratories - UL 746D fabricated parts: use of regrind and recycled materials • Green Seal - Foreign Regulations/Product Safety Standards • Blue Angel and other relevant standards	- Underwriter Laboratories • UL 1459-product safety • UL 94-flammability test (must meet UL94-HB at minimum) - FCC requirements - Limits on polybrominated fire retardants (EC) - Canadian Safety Specs • CSA C22.2 - European Safety Specs • EN 60 950 (IEC950; safety, network capability, EMC, susceptibility) • EN 41003 • EN 71 (lead pigments and stabilizers in plastic parts)	- Product should meet applicable statutory requirements • product should not contain hazardous materials under RCRA • pigments and other plastic additives should not contain heavy metals - Electronic Waste Ordinance (Germany, Jan. 1, 1994) and Packaging Ordinance - UL flammability test: approval of recycled resins difficult - Previous flame retardant banned in Europe which prohibits recycling of old terminals
Process		
- Clean Air Act - Clean Water Act - CERCLA (SARA-313) - RCRA - EPCRA - OSHA - ISO Marking Codes for plastics	- FTC Guidelines: definitions for labeling	- Easy to disassemble - Sherman Anti-Trust Act responsible for developing market for remanufactured phones - Recycled content - ISO Marking Codes for plastics
Distribution		
- DOT (transportation of hazardous materials)		- Specific claims on packaging • Green Dot Program

Local, state, federal, and international regulations comprise a significant fraction of the legal requirements outlined in **Table 5-3**. The balance are quasilegal requirements, mostly product and communication standards a business telephone must comply with. Legal requirements range from EPA regulations and FTC rules pertaining to green product marketing claims to Germany's Packaging Ordinance. Standards such as ISO marking codes for plastics and product safety standards championed by Underwriter Laboratories (UL) and other organizations constitute the set of quasilegal requirements. The large diversity in legal requirements, the frequent inconsistency in those requirements from jurisdiction to jurisdiction, and the fact that many of the rules and regulations have their origin in pollution control legislation, can be a barrier to realizing proactive environmental improvements for a design.

Table 5-4. Cost Requirements

Product		
Manufacture	*Use/Service*	*End-of-Life Management*
- Cost of virgin resin - Cost of recycled resin - Cost of parts, components, and materials from suppliers	- Competitive purchase price of new product using virgin materials - Competitive rate for leased product - Competitive purchase price of reconditioned product	- Cost of replacement parts
Process		
Manufacture	*Use/Service*	*End-of Life-Management*
- Unit cost of manufacturing • capital costs • operating expense • waste management costs - Unit cost of managing: • monitoring and reporting • training • preparedness • environmental liabilities - Corporate image	- Service costs - Improved corporate image - Improved consumer acceptance and loyalty	- Cost of remanufacturing at service center - Cost of recycling at service center - Cost of disposition of materials from service center - Unit cost of managing: • training • manifesting • environmental liabilities - Corporate image
Distribution		
Manufacture	*Use/Service*	*End-of-Life Management*
- Unit cost of packaging	- Packaging cost to consumer is included in total product cost	- Disposal cost to consumer

Specific cost data were not provided to the University of Michigan researchers since cost data are proprietary. Thus **Table 5-4** is not so much a compilation of specific cost requirements or cost targets as a list of costs incurred in connection with the product throughout its life. The lack of good life cycle cost data is a major impediment to implementing life cycle design. Because cost is always a factor in design decisions, it is frequently difficult to make a sound case for life cycle design at present, given that life cycle costs are poorly understood and life cycle accounting systems are at best in their infancy.

Table 5-5. Cultural Requirements

	Manufacture	Use/Service	End-of-Life Management
Product		- 8403 must have "look and feel" of other 84xx series phones and ensure compatibility with: • color palette • shape of housing, handset, and cable • design of faceplate - Style, form, appearance • no scratches • high quality finish - Volume control - 8 personalized ringing options - Raised buttons - Ease of use	- Refurbished 8403 coming from service center must look like new - Color matching important
Process		- Input from user focus groups	
Distribution		- AT&T mail order catalogue shipments should minimize use of packaging for small orders	

Some of the cultural requirements applicable to the 8403 terminal are listed in **Table 5-5**. Cultural requirements are what make the product palatable to the consumer. They address ease and convenience of use, desirable extra features, and aesthetic appeal. While it is tempting to consider some of the cultural requirements frivolous, they are very important in terms of a product's market acceptance.

In general, well-developed requirements should be comprehensive without being so restrictive that they exclude practical and economically feasible solutions. Note that there is considerable overlap in the requirements listed in the different matrices. This is a result of environmental requirements often being closely linked with legal (e.g., regulations), performance (e.g., material efficiency), cultural (e.g., public concern), and cost (e.g., cost competitiveness) requirements.

Ranking and weighting can be used to distinguish between critical and merely desirable requirements. Must requirements are conditions that designs have to meet while want requirements are less important, but still desirable traits. In many cases, significant conflicts may exist between these requirements. The challenge for the development team is to resolve these conflicts and minimize the disharmony between requirements through tradeoff analysis.

Conflicting Design Requirements

In principle, the matrices provide a systematic way of organizing must and want requirements of the product system. (In **Tables 5-1** through **5-5**, no explicit distinction was made between must and want requirements). Inevitably some requirements conflict with others. While the matrices themselves are not a tool for resolving conflicts, they are useful in identifying conflicts and assessing tradeoffs. Two examples of conflicting requirements shall be discussed here.

First consider the environmental want requirement that recycled materials be used for the production of new products. This conserves virgin resources and minimizes impacts due to material extraction and refining. For example, recycled resins should ideally be selected for molding new telephone housings. However, recycled plastics, particularly postconsumer recycled plastics, cannot be used for this purpose because another must requirement for telephone housing is compliance with Underwriter Laboratories (UL) specifications UL 746, Standard for Polymeric Materials - Fabricated Parts. Unlike virgin resins, recycled resins that meet the necessary UL specifications are currently not readily available and AT&T internal recycling programs do not yet have in place the necessary material tracking, testing and certification procedures required by UL 746 for recycled materials.

Even if product safety standards would not impede the use of recycled plastic, other want requirements still might. Cultural requirements were specified in **Table 5-5**. In order to be marketable, a desktop product must be visually appealing. However, housings with flawless surface quality and perfectly matched colors are difficult to obtain with recycled materials.

As an example of another conflict, consider the options of a service center in refurbishing a business phone. Assuming the phone still works and only the housing needs to be reconditioned, the old housing can either be scrapped and replaced with a new one, or the original housing can be cleaned and, if necessary, painted. If one scraps the original housing, virgin resin is consumed in molding a new replacement housing, but the use of solvents for cleaning and painting the original housing, and any resulting emissions and waste streams from the refurbishing operation, are avoided. On the other hand, if the housing is cleaned and painted to cover up wear and other small surface blemishes, virgin resin is conserved, but some undesirable impacts will be incurred as part of the refurbishing operation. Which option is better? At this time, nobody really knows, and AT&T feels it is too costly to perform an analysis to settle questions like this on a routine basis.

Typically, in the absence of useful methods for settling such questions quickly, companies usually choose the less expensive option, which may or may not be the environmentally superior one. This is merely one tradeoff concerning one component at one particular point in its life. The dilemma with practicing life cycle design is that there are virtually countless such tradeoff decisions to be made for the whole product over its entire life.

Life Cycle Design Strategies for the 8403 Terminal

In general, a product's life-time environmental impact can be reduced through, among other things, designing the product to be appropriately durable, repairable, and made of recycled or easily recyclable materials. Furthermore, all waste streams resulting from any material processing, manufacturing, and recycling operations should be as small as possible, both in volume and number, while the use and emission of toxic substances should be minimized. Finally, the packaging should consist of a minimal number of different materials, be reusable or recyclable, and weigh as little as possible, while still meeting its basic product protection function.

A program intended to minimize the lifetime environmental impact of products must by necessity not only involve traditional product design teams, but also all corporate entities and resources that have an impact on the product's life downstream from manufacturing. One of the great challenges in establishing an effective life cycle design program is coordinating design, manufacturing, service, repair, and product disposition activities in such a way that the aggregate corporate product delivery program amounts to more than the sum of its parts. Understanding the life cycle of one's products, and the role various corporate resources play in it, is a necessary step in devising sound life cycle design strategies.

Current Life Cycle of an AT&T Telephone

As mentioned in the project introduction, one of the objectives of the AT&T team in participating in the life cycle design project was to investigate and document to what extent AT&T was already addressing life cycle issues as they pertain to a telephone. Having a thorough understanding of the life cycle of a product is a prerequisite for better executing life cycle design strategies and for understanding how specific design changes are compatible with the existing product life cycle infrastructure.

AT&T is fortunate to have a well-developed, internal life cycle infrastructure in place. This infrastructure provides for both product life extension of still-serviceable and reconditionable telephones as well as the proper recycling of those telephones which can no longer be repaired. From a life cycle perspective, product life extension is preferable to once-through use and recycling. Several AT&T and non-AT&T resources are in place that extend the life of a business telephone. Some of these, such as the various AT&T service and reclamation centers, have their origins in the predivestiture days before the break up of the Bell System (in 1984) when AT&T products could only be leased and

AT&T maintained control and ownership of all the products it manufactured. While these installations were originally not conceived as environmentally-sound product disposition centers, they nevertheless can now be used in that capacity.

The life cycle of a business telephone, complete with product reuse and material recovery loops, is shown schematically in **Figure 5-3**. Business phones, which tend to have more value than consumer phones, rarely have just one life. At the end of their initial tour of duty, many of these phones end up at an AT&T service center. This is not just true of leased phones, but also, increasingly, of purchased phones that are returned as part of trade-in arrangements when customers upgrade their systems. Depending on age and condition, the returned phones are either refurbished and sold or leased again, or they are scrapped and recycled.

Scrapped phones are torn apart and the metal and plastic components recycled. Fully automated product shredding and postshred separation processes are increasingly used to recover materials from phones no longer refurbishable. Telephone housings, for example, become postconsumer acrylonitrile-butadiene-styrene (ABS) regrind. Traditionally, most of the postconsumer material recovered from scrapped phones was sold in the secondary material markets. AT&T is now actively exploring the feasibility of closing the loop internally on some of the recovered materials.[66] This effort is an example of development work intended to lead to better resource use in the future, thus improving AT&T's management of the product and/or material life cycle.

Even if AT&T business phones do not end up at an AT&T service or reclamation center (today many don't), they may still get refurbished and reintroduced to the market. Many independent companies have moved into this field since the breakup of the Bell System. Thus the average life of business phones and whole business phone systems is usually longer than the duration of their initial tour of duty with the first leaseholder or owner.

An inspection of **Figure 5-3** will suggest many ways to improve the life cycle profile of a telephone. There are waste streams generated at every stage of the life cycle that can be eliminated or at least reduced. Although **Figure 5-3** contains repair and reuse loops as well as a material recovery system, it does not depict a closed-loop system. Almost nothing but virgin materials are used for the production of new telephones, and virtually all the materials that are eventually captured are recycled in an open-loop, rather than a closed-loop fashion. From a life cycle perspective, it would be desirable to achieve more closed-loop recycling.

The following discussion focuses on two specific design strategies for the 8403 terminal; redesign of its packaging and design improvements to its housing.

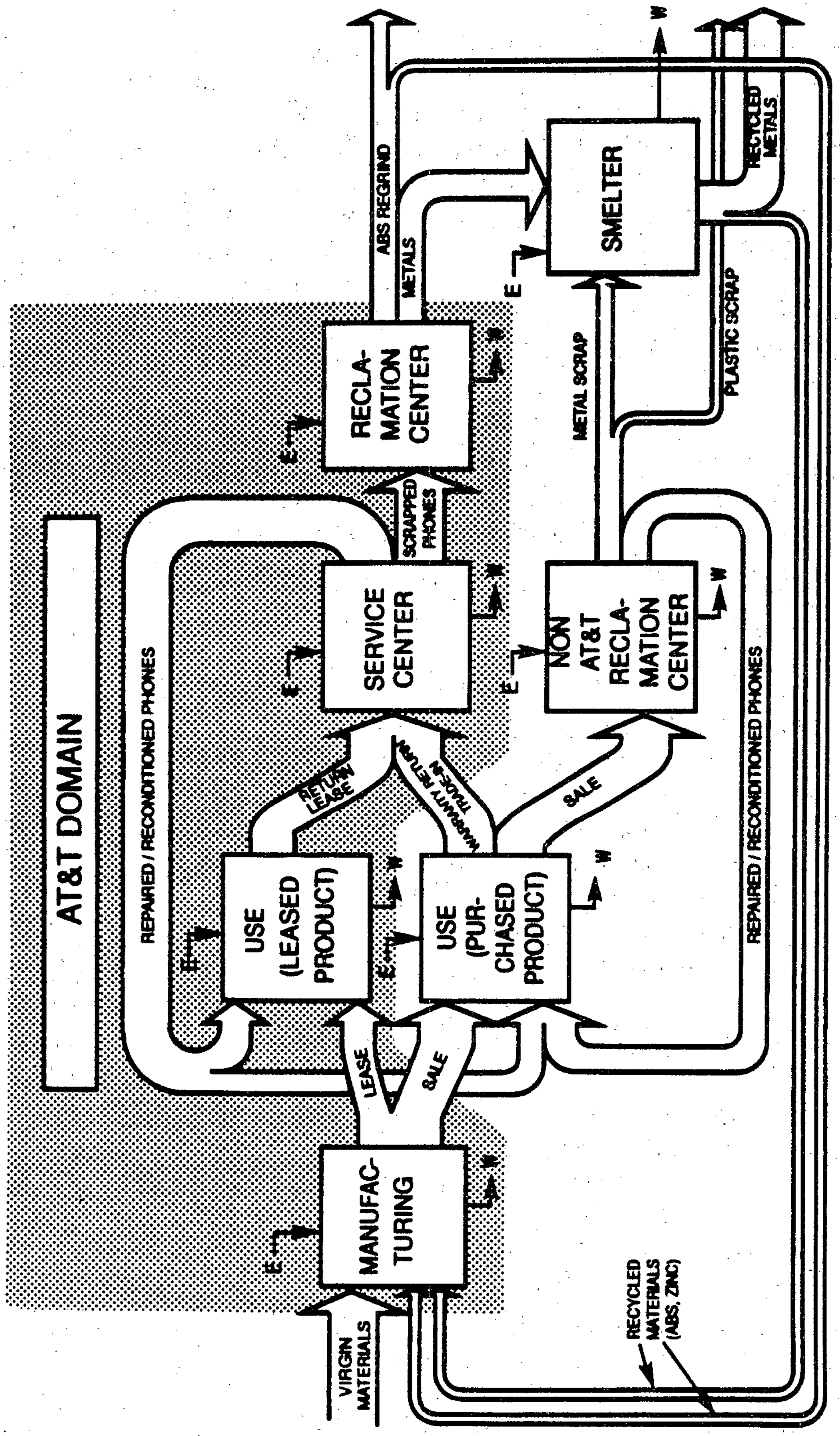


Figure 5-3. Life Cycle of Business Telephones

Packaging Redesign

One of the recommendations made as a result of the 8503 baseline study was to improve the packaging for business terminals. However, by the time the project team began investigating improved packaging options for the 8403, a new packaging system was already under development. System installers' complaints about excessive packaging and product documentation traditionally used for business phones lead to this improvement. Because the Definity® communications system is intended for large businesses, dozens or hundreds of office terminals may be purchased by a customer and installed at a single site. In such situations, it clearly makes no sense to ship individually packaged terminals with an installation guide in each package. Doing so results in maximum rather than minimum packaging for the customer or AT&T technician installing the phones to discard. The new packaging system allows several terminals to be shipped in a single box with a single installation guide. Individually-packaged sets are also still available for customers purchasing single add-on sets through the AT&T Sourcebook (a catalog for business telephone products and accessories). This new dual system, which reduces packaging for quantity shipments of telephone terminals, was first used for the 8403 terminal.

Improved Telephone Housing Design

The most comprehensive life cycle design strategy implemented by the design team addressed the housing of the 8403 DCP terminal. This is no accident. As a result of AT&T having been involved in molding, refurbishing, and recycling telephone housings for many years, the green product realization team learned a good deal about which features enhance the environmental aspects of a plastic housing. This knowledge is now being fed back into the design process through the DFE program.

In this project, environmental requirements for the manufacturing stage specify that housing material be recyclable and nontoxic and that measures be taken to minimize molding scrap to conserve resources and reduce waste. Environmental requirements for the end-of-life stage specify that the housing be reusable, reconditionable, or at least recyclable.

To mold housings for central-office, line-powered telephone sets such as the 8403, AT&T uses ABS resin, a thermoplastic material with good recyclability. The specific ABS resin used contains no heavy metal stabilizers or colors formulated with heavy metals. The resin also does not incorporate any of the polybrominated flame retardants for which restrictions or bans have been proposed in Europe. **Table 5-6** contains a comparison of the housing designs for the 8403 terminal and its predecessor, the 7401 DCP terminal.

The first feature listed, a textured housing surface, helps reduce manufacturing scrap. Sprues, runners, defective parts, and other scrap are an inevitable byproduct of any molding operation. This clean and uncontaminated preconsumer plastic waste can, in principle, be shredded and recycled on-site by mixing the regrind with virgin material and using the blend for new production. In practice, however, the use of regrind material for

Table 5-6. Comparison Between The 7401 And 8403 DCP Terminals

7401 Terminal	8403 Terminal	
Feature	**Improved Feature**	**Impact/Effect**
High gloss housing surface	Textured housing surface	Molding waste reduced
Rubber feet glued to stand	Rubber feet snapped on	Rubber contamination removable
UL listing symbol on paper housing	UL listing symbol molded into housing	Contamination of plastic housing minimized
Acoustic foam piece glued to inside of top part of housing	Acoustic foam piece press fit over speaker	Contamination of plastic housing minimized
Transparent polycarbonate sheet used as light diffuser glued to housing	No light diffuser used	Contamination of plastic housing minimized
Housing material not identified	ISO plastic marking code molded in	Plastic identifiable by non-AT&T reclamation or recycling center

new housings is problematic because the regrind component, having experienced at least one previous heat cycle, makes color control difficult. Thus, although regrind can sometimes be used for nonappearance parts, outside uses for the excess regrind material must be found.

Clearly, minimizing the amount of molding scrap in the first place is desirable. A small contribution to this end can be made by specifying textured surfaces for external plastic parts. All other things being equal, a textured surface tends to hide minor molding flaws better than a high-gloss, smooth surface. Thus, the yield for parts with textured surfaces is generally higher and the amount of molding waste smaller. Textured surfaces also tend to be more scratch resistant, which is a factor that may help extend the life of the housing.

The next four features for the 8403 DCP listed in **Table 5-6** make the part more recyclable. These features are intended to ensure that at end of life, the housing can be turned into high-value, uncontaminated regrind material with near-virgin properties by means of low-cost, automated processes. To accomplish this, the housing of the 8403 was designed to require no glue joints. It also incorporates no foreign materials (with the exception of the serial number label) that are difficult to separate from the base polymer. Finally, the molded-in ISO plastic identification code is intended to facilitate material identification by a non-AT&T-affiliated service or reclamation center.

Compared to the 7401 terminal, the 8403 also has a significant new electrical feature - both 2- and 4-wire connectivity - that makes it a more versatile product. Compatibility with both 2- and 4-wire installations means that the set works with earlier 4-wire Definity® Systems as well as the new 2-wire Definity® G3V2 and G3V3 Systems and future releases. Thus the new 8403 terminal allows users to gain access to additional features and capabilities, but does not necessarily require customers to junk their older Definity® PBX (Private Branch Exchange) and its associated wiring. By retaining this compatibility, the 8403 is designed to protect a customers' investment in, and extend the life of, older Definity® Systems.

Design Evaluation

The design evaluation of the 8403 terminal did not involve a rigorous life cycle assessment (LCA). Such an assessment would have been costly, time intensive, and given the controversies which still surround LCA, of questionable value. Instead, the project team used their best judgment and understanding to select design strategies for improving the product's overall environmental profile. The project team also investigated currently existing corporate activities and programs that affect a product's life cycle and studied how those programs could be improved and better coordinated. For example, the design for recyclability enhancements implemented on the 8403 are intended to maximize material recovery and minimize nonrecyclable residue generation rates for the specific processes AT&T uses to recycle telephone housings.

At the time of this project, AT&T had not yet developed a comprehensive set of environmental metrics or a streamlined life cycle assessment tool for design evaluation, although the ongoing development of the Green Index Scoring System is a step in that direction. Performance measures are needed to determine improvements in environmental performance and assess the effectiveness of a DFE program. Performance measures are clearly a weak link at present. Good performance measures can only be defined once a consensus has been obtained on what constitutes proper green design for a particular product. Such a consensus does not presently exist. Accordingly, performance measures, to the extent that they are used, are of questionable validity. In principle, systems such as design rating or product assessment methods, could constitute suitable measures for the moment.

Scoring systems, like all quantitative environmental assessment methods, are still quite controversial for several reasons. Often the data necessary for a reasonably rigorous analysis do not exist, or they are suspect. Even when data are available, there are currently no commonly agreed upon methods for assessing the environmental merit or impact of a material, let alone a complex product. Among the more complex issues which remain to be resolved are issues of how to assess incommensurable impacts and where to draw boundaries for analysis of a product Recognizing these difficulties, AT&T is actively developing a matrix tool for life cycle assessment of products, processes, and facilities. The matrix is constructed of five columns for life cycle stages and 5 rows for impacts including resource use, energy use, and environmental releases to air, water and land. Until the Green Index tool and the DFE Assessment Matrix are completed, the company is relying on its design guidelines, checklists, and environmental professionals for design evaluation.

MAJOR FINDINGS AND CONCLUSIONS

Having explored at least some life cycle design issues using the 8403 DCP terminal as a vehicle, the joint AT&T/University of Michigan team gained considerable insights into the issues and challenges of practicing life cycle design in the "real world". The research team discovered that life cycle design is very difficult to practice at present. A study of AT&T's DFE program showed that there is a strong focus on developing specific tools to aid designers in addressing environmental issues. AT&T's efforts have primarily focused on design checklists and guidelines, and more recently on streamlined life cycle assessment tools. The origination of DFE from DFX roots at AT&T is apparent, but now emphasis on the life cycle system is gaining momentum.

AT&T's environmental management is beginning to extend further beyond the manufacturing domain. The structure of AT&T's DFE program is essentially similar to the life cycle design framework presented in chapters 1-4. The major difference is that LCD addresses the interactions between environmental, performance, cost, legal and cultural requirements more explicitly.

Major findings and conclusions will now be discussed for each of the key elements of the life cycle design framework.

Environmental Management System

First and foremost, a well structured environmental management system suitable for a particular company's size, culture, and product portfolio, along with clearly articulated life cycle goals, are absolutely essential to support a nascent life cycle design program. The AT&T development team faced difficulties caused by the embryonic state of "green" design, and the lack of an adequate environmental management system. Many companies have good environmental management systems in place, but because these systems evolved in response to escalating regulations, they are primarily equipped to handle compliance matters. Current corporate environmental management systems are typically not structured to support company-wide life cycle design practices. As a result, designers and engineers who attempt to address life cycle issues today lack adequate support.

AT&T is currently attempting to redress this problem by reorganizing its environmental management system and internal infrastructure to address issues associated with the life cycle of products and services. AT&T's newly proposed environmental policy explicitly recognizes the life cycle framework for environmental management. The proposed environmental policy, DFE guidelines and checklists, and simplified life cycle assessment tools clearly demonstrate significant progress toward raising awareness about the importance of the life cycle system throughout the corporation and among its external stakeholders.

AT&T's corporate environmental goals are now focused primarily on the manufacturing domain along with two goals which address office management. From a life cycle design perspective, these goals are not comprehensive because they do not address materials supplied to AT&T or end-of-life management issues. For example, goals have been set for recycling office paper but goals for reusing or recycling plastic components from retired AT&T products have not been set. This distinction between reduction in environmental burden of AT&T's manufacturing and service domain versus total reduction across the life cycle should also be recognized when the next set of corporate environmental goals is established.

Design Requirements

The multicriteria requirements matrices explored in this demonstration project are an attempt to assist the design team in systematically addressing environmental issues over the product life cycle. Multicriteria requirements matrices were recognized by the AT&T project team as a useful organizing tool for identifying and analyzing the key requirements that shape the design of a product system. These matrices provided an effective framework for exploring the complex interactions and conflicts between requirements and for investigating strategies to optimize the overall design with respect to these requirements. All requirements classes must be specified explicitly to successfully guide life cycle design. Without stating requirements explicitly, the design team is less likely to have a cohesive understanding of the design space.

The information in the multicriteria matrices shown in **Tables 5-1** through **5-5** represent some of the key design issues but is by no means comprehensive. Proper management of information for design assessment requires the institutionalization of an elaborate new information system that spans across the full product life cycle. As discussions with different members of the cross-functional team revealed, improved communications functions need to be formalized and responsibilities clearly defined.

Reorganization of the matrices could greatly facilitate their use. It is recommended that a computerized tool be developed to store and access requirements. Rules for organizing matrices provided in **Table 4-5** should be explored to help guide the design process. For example, present versus future requirements can be distinguished. Anticipated legal requirements such as the German Waste Ordinance for Electronic Products can be listed separately from CFC labeling requirements which are now in effect. Computerizing the matrices and making them available as part of a DFE package could be very useful for a large, decentralized corporation such as AT&T. A summary matrix may also be used to highlight key issues; more detailed requirements could then be accessed in a hierarchical fashion. In addition, checklists and other detailed specifications could potentially be stored in a user-friendly data base.

Design Strategies

While AT&T is facing many of the same challenges other companies face in implementing an environmental management structure that effectively supports a life cycle design program, the company is relatively well positioned to address product take back and broader product life cycle issues. This is a result of AT&T having inherited both extensive manufacturing, product service, refurbishing, and recycling operations from the Bell System. Furthermore, through its DFE and "green technologies" development programs, AT&T is actively establishing green design and manufacturing capabilities. However, while large pieces of the necessary internal infrastructure are in place, these pieces need to be better integrated in order to more effectively deliver products with minimum aggregate environmental impact.

The design strategies that AT&T has implemented to reduce environmental burden mainly target factory waste streams and emissions, and preconsumer and postconsumer recycling. Strategies such as product life extension, which include reuse of components, adaptability for upgrading, and appropriate durability, were not emphasized by the design team.

However, AT&T has recently introduced the Signature® Series telephones, which are a line of more robust phones designed specifically for the lease market. Maintaining ownership through leasing products clearly allows for better life cycle management. However, in a free market with no strict product take back regulations, there are limits to maintaining control of the product AT&T manufactures. This restricts the product life extension strategies AT&T can realistically implement.

Design Evaluation

Product realization stakeholders, most of whom are not environmental experts, need help evaluating design strategies for reducing environmental burden. Perhaps most critically, design teams must have access to environmental data of the same quality and utility that is available for other classes of requirements. AT&T has recognized this need by developing streamlined tools for environmental assessment such as the Green Index and more recently a life cycle assessment scoring system. Unfortunately, life cycle design is much further advanced as a concept than as a practice. The lack of a broad consensus in the scientific and engineering community on what really constitutes environmentally-conscious products and services is clearly an impediment to companies moving more aggressively on life cycle design. Nonetheless, judgment will always be required to weigh environmental impacts (resource use, energy use, environmental releases) along with other design issues. Life cycle design offers a framework to address this challenge in a more systematic way.

6. ALLIEDSIGNAL DEMONSTRATION PROJECT

The purpose of the Life Cycle Design Demonstration Project with AlliedSignal, Filters and Spark Plugs (ASFSP) was to explore opportunities to reduce environmental burdens associated with oil filters. AlliedSignal's project team used the life cycle design framework outlined in the Life Cycle Design Guidance Manual to compare two alternative oil filter designs. The specific objective of the demonstration project was to establish design criteria that would determine if a new design alternative offered significant environmental benefits over the existing filter design.

Because the project team members had extensive experience with the design and manufacture of an existing standard filter design, the group decided to baseline this product. After identifying material and energy inputs and outputs and residuals for the life cycle of the product system, the team evaluated multicriteria requirements for guiding environmental improvement of AlliedSignal's filter products. The team applied its knowledge of a newer prototype model with a reusable housing to help establish design criteria for future products. Although the group did not compare the environmental profile of the two filters in the demonstration project, criteria were set for developing a cleaner product in the future. AlliedSignal selected an oil filter for this demonstration because of growing concern about the environmental impacts associated with disposing used filters.

Oil filters are a vital component of automotive engine systems. They protect engine components from abrasive contaminants by removing grit and dirt from the lubricating oil of the engine. Well designed and maintained filtration systems can extend the life of the engine and thus play an important role in overall vehicle performance. In addition to performance, design engineers are becoming increasingly concerned about the environmental burdens associated with these systems.

The automobile is one of the most significant contributors to global, regional, and local environmental problems through its intense resource use, energy consumption, pollution, and waste. A successful reduction in environmental impacts from the life cycle of an oil filter represents one improvement in the environmental profile of the automobile.

Approximately 400 million oil filters are sold annually in the United States. At present, the majority of used oil filters are disposed in landfills. The residual oil associated with a retired oil filter presents a potential landfill leaching problem. Currently, only a relatively small fraction of used filters are recycled. AlliedSignal estimated that as of June 1993, 750 tons per month of filter scrap are being recycled into steel and iron products. This equates to approximately 18 million filters recycled annually in the US.

PROJECT ORIGIN AND BACKGROUND

AlliedSignal Participation

AlliedSignal's participation in this project was linked directly to their prior recognition of the life cycle framework as an important element of their environmental management system. In 1991, AlliedSignal hosted a life cycle analysis (LCA) meeting of representatives from aerospace and automotive business units to discuss critical issues in LCA and its application to product development. Dr. Keoleian presented the life cycle design framework at this meeting. After a series of informal meetings about life cycle design, Filters and Spark Plugs decided to participate in a demonstration project. The Engineering arm of Filters and Spark Plugs took lead responsibility for this project.

Cross-Functional Team & Product Development

AlliedSignal organized a multidisciplinary team from Filters and Spark Plugs to participate in this project. Members of this core group were located at the Perrysburg, Ohio and East Providence, Rhode Island facilities. The following lists contains the titles of the AlliedSignal team members.

AlliedSignal Project Team Members

Vice President, Engineering	Vice President, Product Marketing
Director, Filter Engineering	Vice President, Passenger Car Product Marketing
Engineering Manager, Labs	Manager, Heavy-duty Product Marketing
Engineering Manager, Materials	Manager, Passenger Car Product Marketing
Engineering Manager, Air Filters	Engineering Manger, Liquid Filters
Product Engineers	Plant Business Center Managers
Director, HS&E	Director, Original Equipment Sales

SELECTION AND DESCRIPTION OF PRODUCTS

The demonstration project team selected a spin-on oil filter to evaluate for design improvement because they were already testing a prototype cartridge filter design as a replacement. The spin-on oil filter unit is a single-use product whereas the cartridge filter features a reusable housing in combination with a single-use filter media. The cartridge filter design, also referred to as a quick disconnect filter, can be disassembled, allowing the filter media to be removed and replaced and the entire unit remounted to the engine. **Figures 6-1** and **6-2** illustrate both designs.

The primary components of the spin-on filter are the filter media, steel housing, steel base (puck) which mounts the engine, and a gasket. The primary components of the quick disconnect filter are the filter cartridge, steel shell, steel base which mounts to the engine, o- ring, gasket, and a retaining ring that locks the assembly together.

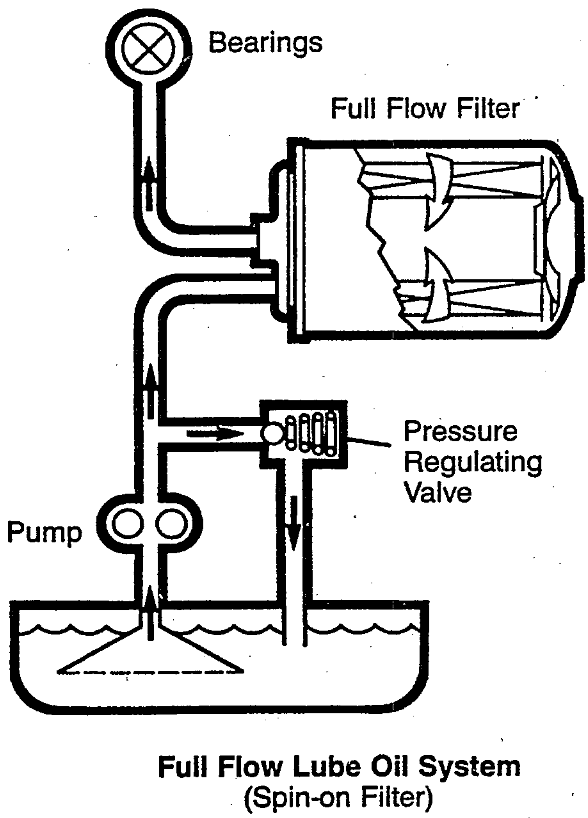
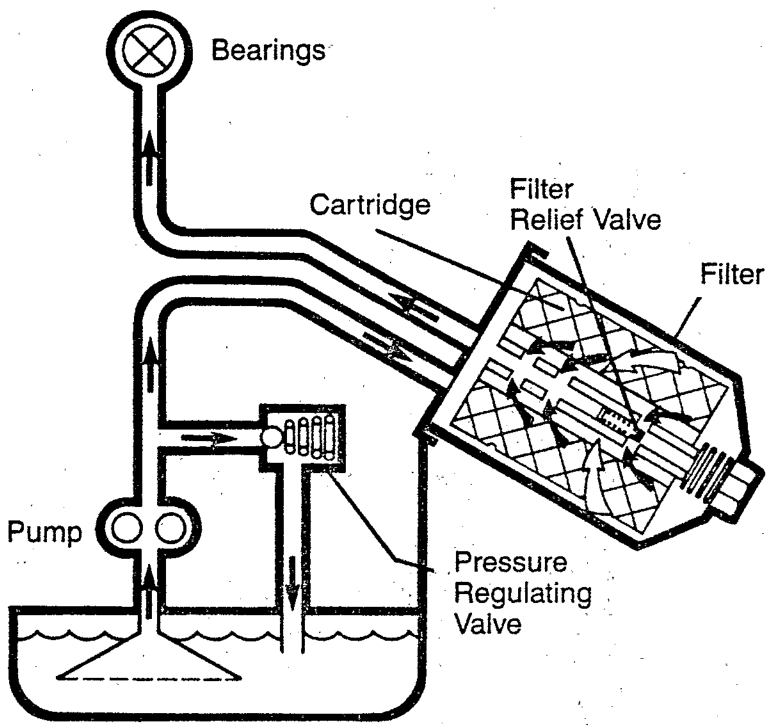


Figure 6-1. Schematic of the Spin-On Type Filter



Full Flow Lube Oil System
(Replaceable Cartridge Filter)

Figure 6-2. Schematic of the Quick Disconnect Filter (Cartridge Filter with Reusable Housing)

The PH3612 model spin-on type oil filter was selected as a basis for design improvement. This filter is used with heavy-duty truck engines. It has an outside diameter of 4 19/32" and height of 10 15/64", which is considerably larger than the models used on cars. However, the heavy-duty truck filter is functionally identical to the car filter design except for size.

CARTRIDGE FILTERS AND SPIN-ON FILTERS

Cartridge filters are typically a replaceable pleated paper filter media formed in a cylinder around a perforated metal center tube. Metal end caps and nitrile rubber grommets are used to prevent flow around the filter media. Spin-on filters are essentially cartridge filters that are assembled into a filter can or body.

ENVIRONMENTAL MANAGEMENT SYSTEM

Several key elements of AlliedSignal's environmental management system, including environmental policies and organizational structure, will be described in this section. First, a short business description is provided.

Business Description of AlliedSignal

AlliedSignal is a $12 billion international company with 110,000 employees. The company is organized into three major business sectors: chemicals, aerospace products, and automotive products. The AlliedSignal Filters & Spark Plugs (ASFSP) business unit is part of AlliedSignal's Automotive Sector. ASFSP is responsible for designing, manufacturing, marketing, and selling all filters and spark plugs.

Environmental Policy and Goals

AlliedSignal addresses environmental protection through both a vision statement and an environmental policy. A section of the AlliedSignal mission statement entitled Our Values includes seven areas: customer integrity, people, teamwork, speed, innovation, and performance. Environmental protection is addressed under "integrity" with the following statement:

> We are committed to the highest level of ethical conduct wherever we operate. We obey all laws, produce safe products, protect the environment, practice equal employment, and are socially responsible.

AlliedSignal's health, safety, and environmental policy, effective April 1992, states:

> It is the worldwide policy of AlliedSignal Inc. to design, manufacture and distribute all its products and to handle and dispose of all materials without creating unacceptable health, safety or environmental risks.
> The corporation will:
> - Establish and maintain programs to assure that laws and regulations applicable to its products and operations are known and obeyed;
> - Adopt its own standards where laws or regulations may not exist or be adequately protective;
> - Conserve resources and energy, minimize the use of hazardous materials and reduce wastes
> - Stop the manufacture or distribution of any product or cease any operation if the health, safety or environmental risks or costs are unacceptable.
>
> To carry out this policy, the corporation will:
> 1. Identify and control any health, safety or environmental hazards related to its operations and products;
> 2. Safeguard employees, customers and the public from injuries or health hazards, protect the corporation's assets and continuity of operations, and protect the environment by conducting programs for safety and loss prevention, product safety and integrity, occupational health, and

pollution prevention and control, and by formally reviewing the effectiveness of such programs;

3. Conduct and support scientific research on the health, safety and environmental effects of materials and products handled and sold by the corporation; and
4. Share promptly with employees, the public, suppliers, customers, government agencies, the scientific community and others significant health, safety or environmental hazards of its products and operations.

Every employee is expected to adhere to the spirit as well as the letter of this policy. Managers have a special obligation to keep informed about health, safety and environmental risks and standards, so that they can operate safe and environmentally sound facilities, produce quality products and advise higher management promptly of any adverse situation which comes to their attention.

Environmental Management Organization

The responsibility for environmental management is decentralized to each operating unit within AlliedSignal. Health, Environment and Safety (HS&E) is headed by a corporate vice president, and HS&E presidents for automotive, aerospace, and chemical sectors report to the corporate vice president. There are counterpart organizations within the sectors. Each operating unit has an HS&E manager who reports directly to both its president and the HS&E sector president.

Product Responsibility Guide

AlliedSignal has an established mechanism for addressing environmental considerations in product development. This mechanism is documented in their Product Responsibility Guide. This guide provides key elements for implementing effective "product safety and integrity programs" at AlliedSignal. Its contents include:

- New Product Review
- Customer/User Application
- Design Review
- Product Testing and Evaluation
- Reliability Review
- Failure Mode and Effects Analysis (FMEA)
- Process Review
- Process Control
- Purchased Parts and Material
- Product Quality Assurance
- Product Literature
- Product Hazard Communications
- Transportation

- Customer Complaints, Returns, Failures and Warranty
- Product Recall
- Regulatory Affairs
- FDA Regulatory Compliance for Medical Devices
- Compliance with The Toxic Substances Control Act (TSCA) Inventory and Premanufacture Notification (PMN)
- AID-Free Products
- TRAC - Risk Identification and Reporting System
- Product Responsibility Evaluation Review

The guide "recognizes that each employee has an obligation to contribute to the manufacture of quality products and to protect himself (and herself) and other employees, customers, the public at large, and the environment in the design, manufacture, marketing and distribution, use and disposal of Allied's products."

For each section of the Product Responsibility Guide, guidelines, scope, purpose, requirements and responsibilities are presented. This manual has a number of shortcomings, such as an orientation toward compliance and safety rather than pollution prevention, and lack of guidance on implementing design strategies that reduce aggregate environmental burden.

To address these concerns, AlliedSignal is currently developing a Design for the Environment guidance manual to facilitate the integration of environmental considerations into product and process design in a more comprehensive manner. A draft version of this document includes a series of DFE checklists for research and engineering design, process engineering, manufacturing, marketing, and packaging.

PROJECT DESCRIPTION

Needs Analysis and Project Initiation

The AlliedSignal team's stated objectives for this project were:

> We will use the Life Cycle Design Guidance Manual to contrast the quick disconnect design (cartridge filter with reusable housing) and the standard PH3612 (spin-on oil filter), from manufacturing and assembly through treatment and disposal stages of the product's life cycle. Our goals are to evaluate the EPA Life Cycle Design Guidance Manual and to satisfy our customer's needs.

The core team from Filters & Spark Plugs initiated the demonstration project by defining the project objective and identifying critical issues to address in improving oil filter design. A list of issues was formulated during a brainstorming exercise of the core team. The resulting list highlights in general terms some of the important design issues for oil filter design.

Significant Needs and Functional Attributes of Oil Filter Design Identified by Brainstorming

Filter oil	**Trouble free operation**
Product differentiation	Reduced operating Expenses
Used Filter disposal	Warrantee concerns
Convenient handling	Availability
Convenient servicing	Education/training
Economical	Comfort acceptability
Engine protection	Support
Reduce disposal	Peace of mind

Scope and System Boundaries

At the onset of the project, the development team decided to limit its focus to the manufacturing through disposal stages of the product life cycle. Although the group recognized the importance of the raw materials acquisition stage, limited time and resources did not permit a full investigation of this stage.

A simplified process flow diagram for both the spin-on and cartridge filter designs is shown in **Figure 6-3.** For the spin-on type filter landfill disposal is currently the most

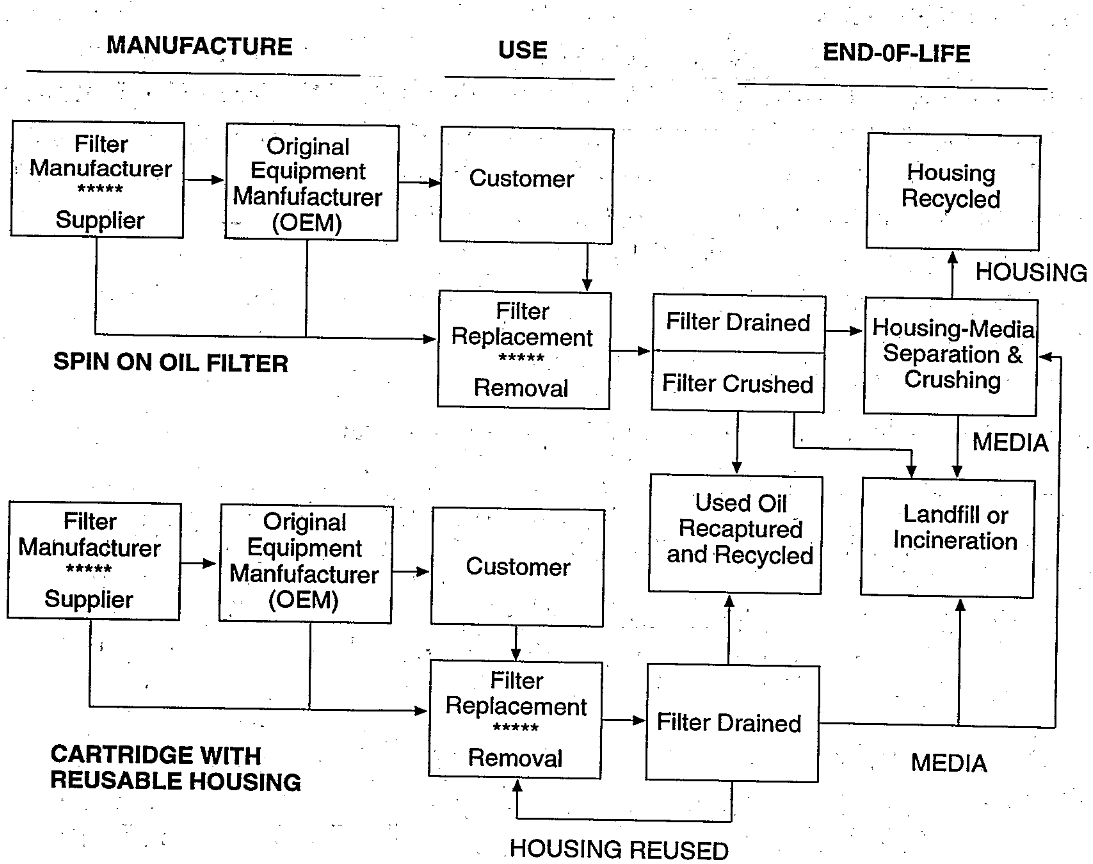


Figure 6-3. Process Flow Diagram for Spin-on and Cartridge Filter Designs

widely practiced end-of-life management option. Other options include recycling the metal housing with and without separation of the filter media. Steel mills have different specifications for recycling. Some require removal of gaskets, while others accept only shredded or cubed filters, and/or pucks. The filter media may be separated and incinerated with or without energy recovery. For the cartridge filter design, a durable housing is reused and the filter cartridge may be incinerated or disposed in landfills after the residual oil is drained or pressed out. In either case, residual oil may be refined or incinerated.

It is also important to recognize that the oil filter is a component of the powertrain, which is a subsystem of the total vehicle. This interrelationship adds complexity to the design process for a filter product and points out the importance of establishing an effective supplier (filter manufacturer) and automotive manufacturer relationship.

The following two options for the oil filter/engine interface can be considered in redesigning the oil filter system:

- retrofit the oil filter to the existing engine mount
- redesign the filter and engine concurrently

The scope of this demonstration project was limited to the consideration of the existing engine mount. Major oil filter design changes would require engine design modifications. The development team indicated that is difficult to get OEMs (original equipment manufacturers) to redesign the engine because of the large capital investment necessary for tooling.

The hierarchy of systems in **Table 6-1** shows how the oil filter is part of several higher order systems, each of which has its own complex set of design requirements that must be addressed. Understanding some of the higher level design requirements and the distribution of environmental impacts across each level is useful for achieving a successful oil filter design.

Table 6-1. Oil Filter System Within Higher Level Systems

System Level	Need
Oil Filter Product System	Remove contaminants from engine oil
Power Train System	Convert fuel to mechanical energy to propel the vehicle
Automotive Product System	Provide mobility (independence In setting time and destination)
Transportation System Level	Provide for the movement of people and goods via automobiles, buses, trains, planes, ships, bicycles, etc.

Baseline Analysis

The project team conducted an inventory analysis that identified the material and energy inputs and outputs for the spin-on filter product system. The input/output analysis was conducted using the framework defined in the Life Cycle Design Guidance Manual. Inventory items were identified for each component of the product system (product, process, and distribution) across each stage of the life cycle considered in this project (manufacture, use/service, retirement, and disposal). Multicriteria requirements matrices were used to organize information and guide the analysis.

Table 6-2 summarizes the results of the baseline analysis as compiled by the University of Michigan researchers. To simplify presentation, retirement and disposal are combined into one stage: end-of-life management. Changes in the matrices were also made to reflect the modified product system components introduced in this report. In the current version of the product system, management functions are included in both the process and distribution components. Although the project team was very thorough in identifying inputs and outputs, a quantitative inventory analysis was not performed.

Establishing Design Requirements

After identifying inventory items for the spin-on filter, the project team used the guidelines offered in the Life Cycle Design Guidance Manual to develop design requirements for filters that they referred to as "directions for new designs." They completed all environmental requirements for the entire life cycle first, then developed full sets of performance, legal, cost, and cultural criteria, one matrix at a time. This complete set of requirements established a framework for evaluating and comparing the spin-on and cartridge filter designs.

Weekly meetings were scheduled to identify and formulate requirements for each element of the multicriteria matrix. The design requirements developed by the project team are summarized in **Tables 6-3** through **6-7**. As in the baseline analysis, the information provided by the project team was reorganized into a three column matrix (retirement and disposal stages combined into end-of-life management) to simplify presentation of the results. Some of the design requirements used for comparative analysis of the two design alternatives are discussed in the following sections.

Table 6-2. Results of Baseline Analysis

Manufacture	Use/Service	End-of-Life Management
Product		
Input - Steel e.g., tin plated, HRPO, heat treated 1050 - Gasket with nitrile rubber and adhesive - Element and end disc - Sealant (solvent based) - Paint and litho *Output* - PH3612 *Residuals* - See retirement stage	*Input* - PH 3612 *Output* N/A *Residuals* N/A	*Input* - Used PH 3612 - Storage materials - Oil retained in filter *Output* - Retired PH 3612 *Residuals*
Process		
Input - Energy for plant operations including ovens, conveyors, wire tie, welding, tapping, pleating, compressors, curing, painting/priming - Materials i.e., wire ties, die lubricants, solvents, and cleaning chemicals, compressed air, tapping coolant, and test fluids - Energy for facilities i.e., lighting, heat, air, computers, lab equipment - Labor from engineers, designers, sales, quality, maintenance, purchasing, finance, MIS, HR/ER, scheduling, clerks - Office materials e.g., paper, lab supplies, microfilm, samples Output - Scrap steel, product, paper - Materials containers - Wire ties - Information including budgets, reports, and specs *Residuals* - Generated and lost heat from processes - Waste paint, roll cores, coolant and plasticsol - Stack emissions, waste water, - Worn tools and rejected materials - Spill absorbent - Lab wastes - Packaging	*Input* - Oil - Energy to power shop equipment and facility - Labor from installers - Solvents - Rags and clean up materials - Speedi-dri *Output* - Oil change - Filter change *Residuals* - Used oil (stored) and solvents - Oil containers - Waste water - Packaging - Dirty rags and uniforms - Used hygiene materials and speedi-dri (stored)	*Input* - Energy to power equipment such as crusher and cutter and shop environment - Labor from handler - Rags, speedi-dri, uniforms, and clean-up materials - Solvent - Oil and used oil containers - Drain rack and drums - Energy for facilities and equipment - Labor from HS&E, safety, service center, office, and scheduler - Office supplies *Output* - Processed used oil filter - Dirty oil removed from processed filter - Barrels to hold processed filters - Policy, compliance reports, and schedules *Residuals* - Dirty rags, uniforms, and hygiene materials - Used filters, used oil and containers, sludge - Packaging - Used solvent and waste water - Paper and packaging
Distribution		
Input - Energy for machines • shrink wrapping, boxing carton ID, and labeling • palletizers, forklifts, pick/place, materials handling • EDI and WMS • transportation - Labor from operators, drivers, maintenance, shippers/pickers, receivers, forklift, and data entry and administrative services. - Office materials e.g., paper, lab supplies, microfilm, samples - Materials including boxes, cartons, staples, glue, shrink wrap, banding, pallets, inks, labels, cleaning fluid, and solvents *Output* - PH 3612 packaged and delivered - Information including budgets, reports, and specs *Residuals* - Waste oil, heat, water, and solvents - Used tires and maintenance parts - Emissions from IC motors - Scrap shrink wrap, packaging, pallets	*Input* - Energy for facilities and equipment - Travel and parts pick-up - Delivery system - Labor from sales, service manager, counter people, office and quality staff, scheduler, safety and engineering, and warrantee staff - Office materials e.g., paper and computers *Output* - Paperwork e.g., billing, schedules *Residuals* - Paper and packaging	*Input* - Energy for handling equipment and facilities - Labor from handler and driver *Output* - Stored "processed" filters moved to removal point *Residuals* - Used oil and emissions from handling equipment

Table 6-3. Environmental Requirements

Manufacture	Use/Service	End-of-Life Management
Product		
- Commonize/homogenize materials - Reduce amount of material used in product - Use lower impact materials - Eliminate/reduce paper use, travel, and testing - Decrease variability - Streamline procedures - Reduce cycle time	- Reduce usage rate - Increase service intervals - Eliminate need for oil and filter changes - Reduce materials - Use "greener" materials	- Eliminate need for retirement - Reduce materials - Use greener materials
Process		
- Lower energy requirements - Reduce material needs - Use more efficient processes - Investigate recycle/reuse of residuals	- Reduce usage rate/increase service intervals - Reduce oil/filter change cycle time - Less messy, "neat and clean" filter change - Eliminate need for oil and filter change - Use recyclable residuals	- Less messy/"neat and clean" retirement process - Eliminate need for retirement - Recyclable residuals
Distribution		
- Lower energy requirements - Commonize/homogenize materials used - Reduce materials needed - Use low impact materials - Use more efficient processes - Reuse, recycle residuals - On-site manufacturing and distribution	- Direct ship to customer - Reusable, recyclable, returnable packaging	- Eliminate need for retirement - Recyclable residuals

Environmental

Environmental requirements were specified to reduce the environmental burden of manufacturing, use, and end-of-life management of the oil filter. These environmental requirements also address key issues relevant to each of the stakeholder groups including the auto manufacturers, vehicle owners, and service personnel. For example, criteria to reduce material intensiveness may ultimately be set by the OEM. This requirement relates to powertrain weight constraints. Light weighting the vehicle can increase fuel efficiency and reduce emissions accordingly.

Other requirements targeted the environmental burdens associated with filter changes. Frequency of filter changes and impacts related to spilled oil and used rags were addressed. The frequency of filter changes is a critical requirement that affects the total environmental burden associated with the filter life cycle. Clearly, less frequent filter changes would reduce burden but only so far as this doesn't shorten engine life. Explicit instructions on how frequently to change filters is not provided by AlliedSignal. Instead, customers are instructed to change the filter according to vehicle manufacturers recommendations. Better guidance to filter users could lead to more optimal use.

The project team even formulated some idealized requirements such as eliminating the need for oil and filter changes.

Recognizing the importance of eliminating landfill disposal of oil filters, AlliedSignal created a special task force on Used Oil Filters (UOF). At present, UOF scrap is being recycled into rebar, fence posts, steel billets, construction channel steel, cast iron manhole covers, and cast iron pipe. The task force focused on recycling the spin-on filter. A survey was conducted to evaluate the recycling infrastructure available to process used filters and also identify mill specifications for processing the filter metal. AlliedSignal compiled a list of steel mills and foundries that accept used oil filters. This list included the following information:

- mill location
- furnace type
- filter specs for mill use (e.g., pucks, shredded, cubed)
- transporter/processor requirements, price paid or charge ($/ton),
- transport mode
- geographic are of used oil filters (UOF's) received
- UOF quantity consumed
- use more UOF scrap (yes or no)
- product manufacturer and general comments

The recycling task force made the following observations about used oil filter recycling markets:

- Increasing number of mills testing or purchasing UOF scrap
- All user mills require UOF free of residual oil
- Most mills want filters crushed or cubed to min. 20,000 psi. Some accept shredded scrap (free of oil and paper media)
- Scrap pricing varies

Table 6-4. Performance Requirements

Manufacture	Use/Service	End-of-Life Management
Product		
Manufacture	*Use/Service*	*End-of-Life Management*
- Processable materials - Meets FMSs	- Meet minimum internal and external specs - Meet customer specs - Serviceable - Protect engine - Safety factors - Withstand environment	- Easily removed - Drainable - Crushable - Disassemblable - Appropriate life span
Process		
Manufacture	*Use/Service*	*End-of-Life Management*
- Warehouse management - Information flow - Staffing - Schedules and quotes - Inspection - QC instructions - Training - Certification - TQM	- Robust - Reliable - No leaks - Effective filtration - Technical information - Performance information - Application information - Customer service	- Simple - Minimize spills - No special tools required - Instructions - Training - Scheduling - Safety
Distribution		
Manufacture	*Use/Service*	*End-of-Life Management*
- Identifiable components - Traceable components - Appropriate lot sizes - Packaged for manufacture - J.I.T. - Minimum inventory - Appropriate storage environment	- Available - Appropriate carton quantity - Appropriate packaging i.e., size and protection - Bar coding - Identification	- Appropriate storage area prior to treatment/disposal

Performance

The main performance requirement of the oil filter is to protect the engine. It is useful to understand the function of engine oil before addressing performance requirements for the oil filter. Engine oil has the following functions:

- lubricates moving parts
- acts as cleaning agent (flushes contaminants)
- protects against corrosion
- cools (heat transfer media)
- seals (combustion seal)

Maximum engine life depends on correctly using and maintaining oil filters to protect vital engine components by filtering out abrasive contaminants that accumulate in the lubricating oil.

An important set of performance requirements focus on the process for replacing the filter. The time requirement, tools, and level of difficulty are all key factors in guiding design choices.

Table 6-5. Cost Requirements

Manufacture	Use/Service	End-of-Life Management
Product		
- Cost effective materials - Preferred suppliers - Common materials - Design for assembly	- Extend service life - Ease of service - Reduce total cost - No warrantee problems	- Easily removed - Minimize time - Minimize spills - No special tools
Process		
Manufacture	*Use/Service*	*End-of-Life Management*
- Use existing equipment - Flexible manufacturing - Low maintenance - Short set-up times - Minimize labor - Optimum throughput/line speed - Minimize scrap - Waste disposal - Use of self-managed work groups - Training	- Easy installation - No special tools - Warrantee/recalls	- No special tools - Drainable - Easily removed - Simple - Instructions - Scheduling - Training - Safety
Distribution		
Manufacture	*Use/Service*	*End-of-Life Management*
- Common parts - No specialized storage - Minimize handling - Optimize material flow - Minimize packaging/reusable packaging	- Optimize distribution - Appropriate packaging	- Storable

Cost

Cost criteria weigh heavily in decisions regarding design of an oil filter product system. For example, the retooling cost for manufacturing processes can be significant. Unit production costs and replacement costs to users must be competitive for the product to succeed. In addition to costs to manufacturers and service facilities, the total life cycle cost to the vehicle owner should also be considered. For each case, it is also important to recognize which stakeholder will accrue costs or savings.

Table 6-6. Legal Requirements

Product		
Manufacture	*Use/Service*	*End-of-Life Management*
- MSDS sheets - Meets published claims - Use of non-toxic materials - Non-infringement on patents	- Warrantee - Safety - Labeling - Warnings	- EPA requirements - Local regulations and ordinances
Process		
Manufacture	*Use/Service*	*End-of-Life Management*
- OSHA requirements - EPA requirements - ICC requirements - EEOC requirements - Other government regulations - Record keeping - Evacuation/emergency plans - Corporate ethics	- Easy/safe installation - Clear, concise instructions - Materials - MSDS sheets - Correct application published	- EPA requirements - Local regulations and ordinances
Distribution		
Manufacture	*Use/Service*	*End-of-Life Management*
- OSHA requirements - EPA requirements - ICC requirements - EEOC requirements - Other government regulations	- Labeling on packaging - CC packaging rules - Warnings on packaging	- EPA requirements - Local regulations and ordinances

Legal

Legal requirements for the filter product system are constantly changing. During the course of the demonstration project several new legal requirements were set. For example, EPA ruled on hazardous waste management of used oil on 20 May 1992 (40 CFR Part 261 Hazardous Waste Management System; General; Identification and Listing of Hazardous Waste; Used Oil; Rule). EPA decided not to list used oils destined for disposal as hazardous waste. The EPA also finalized an exemption for used oil filters. This exemption is limited to nonterneplated filters. Terneplate steel coating is a lead compound which could cause a used filter of this type to exceed acceptable lead levels. AlliedSignal uses no terneplate in any liquid filter they manufacture.

EPA's exemption applies only to used oil filters that have been drained of free flowing oil. If an oil filter is picked up by hand or lifted by machinery and used oil immediately drips or runs from the filter, the filter should not be considered to be drained.

In addition to federal regulations, many states have passed their own regulations on used oil and used oil filters. Life cycle designers should be aware of current and likely regulations to avoid costly redesign at any stage of the development process.

Table 6-7. Cultural Requirements

Manufacture	Use/Service	End-of-Life Management
Product		
Manufacture - Old vs. new product - Old vs. new paradigms	*Use/Service* - Customer perceptions - Graphical instructions - OE look-alike vs. different look - Brand recognition/preference	*End-of-Life Management* - Lack of environmental concern - Safety - Eliminate retirement
Process		
Manufacture - Pride in work - Old vs. new paradigms - Diverse workforce - Change the way we do business - Us vs. them attitudes	*Use/Service* - DIY or not DIY - Clear, concise instructions - Multilingual instructions	*End-of-Life Management* - Clear, concise instructions
Distribution		
Manufacture - Old vs. new paradigms	*Use/Service* - Availability - Tradition channels	*End-of-Life Management* - Safely handled - Reuse/recycle vs. throwaway

Cultural

The project team identified several cultural criteria that should be considered when comparing the spin-on and cartridge filter designs. The level of difficulty for changing a filter and the convenience in making a filter change was identified as an important factor. Both service centers and customers who are "do-it-yourselfers" prefer to have a design that is easy to find, take off, and replace.

The project team also indicated that packaging of the filter product was an important marketing factor. AlliedSignal's research revealed that consumers may be influenced by packaging design when determining which filter to buy at a store. The design team's effort to simplify or reduce packaging were limited by this marketing constraint. Less environmentally harmful packaging designs that limited the product's marketability were not considered a feasible business strategy in this case. However, innovative responsible packaging designs may be a marketing tool for future product design efforts.

EVALUATION

The matrices described in the preceding tables include a comprehensive set of design requirements which must then be assigned priority to properly guide design. In AlliedSignal's judgment, the following criteria were the key drivers for making design decisions in this project:

- Satisfy regulations that ban landfill disposal of used filters
- Minimize life cycle cost to user, including replacement parts, labor, and retirement costs
- Make filter design compatible with current OEM design of filter-engine interface
- Extend useful life of filter system
- Minimize total waste associated with filter use

Table 6-8. Total Costs for Heavy-Duty Fleet Use of Several Oil Filter Alternatives

	Change (Clean) Interval in Miles	Engine Life in Miles	Filter Cost with disposal	Labor Cost	Associated Servicing Costs[1]	Total User Cost
Spin On (crushed at disposal)	20,000	500,000	$377	$350	$87	$814
Cartridge (filter media crushed at disposal)	20,000	500,000	$265	$569	$87	$921
Cleanable Filter						
Option A: filter lasts 500,000 miles	20,000	500,000	$240	$438	$193	$871
Option B: filter replaced at 250,000 miles[2]	20,000	500,000	$288	$263	$251	$802

[1] Includes crushing equipment, cleaning fluids and equipment
[2] Filter less durable than option A, but requires less cleaning labor

Comparison of Design Alternatives

Our analysis indicates that the cartridge filter best meets the environmental design requirements developed for this project. However, the cartridge filter does not appear to offer compelling advantage when other requirements are considered. In terms of total user cost, the cartridge filter is somewhat more expensive compared to the spin-on alternative. **Table 6-8** shows total user costs associated with each filter. A cleanable filter that does not rely on a single-use medium is also included in this table to demonstrate a possible future design direction that reduces landfill disposals related to filter use.

The project team identified the following key results of the design evaluation:

- The primary conflict in changing to a new filter design is the culture of the producer and, more importantly, the customer. It is difficult to promote a change from a system (spin-on filters) which has worked well for so many years to a less attractive alternative unless there are overriding drivers like government regulation.
- Functionally, a change from a spin-on filter to an alternative like the quick disconnect with a cartridge has little impact on the design or manufacturing communities; these products are already produced in slightly different forms.
- Within the identified requirements there is little conflict. AlliedSignal is already driven to use materials and processes with minimum environmental impact by legislation governing our manufacturing operations as well as our own corporate directives.
- The critical requirements are for the performance of the filter to meet the required engine specification needs and for the product to be salable to our customers.

- There is only a trivial difference between the two products' performance, because the designs in effect only alter the "packaging" of the filter by changing the pressure housing from non-opening to opening.
- Customer acceptance is a much more important and difficult issue to resolve. Without a regulatory driver, the new product must be sold on the basis of a cost benefit to the final customers. This is not a product to product cost comparison, but a life cycle cost analysis, incorporating all aspects of filter life and associated cost, as shown in **Table 6-8**. Unless a cost benefit can clearly be demonstrated, this is not a salable product, and it is of no use to anyone.
- Under current filter disposal regulation, the cartridge filter does not clearly meet the requirements as a salable product. With the broadening of landfill bans, this situation would change.
- In Europe the cartridge filter is gaining popularity, probably due to a different regulatory climate.

Action Plan for New Design

The cartridge concept can be extended to encompass a totally non-metallic cartridge construction which simplifies waste disposal or incineration. A further extension incorporates a cleanable filter medium which eliminates all filter waste disposal. This is currently a very active area of investigation for ASFSP.

AlliedSignal plans to continue pursuing environmentally compatible filter design with the emphasis on a reusable filter system. ASFSP is now field testing this design while also further developing cleanable filter media and the supporting cleaning process.

MAJOR FINDINGS AND CONCLUSIONS

The AlliedSignal demonstration project was an important test of multicriteria requirements matrices for guiding the reduction of environmental burdens. Although AlliedSignal had been investigating the application of the life cycle framework to environmental assessment and design, most members of the project team had not been exposed to this concept at the initiation of the project. Although an HS&E professional from Filters and Spark Plugs was a member of the core team, the demonstration project was conducted independently of corporate HS&E involvement.

Environmental Management System

Both AlliedSignal's existing product realization process and its total quality management program provided a basis for implementing life cycle design. AlliedSignal has a comprehensive product review process which covers HS&E issues. The product life cycle concept is expressed in AlliedSignal's HS&E policy statement, but the term "life cycle" is not stated explicitly. The objective to reduce waste was well defined in the context of TQM, but corporate environmental goals with quantitative targets were not identified by the project team.

A draft Design for the Environment Guidance Document indicates that the company wishes to place additional emphasis on integrating environmental issues into product and process design. A corporate-wide educational training program on DFE and life cycle design is essential to institutionalizing such a program.

Design Requirements

The project team did not use assistance from corporate HS&E or the University of Michigan research group in developing the matrices. After one introductory presentation on life cycle design, the project team relied exclusively on the Life Cycle Design Guidance Manual for instructions on using the matrices. The project team concluded that matrices are useful for specifying requirements, but identifying material and energy inputs and outputs during the baseline phase was very time consuming.

The interaction between members of the cross-functional team may have been better facilitated if the participants had identified and discussed the full set of requirements for one life cycle stage at a time rather than complete all environmental requirements for the entire product system before addressing another entire class of requirements.

The team indicated that the matrices would be particularly useful for guiding a major design change because of the amount and complexity of issues that need to be analyzed. Interviews with team members indicated that a major benefit of applying the multicriteria approach was that it enabled each member of the team to understand the full set of requirements affecting the filter product life cycle.

The matrix approach also served to close communication gaps between design and manufacturing. One member of the project team recommended involving AlliedSignal's suppliers and customers (auto manufacturers and service industry) in the process of specifying requirements. This involvement could potentially strengthen the relationship between stakeholders in the product life cycle.

Although use of the requirements matrices was initially cumbersome and time intensive, this process will be simplified in the future. Problems encountered here were due in part to the level of detail used by the AlliedSignal team. Focusing on major issues can greatly streamline this process, but project teams should be aware that important criteria may be overlooked if requirements development is oversimplified. In the end, the ASFSP team identified a small number of critical requirements to guide their decision making.

After the initial set of requirements has been established, they can be modified easily during the next development cycle. Entering these requirements into a computerized database could greatly facilitate both their modification and accessibility.

The project team indicated that it was difficult in the beginning to understand the organization of the matrices, particularly the distinction between product and process components. Part of the confusion was due to the association of the term "process" with manufacturing alone and not the use and end-of-life management stages of a product. Only qualitative requirements were specified for this demonstration project. In the future, quantitative constraints for guiding environmental improvement could better serve the design team in comparing alternative design solutions.

The project team recognized that the requirements matrices could also be useful for strategic planning purposes. By organizing the matrix requirements along a time dimension, design objectives can be differentiated according to present, short-range, and long-range issues (or other business plan horizons). This type of organization can facilitate effective strategic planning of product improvements.

Design Evaluation

Members of the project team indicated that legal requirements were primary factor driving the design. If used oil filters were classified as a hazardous waste, the cartridge filter design would become more attractive due to increased cost for hazardous waste disposal.

Economics is also a critical factor in evaluating design alternatives. The cartridge filter design is currently being implemented on many heavy-duty vehicles. For large truck fleets there is no clear economic incentive, because total user costs are slightly higher for cartridge filters. In addition, production of a cartridge filter may not be the most profitable strategy for a manufacturer. Economic analysis is complicated because costs and benefits accrue to multiple stakeholders (e.g., OEMs, suppliers, customers, automotive service industry).

The project team was confident that the quick disconnect is an environmental improvement over the spin-on design because it allows easier recovery of used oil and results in less metal waste. Even though the spin-on filter housings may be recycled, the environmental impacts associated with collection, processing, and transportation can be significant. A rigorous comparative life cycle assessment of the two designs, however, was not performed.

Clearly, the spin-on filter itself represents an investment of more steel and rubber gasket material compared to the cartridge filter. Although the cartridge filter is a more material-intensive design initially, over the life of the filter fewer resources are used. With a vehicle and cartridge housing life of 500,000 miles and a filter change every 20,000 miles (as shown in **Table 6-8**), one cartridge filter housing would be required compared to 25 housings for the spin-on design over vehicle life. The cartridge filter may require replacement of gaskets, but the housing would not need replacement.

One tradeoff to be considered in terms of material intensiveness is the overall effect of the differential weight of the two systems. The increased weight of the cartridge design results in a decrease in fuel economy and an increase in associated vehicle emissions, although this differential for heavy-duty vehicles is slight (1-2 pounds). The project team is very sensitive to weight specifications, but the significance of this factor was not discussed. A similar weight differential would be more important for passenger cars. Even so, ASFSP is confident that the weight of cartridge or cleanable filters can be reduced if the OEMs cooperate in redesigning the filter interface.

As previously mentioned, since the completion of this study of spin-on and cartridge oil filters, ASFSP has focused on designing a cleanable filter. This design may have lower total costs to users compared to either the cartridge or spin-on alternative, and thus be a more attractive product. Although no analysis of environmental burden has been done on this alternative, it seems to be a clear improvement over current filters.

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GLOSSARY

checklists A series of questions or criteria formulated to help designers be systematic and thorough when addressing design topics such as environmental issues. Proprietary checklists for DFE have been developed by AT&T which are similar to the Design for Manufacturability (DFM) checklists widely used by designers.

cross-disciplinary team A design team that includes representatives from all the major participants in the product development and implementation process (e.g., product designers, process engineering, marketing, legal, environmental health and safety).

concurrent design Simultaneous design of all components of the product system including processes and distribution networks. Concurrent design requires an integrated team of specialists from various areas.

Design for Environment DFE has been defined as "a practice by which environmental considerations are integrated into product and process engineering design procedures" Life cycle design (LCD) and DFE are difficult to distinguish from each other; they are usually considered different names for the same approach. Yet, despite their similar goals, the genesis of DFE is quite different from that of LCD. DFE evolved from the design for X (DFX) approach, where X can represent manufacturability, testability, reliability, or other downstream design considerations.

design strategies Approaches that explore and synthesize ways to translate design requirements into products. Strategies act as a lens for focusing knowledge and new ideas on a feasible design solution.

downcycle To recycle for a less demanding use. Degraded materials are downcycled.

embodied energy Energy contained in a material that can be recovered for useful purposes through combustion or other means.

environmental equity Addresses the distribution of resources and environmental risks among generations and elements of society. Issues of equity apply both within and between nations.

environmental management system An organization's plan and programs for achieving environmental improvement and/or ensuring regulatory compliance. Environmental management systems include environmental policies and goals, performance measures, strategic plans, environmental information management systems, and training and education programs.

environmental accounting Accounting practices used to measure environmental burdens. Costs may accrue to manufacturers, consumers, and/or society at large. Key challenges relate to methods for estimating and allocating environmental costs. Some confusion surrounds the use of terms such as full cost accounting, life cycle costing, and total cost assessment.

equivalent use Delivery of an equal amount of product or service. Usually stated in terms of distance, number, volume, weight, or time. For example, the amount of detergent required to wash a certain number of identical loads.

externalities Costs borne by society rather than those involved in a transaction.

home scrap Materials and by-products commonly recycled within an original manufacturing process.

industrial ecology Study of the interactions and relationships between industrial systems and natural ecosystems based on analysis of material and energy flows and transformations. Industrial ecology is founded on the assumption that industrial systems should be patterned after the highly integrated, efficient cycling of natural ecosystems.

life cycle assessment (LCA) A comprehensive method for evaluating the full environmental consequences of a product system. LCA consists of four components: goal definition and scoping, inventory analysis, impact assessment, and improvement analysis.

life cycle costing In the environmental field, this has come to mean all costs associated with a product system throughout its life cycle, from materials acquisition to disposal. Where possible, social costs are quantified; if this is not possible, they are addressed qualitatively. Traditionally applied in military and engineering to mean estimating costs from acquisition of a system to disposal.

life cycle design (LCD) Life cycle design seeks to minimize environmental burdens associated with a product's life cycle. It offers a framework for integrating environmental requirements more effectively into product system design and management. Key principles are:

- Systems analysis of the product life cycle from raw materials acquisition through manufacturing, use, service, and end-of-life management (reuse, recycling, disposal). The product system for design includes product, process, and distributions components
- Multicriteria analysis for identifying and evaluating environmental, performance, cost, cultural, and legal requirements
- Multistakeholder participation and cross-functional teamwork throughout design

life cycle impact assessment A quantitative and/or qualitative process to characterize and assess the effects of the environmental burdens identified in the inventory analysis.

life cycle improvement assessment A process that identifies and evaluates opportunities to reduce environmental burdens based on the results from an inventory analysis and impact assessment.

life cycle inventory analysis Identifies and quantifies all inputs and outputs associated with a product system. Items inventoried include resource and energy inputs, air emissions, waterborne effluents, solid waste, products, coproducts, and energy produced.

life cycle management Life cycle management includes all decisions and actions taken by multiple stakeholders which ultimately determine the environmental profile and sustainability of the product system.

needs analysis The process of defining societal needs that will be fulfilled by a proposed development project.

physical life cycle The material and energy flows in a product life cycle. See product life cycle.

pollution Any byproduct or unwanted residual produced by human activity. Residuals include all hazardous and nonhazardous substances generated or released to the air, water, or land.

pollution prevention Any practice that reduces the amount or 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, reformulation or redesign of products and processes, substitution of raw materials, and improvements in housekeeping, maintenance, training, or inventory control. It does not include activities that are not integral to producing a good or providing a service.

postconsumer material In recycling, material that has served its intended use and been discarded before recovery.

preconsumer material In recycling, overruns, rejects, or scrap generated during any stage of production outside the original manufacturing process.[67]

product life cycle The life cycle of a product system begins with the acquisition of raw materials and includes bulk and specialty processing, manufacture and assembly, use and service, retirement, and disposal of residuals produced in each stage.

product system Consists of product, process, and distribution components. The product includes all materials in the final product and all forms of those materials in each stage of the life cycle. Processes transform materials and energy. Distribution includes packaging and transportation networks used to contain, protect, and transport products and process materials. Wholesaling and retailing are part of distribution. Equipment and administrative services related to managing, including developing and conveying information, occur throughout processing and distribution and are included in these components.

recycling The reformation, reprocessing, or in-process reuse of a waste material. 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."[67]

renewable Capable of being replenished quickly enough to meet present or near-term demand. Time and quantity are the critical elements in measures of renewability.

requirements The functions, attributes, and constraints used to define and bound the solution space for design. General categories of requirements include environmental, performance, cost, cultural, and legal. Requirements can be classified as follows:

Must requirements Conditions that designs have to meet. Arrived at by ranking all proposed functions and choosing only the most important.

Want requirements Desirable traits used to select the best alternative from possible solutions that meet must requirements. Want requirements are also ranked and used to evaluate designs.

Ancillary requirements Desired functions judged to be relatively unimportant and thus relegated to a "wish list". Included in the final product only if they do not conflict with other criteria.

residual The remainder. In the life cycle framework, those wastes remaining after all usable materials have been recovered.

retirement The transitional life cycle stage between use and disposal. Resource recovery options are decided in this stage. Products and materials may be reused, remanufactured, or recycled after retirement.

reuse The additional use of a component, part, or product after it has been removed from a clearly defined service cycle. Reuse does not include reformation. However, cleaning, repair, or refurbishing may be done between uses. When applied to products, reuse is a purely comparative term. Products with no single-use analogs are considered to be in service until retired.

sustainable development Seeks to meet the needs of the present generation without compromising the ability of future generations to fulfill their needs. Principles include: sustainable resource use (minimize the depletion of non-renewable resources and use sustainable practices for managing renewable resources), pollution prevention, maintenance of ecosystem structure and function, and environment equity.

system boundaries Define the extent of systems or activities. Boundaries delineate areas for design or analysis.

total cost assessment A comprehensive method of analyzing costs and benefits of a pollution prevention or design project. TCA includes:

- full cost accounting, a managerial accounting method that assigns both direct and indirect costs to specific products
- estimates of both short- and long- term direct, indirect or hidden, liability, and less tangible costs
- costs projected over a long horizon, such as 10-15 years
- use of standard procedures such as net present value and internal rate of return to measure profitability

useful life Measures how long a system will operate safely and meet performance standards when maintained properly and not subject to stresses beyond stated limits.

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