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ENVIRONMENTAL LIFE-CYCLE ASSESSMENT

Mary Ann Curran

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PREFACE

The environmental movement is on a fast track. Just when we become somewhat comfortable with terms such as *waste minimization* and *pollution prevention*, new terms such as *sustainability, environmental justice, industrial ecology*, and *life-cycle assessment* are added to the list. The result is a lot of enthusiastic people running around using these terms without clear definitions. The main intent of this book is to offer insight into the term *life-cycle assessment* (LCA) as viewed by several prominent players in the development and application of LCA worldwide.

The following chapters cover all facets of LCA in order to help the reader thoroughly understand the subject. The discussions range from the full, robust LCA model (inventory, impact assessment, and improvement analysis) to issues surrounding the development of a streamlined approach. Applications in life-cycle design and ecolabeling are presented, as well as initial attempts to include life-cycle thinking in the development of public policy in the United States and abroad. Of course, no discussion of industrial applications would be complete without consideration of life-cycle costing and its importance as a factor in decision making.

Since LCA is as much a concept as it is a tool, it can be viewed in different ways and through different applications. While much has been achieved in order to define life-cycle assessment, consensus has not been reached at all levels. As you progress through the book, you may notice the coauthors presenting differing viewpoints. This reflects the dynamic situation of the practice called LCA.

The goal of this book is to bring perspective to the practical application of LCA to products, processes, and activities. The chapters address how LCA is being applied by industry and government and assess its potential as it evolves both as an environmental tool and as an ethic, much as pollution prevention has. As with any new field that is in the developmental stage as LCA is, some of the information presented here may be outdated by the time of publication. The case studies presented here are offered as examples to product manufacturers and their suppliers of how the use of LCA can lead to beneficial results.

I encourage you to begin thinking about your operations and activities in the context of life-cycle thinking, to achieve true reduced environmental impacts.

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CHAPTER 6
LIFE-CYCLE DESIGN

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6.1 INTRODUCTION

Design offers an excellent opportunity to reduce environmental burdens associated with products and processes, which ultimately can lead to a more sustainable relationship between economic and ecological systems. Guiding environment improvement and sustainable development through design requires framework(s), tools, and innovation. Decisions involving material selection, useful product life, packaging systems, manufacturing processes, and strategies for product service and retirement shape the environmental profile of a product. But even if a designer were unconstrained by performance and cost requirements, it is not obvious what an environmentally optimal design would represent. In addition to this challenge, design participants face pressing issues such as shortening development cycles, expanding global competitiveness, increasing and inconsistent regulations, and continually shifting market demand. Evaluating and improving environmental performance have become major challenges facing the design community.

Life-cycle design is beginning to emerge as a new field for addressing this challenge.[1] For example, the Environmental Protection Agency (EPA) has sponsored the development of the *Life Cycle Design Framework and Demonstration Projects: Profiles of AT&T and AlliedSignal.*[2] The basic theory of life-cycle design is that the product life-cycle system provides a logical framework for representing the diverse interests of multistakeholders in the development of sustainable products. The product life cycle which encompasses raw materials acquisition, manufacturing, use and service, and end-of-life management (e.g., remanufacturing, recycle, disposal) defines the boundaries of the system for addressing the full environmental consequences associated with a product.

Recognition of the life-cycle framework has been driven by a variety of reasons including public concern about municipal solid waste which represents the end of a product life cycle, environmental marketing claims to distinguish products, and product take-back regulations. The application of the life-cycle framework is still in its infancy. Many organizational and operational changes in corporate environmental management systems, the design process, and government policy and regulation are necessary to realize the benefits of life-cycle design and related approaches.

This chapter presents the key elements of life-cycle design and examines the role of life-cycle assessment and other tools in its application.

6.2 TERMINOLOGY

A wide assortment of terminology has been introduced in this field. The terminology, however, is often used without a clearly defined framework, objectives, and boundaries; hence its use may not be consistent. For example, the product life cycle may or may not be recognized as a system boundary. The following is a set of definitions of commonly used terms. Many other terms have been used in this field, but they do not necessarily represent a life-cycle approach. Such terms include ***environmentally conscious design, environmentally conscious manufacturing, cleaner products, cleaner production,*** and ***ecodesign.***

Life-Cycle Assessment (LCA): A comprehensive method for evaluating the full environmental consequences of a product system. LCA has four components: goal definition and scoping, inventory analysis, impact assessment, and improvement analysis. Life-cycle assessment represents the most comprehensive analytical tool for evaluating environmental burden, but unfortunately there are several practical barriers limiting its widespread application.[4]

Life-Cycle Costing: In the environmental field, this has come to mean all costs associated with a product system throughout its life cycle, from raw materials acquisition to disposal. Currently, *life-cycle costing,* also referred to as *full cost accounting or environmental accounting,* has limited practical applicability. Some environmental costs can be difficult to measure (future liabilities) and/or allocate (externalities). Traditionally the term is applied in military and engineering to mean estimating costs from acquisition of a product to disposal (includes operating and maintenance costs).

Life-Cycle Design: A systems-oriented approach for designing more ecologically and economically sustainable product systems. It couples the product development cycle used in business with the physical life cycle of a product. Life-cycle design integrates environmental requirements into the earliest stages of design so total impacts caused by product systems can be reduced. In life-cycle design, environmental, performance, cost, cultural, and legal requirements are balanced. Concepts such as concurrent design, total quality management, cross-disciplinary teams, and multiattribute decision making are essential elements of life-cycle design.

Design for Environment: This is another widely used term for incorporating environmental issues into a product system design process. DFE has been defined as "a practice by which environmental considerations are integrated into product and process engineering design procedures."[5] Life-cycle design 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 life-cycle design. DFE evolved from the *design for X* (DFX) approach, where X can represent manufacturability, testability, reliability, or other downstream design considerations.

6.3 DEFINITION OF THE PRODUCT SYSTEM

6.3.1 Life-Cycle Stages

Figure 6.1 presents a general flow diagram of the product life cycle. As this figure shows, a product life cycle is circular, beginning with resource consumption and ending as residuals eventually accumulate in the earth and biosphere. A product life cycle can be organized into the following stages:

- Raw material acquisition
- Bulk material processing
- Engineered and specialty materials production
- Manufacturing and assembly

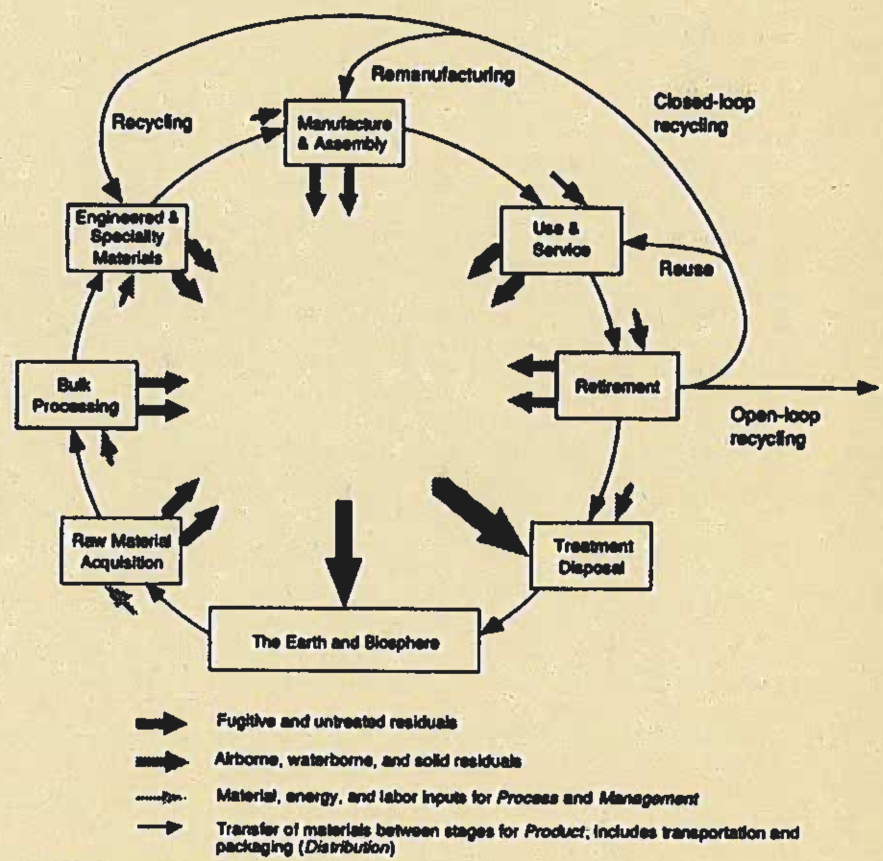

FIGURE 6.1 Life-cycle stages.

- Use and service
- Retirement
- Disposal

Raw materials acquisition includes mining nonrenewable material and harvesting biomass. These bulk 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 engineered and specialty materials. Examples include polymerization of ethylene into polyethylene pellets and the production of high-strength steel. Base and engineered 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, wastewater 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 geographic 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 geographic basis, and environmental consequences occur on global, regional, and local levels.

6.3.2 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 to 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.

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 material inputs
- Energy

In the *Life Cycle Design Guidance Manual*, management was considered a separate component. Experience gained in life-cycle design demonstration projects 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 a 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 percent (64.4 million tons) of municipal solid waste generated in the United States.[6] 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.

Table 6.1 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.

6.4 LIFE-CYCLE FRAMEWORK AND GOALS

The life-cycle framework provides a logical structure 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 product system, designers and managers can prevent the shifting of impacts between media (air, water, land) and between stages of the life cycle.

TABLE 6.1 Partial Example of Product System Elements for a Reusable Plastic Cup over Its Life Cycle

	Raw material extraction	Bulk processing or engineered material	Manufacturing	Use	Retirement or 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, packaging	Trucks, containers

The life-cycle framework encompasses information from multiple stakeholders whose involvement is critical to successful design improvement. The primary elements of the framework are goals, life-cycle management, and life-cycle development process.

6.4.1 Life-Cycle Design Goals

The fundamental goal of life-cycle design is to promote sustainable development at the global, regional, and local levels. Specifically, life-cycle design seeks to reduce the total environmental burden associated with product development by applying sustainable principles to the product system.

Achieve Sustainable Development. Sustainable development seeks to meet the needs of the present generation without compromising the ability of future generations to fulfill their needs. Translation of this broad goal to practical tools for design is a major challenge. The following general principles for achieving sustainable development, however, can be defined: sustainable resource use (conserve resources, minimize depletion of nonrenewable resources, use sustainable practices for managing renewable resources), pollution prevention, maintenance of ecosystem structure and function, and environmental equity. These principles, described in Table 6.2, are interrelated and highly complementary.

Life-cycle design seeks to minimize adverse environmental impacts and utilize resources efficiently to meet basic societal needs. Determination of what constitutes basic societal needs is based on individual value judgments and preferences, which is a topic outside the scope of this chapter. Achieving sustainable development goals, however, requires design innovation and in some cases forgoing the production of products that contribute large environmental burdens.

Specific Environmental Goal of Life-Cycle Design. The environmental goal of life-cycle design is to maximize resource efficiency and minimize the aggregate life-cycle environmental burden associated with product systems. Environmental burden can be classified into the following impact categories:

TABLE 6.2 Principles of Sustainable Development

Promote Sustainable Resource Use and Efficiency

- Conserve resources, minimize depletion of nonrenewable resources, and use sustainable practices for managing renewable resources.
- The amount and availability of resources are ultimately determined by geological and energy constraints, not human ingenuity.

Promote Pollution Prevention

- Proactive approach based on source reduction avoids the transfer of pollutants across media (air, water, land).
- Addressing environmental issues in the design stage is one of the most effective approaches to pollution prevention.

Protect Ecological and Human Health

- Healthy, functioning ecosystems are essential for the planet's life support system.
- Avoiding irreversible damage to the ecosystem such as loss of biodiversity is necessary to protect human health.

Promote Environmental Equity

- Address the distribution of resources and environmental risks.
- Intergenerational equity—meet current needs of society without compromising the ability of future generations to satisfy their needs.
- Intersocietal equity—change patterns of resource consumption and associated environmental risks within developed and less developed countries to achieve sustainable development and to address the disparity among socioeconomic groups within a country.

- Resource depletion
- Ecological and human health

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.

ENVIRONMENTAL BURDEN

Environmental burdens are not distributed evenly over the product 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.

Although there are no universal methods for precisely characterizing and aggregating environmental burdens, Fig. 6.2 shows a hypothetical example of an environmental profile. As illustrated, impacts are generally not uniformly distributed across the life cycle. 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.

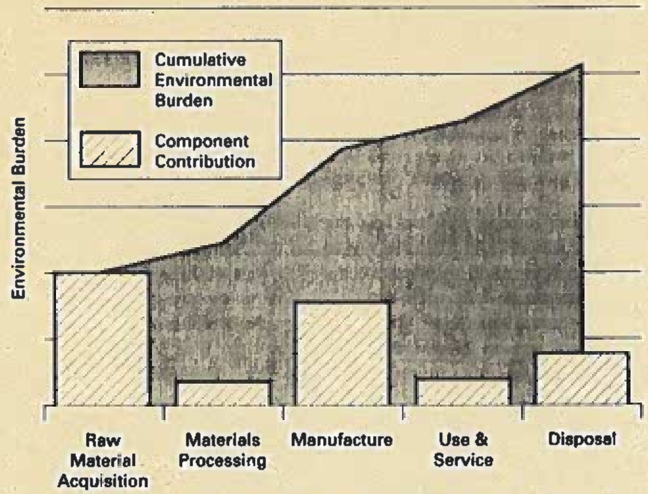

FIGURE 6.2 Environmental burden in hypothetical units of a product system.

6.5 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 box. A major challenge for product manufacturers lies in coordinating the diverse interests of these stakeholder groups.

ROLES FOR KEY STAKEHOLDERS IN LIFE-CYCLE MANAGEMENT

Users and Public
- Advance understanding and values through education
- Modify behavior and demand toward 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 and Shareholders
- Support cleaner product system development

Service Industry
- Maintain and repair products

Insurance Industry
- Assess risk and cover losses

A range of internal and external factors influence the product development team's ability to effectively address environmental considerations through design. These factors form the context for the design process.

6.5.1 Internal Elements

Environmental stewardship issues are increasingly addressed within corporations by formal environmental management systems.[7,8] Ideally, the environmental management system is interwoven within the corporate structure and not treated as a separate function.[8]

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 strategic plan. This system must also provide access to accurate information about environmental impacts. An effective environmental information system is critical to guiding the design process in the direction of environmental improvement. Three main attributes of a well-designed environmental management system are *vision, organization,* and *continuous improvement.*[9] Figure 6.3 summarizes these issues.

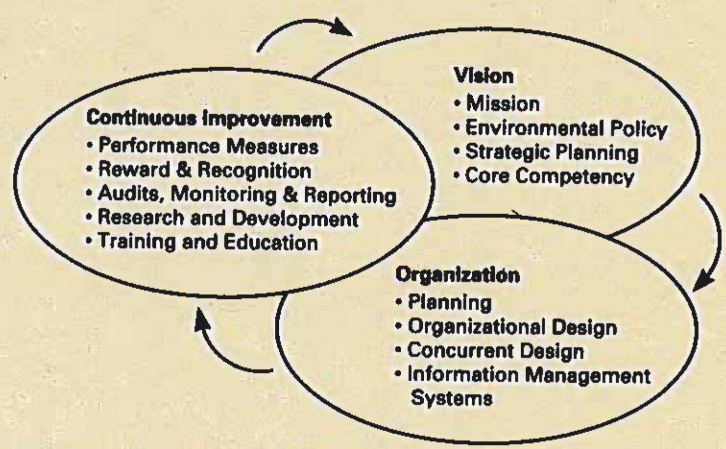

FIGURE 6.3 Internal elements of life-cycle management.

Figure 6.4 depicts the various members of the design team that could participate in product development and graphically shows how the cross-functional team translates the interests and needs of external stakeholders to product system requirements. The product system links these diverse groups.

6.5.2 External Factors

External factors that strongly influence life-cycle design, but may be beyond the firm's immediate control, include government regulations and policy, infrastructure, and mar-

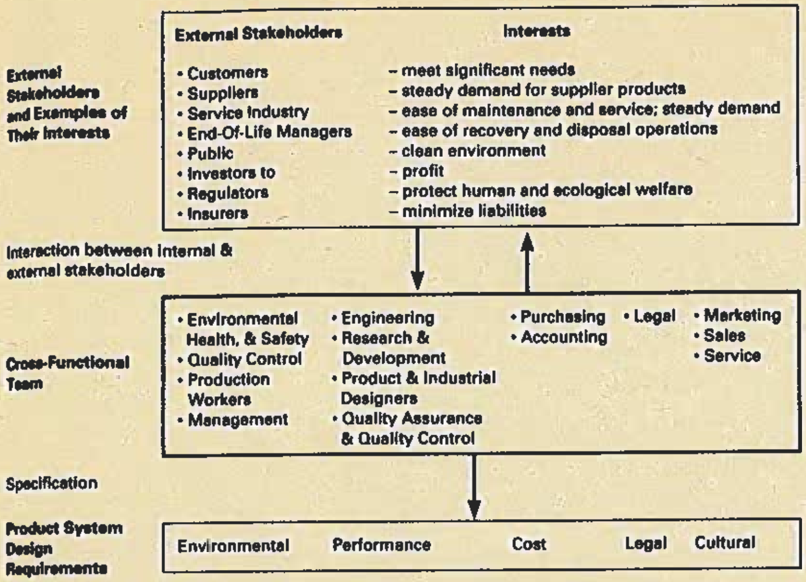

FIGURE 6.4 Cross-functional design team develops product system requirements.

ket demand, which depends on the state of the economy, state of the environment, scientific understanding of environmental risks, and public perception of these risks.

6.6 LIFE-CYCLE DEVELOPMENT PROCESS

The life-cycle development process, which occurs in the context of sustainable development and life-cycle management, is shown in Fig. 6.5. 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 begin with a needs analysis and then proceed through formulating requirements, employing various strategies, and performing evaluations of alternative designs. A design solution is then implemented, resulting in various environmental consequences. A simplified diagram of the development process is shown in Fig. 6.5.

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 onto 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 (LCAs) may be used in addition to other analytical tools.

The development process is best characterized by an iterative process rather than a linear sequence of activities. Ideas, requirements, and solutions are continuously modi-

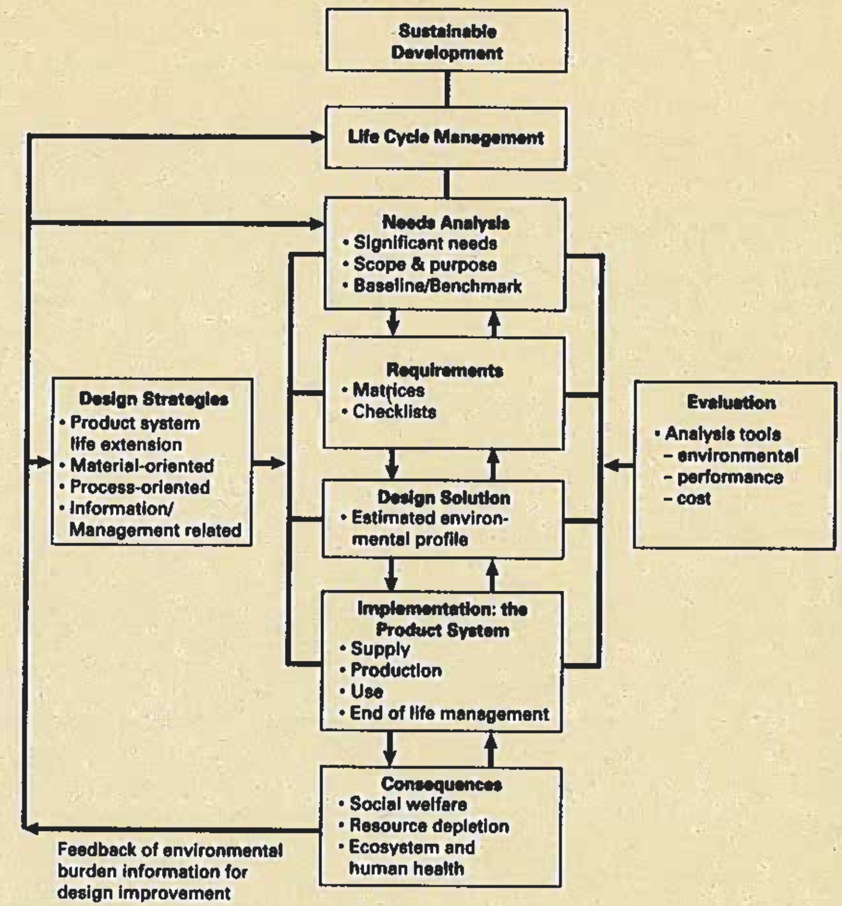

FIGURE 6.5 Life-cycle development process.

fied 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.

Implementation of the design solution requires inputs of material and energy 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 step from needs analysis through implementation undergoes continuous change. Figure 6.5 shows the iterative nature and feedback mechanisms of the development process which includes multiple sequences of analysis, synthesis, and evaluation.

6.7 NEEDS ANALYSIS AND PROJECT INITIATION

Life-cycle development projects should focus on filling significant customer and societal needs in a sustainable manner. Unless life-cycle principles such as sustainable development shape the needs analysis, design projects may not create cleaner products. LCA can be used to identify cleaner substitutes and alert product managers to begin to phase out products of higher environmental burden.

Defining the system boundaries is necessary for both life-cycle design and LCA. Both begin with a clear definition of the need being addressed by the product system. Whenever possible, it is useful to express this "need" in terms of a functional unit which can serve as a basis for comparison of alternative designs. The basis for analysis should be *equivalent use,* defined as the delivery of equal amounts of product or service. It is useful to define a functional unit of the product whenever possible, but it is often difficult to express performance in a single measure. The functional unit, e.g., volume of beverage delivered (beverage containers), or surface area protected (paint), serves as a basis for comparative analysis of product or design alternatives. Incorporating primary functional attributes into a single parameter can be arbitrary and demonstrates the multigoal nature of design.

6.7.1 Define Project Scope and Purpose

The type of environmental assessment tools and design strategies explored in a design project will depend on the nature of the product system and the timeline and resources available. Conducting a comprehensive LCA of an entire automobile with over 25,000 parts is not feasible at this time, so the scope of initial activities must be limited. For example, life-cycle inventories have been conducted on alternative materials for a single component of the vehicle.

Practitioners of life-cycle design must also decide whether the project will address a current or future design. In addition, the life-cycle framework can be employed in strategic planning or in the conceptual design phase rather than in detailed design.

6.7.2 Set System Boundaries

Determine which stages of the product life cycle the design team will emphasize and what spatial and temporal scales will be used.

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. More restricted system boundaries may be justified by the development team. Beginning with the most comprehensive system, design and analysis can focus on the

- Full life cycle
- Partial life cycle
- Individual stages or activities

Choice of the full life-cycle system will provide the greatest opportunities for overall adverse-impact reduction.

In some cases, the development team may confine analysis to a partial 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 chosen, 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.

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; therefore, worst- and best-case scenarios should be used whenever possible. In regard to spatial conditions, the design team must recognize that the same activity may have quite different impacts in different places. For example, consumptive water use in arid regions has a greater resource depletion impact than in areas where water is abundant.

6.7.3 Evaluate Baseline and Benchmark Competitors

Baseline and benchmark activities assist practitioners of life-cycle design in developing environmentally conscious designs of new or existing products and processes. The purpose of evaluating the *baseline* condition of manufacture, use or service, and end-of-life management is to gain an understanding of the environmental profile of an existing product system. Baseline analysis of existing products may indicate opportunities for improving a product system's environmental performance.[10,11] Baseline analysis may consist of a life-cycle inventory analysis, audit team reports, or monitoring and reporting data. *Benchmarking* activities are designed to ascertain information that facilitates comparisons with other products that fulfill similar customer needs. While companies and trade publications have programs to compare product performance and cost against those of their competitors, environmental criteria are generally more difficult to benchmark due to lack of information, insufficient scientific understanding, and limited availability of resources.

6.7.4 Identify Opportunities and Vulnerabilities

The objective of this phase of the life-cycle design development process is to state explicitly the current and future design goals. Current and future design goals must reflect a company's strategic direction including its corporate goals, consumer market, competitive strategy, and image, among other fundamental business criteria. The results of the design team's baseline analysis and benchmarking activities can serve as a basis for developing short- and long-term goal horizons.

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 core environmental issues, including 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.

6.8 PRODUCT SYSTEM REQUIREMENTS

Formulating requirements may well be the most critical phase of design.[12] Requirements define the expected outcome and thus are crucial for translating needs and environmental goals to an effective design solution. 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. But 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 (approximately 70 percent) of product system costs are fixed in the design stage. Activities through the requirements phase typically account for 10 to 15 percent of total product development costs, yet decisions made at this point can determine 50 to 70 percent of costs for the entire project.[13,14]

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 the "house of quality" approach.

6.8.1 Design 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 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 DFE 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 so that they do not place 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 most important to the specific project.

6.8.2 Requirements Matrices

Matrices allow product development teams to study the interactions between life-cycle requirements. Figure 6.6 shows a multilayer matrix for developing requirements. The

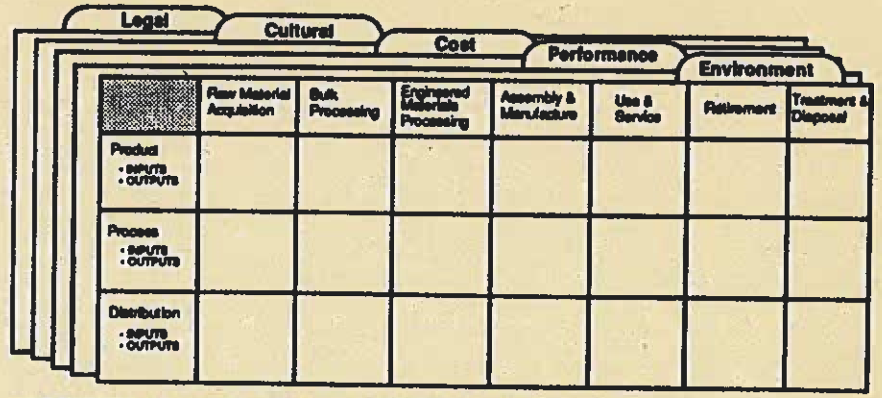

FIGURE 6.6 Conceptual multilayer matrix for developing requirements.

matrix for each type of requirement contains columns that represent life-cycle stages. Rows are formed by the product system components described under "Performance Requirements"—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 6.3 shows how each row in the environmental matrix can be expanded to provide more details for developing requirements.

TABLE 6.3 Example of Subdivided Rows for Environmental Requirements Matrix

	Product	Process	Distribution
Inputs			
Materials	• Content of final product	• Direct: process materials • Indirect: First level (equipment and facilities, office supplies) Second level (capital and resources to produce first level)	• Packaging • Transportation Direct (e.g., oil and 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•mi)] • 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 in Fig. 6.6 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. The section entitled "AT&T Life-Cycle Design Project" describes the application of requirements matrices for a business telephone.

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 to clear functions, environmental requirements help identify and constrain environmental impacts and health risks.

Table 6.4 lists issues that can help development teams define environmental requirements. This book cannot provide detailed guidance on environmental requirements for each business or industry. Although the lists in Table 6.4 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 be used to set requirements. For example, the Integrated Solid Waste Management Plan developed by the EPA in 1989 targeted municipal solid waste disposal for a 25 percent reduction by 1995.[6] 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 may also be wise to set environmental requirements that exceed current government regulations. These requirements may have been identified during the investigation of opportunities and vulnerabilities early on in the needs analysis and project initiation phase of the design project. At this stage in the design process, goals are translated to specific requirements. Designs based on such 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. Typical performance requirements for an automobile include fuel economy, maximum driving range, acceleration and braking capabilities, handling characteristics, passenger and storage capacity, and ability to pro-

TABLE 6.4 Issues to Consider in the Development of Environmental Requirements

Materials and energy			
Type	**Character**	**Resource base**	**Impact caused by extraction and use**
Renewable Nonrenewable	Virgin Reused and recycled Reusable and recyclable	Location—local vs. other Scarcity Quality Management and restoration practices	Material and energy use Residuals Ecosystem health Human health
Residuals			
Type	**Characterization**	**Environmental fate**	**Treatment and disposal impact**
Solid waste Air emissions Waterborne	Nonhazardous—constituents, amount Hazardous, radioactive—constituents, amount, concentration, toxicity	Containment Bioaccumulation Degradability Mobility and transport	
Ecological health			
Ecosystem stressors	**Impact categories**	**Impacts**	**Scale**
Physical Biological Chemical	Diversity Sustainability, resilience to stressors	System structure and function Sensitive species	Local Regional Global
Human health and safety			
Population at risk	**Exposure routes**	**Toxic character**	**Accidents**
Workers Users Community	Inhalation, skin contact, ingestion Duration and frequency	Acute effects Chronic effects Morbidity and mortality	Type and frequency Nuisance effects Noise and odors

tect passengers in a collision. Environmental requirements are closely linked to and often constrained by performance requirements.

Performance is limited by technical factors. 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 partial 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 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 20 years, yet U.S. gasoline consumption 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.

PERFORMANCE REQUIREMENTS LIMITING ENVIRONMENTAL IMPROVEMENTS

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

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 decisions in developing requirements 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. By providing an estimate of costs for the entire product life, quality products may be judged on more than least first cost, which addresses only the initial purchase price or financing charges. Table 6.5 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 customer cultural requirements.

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, to create 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 therefore

TABLE 6.5 Example of General Cost Requirements over Product Life Cycle

	Stakeholders: Manufacturers	Stakeholders: Consumers
Raw materials and supplies	• 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

may 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 advisers, 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.

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 take into consideration 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.

LEGAL AND QUASI-LEGAL REQUIREMENTS

- International regulations
- National regulations (U.S.)
- State
- Local (municipalities)
- Voluntary standards

Assigning Requirements Priority. Ranking and weighting design requirements help to distinguish between critical and merely desirable requirements. After requirements are assigned a weighted value, they should be ranked and separated into several groups. An example of a useful classification scheme (after Ref. 12) follows:

- *Must requirements* are conditions that designs have to meet. No design is acceptable unless it satisfies all these must requirements.
- *Want requirements* are less important, but are 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. They are relegated to a wish list. Designers should be aware that such desires exist, but ancillary functions can be expressed in design only when they do not compromise more critical functions. Customers or clients should not expect designs to reflect many ancillary requirements.

Once the 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. Table 6.6 provides some additional methods for organizing the requirements in each component of the matrix.

Resolving Conflicts. Development teams can expect conflicts between requirements. If conflicts between must requirements cannot be resolved, there is no solution space for design. When a solution space exists but is so restricted that little choice is possible, the 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.

In all 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 ensue from resolving conflicts and developing new priorities that more accurately reflect customer needs.

TABLE 6.6 Organizing Frames for Requirements

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

AT&T Life-Cycle Design Project. The matrix method of formulating requirements was recently applied to designing a business telephone in a demonstration project conducted between the authors and AT&T.[15] Radical departures from previous designs were not deemed feasible for this next-generation product. Given this and other constraints, the project concentrated on a partial, consolidated life cycle consisting of manufacturing, use, and end-of-life management stages. Examples of some environmental and legal must and want design requirements formulated by the project team are listed in Tables 6.7 and 6.8. These matrices resulted from seven "green product realization" team meetings attended by representatives from product line management, marketing, research design, product engineering, and environmental health and safety engineering. Tables 6.7 and 6.8 contain some examples of the critical requirements relevant to this particular design and certain considerations for the future.

The environmental requirements in Table 6.7 contain both elements defined in terms of results and elements specifying how a desired result is to be achieved. Results-oriented requirements address quantitative corporate goals for reducing CFC emissions, toxic air emissions, process wastes, and paper consumption as well as increasing the use of recycled paper. Other requirements specify mechanisms to facilitate parts and components reuse and material recycling, especially of plastic housings.

Local, state, federal, and international regulations and standards provide a framework for the legal requirements outlined in Table 6.8. Legal requirements relevant to this design range from EPA regulations, FTC guidelines, and Germany's packaging ordinance to International Standards Organization (ISO) marking codes for plastics and Underwriters Laboratories (UL) requirements. Such diversity in legal requirements for widely sold products can be a barrier to realizing environmental improvements.

As an example of the conflicts that arise between requirements, one environmental want requirement for this project states that recycled materials must be used for new products. However, a legal *must* requirement calls for housings of telephone equipment to comply with UL specification UL 746, Standard for Polymeric Materials—Fabricated Parts. Recycled resins that meet the material testing and certification procedures required for this standard are not now available, from either internal recycling programs or commercial vendors. Even if this conflict did not exist, use of recycled materials for housings might still be impeded by other types of want requirements. To be marketable, a desktop product must also comply with perceived cultural requirements for flawless surface quality and perfectly matched colors. These attributes may not be possible to achieve with recycled materials because they have experienced additional heat cycles and typically contain at least trace amounts of contaminants.

6.9 DESIGN STRATEGIES AND SOLUTION

6.9.1 Design Strategies

Selecting and synthesizing design strategies for meeting the full spectrum of requirements are 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 6.7 Environmental Requirements for Business Phone[3]

Manufacture	Use or service	End-of-life management
Product		
Materials should be recyclable on-site Engineering plastics production can reuse scrap Use recyclable materials Choose ozone depleting substance (ODS)-free components Eliminate the use of toxic materials (e.g., lead) Minimize defective products		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		
Minimize process wastes including air emissions, liquid effluents, and hazardous and nonhazardous solid wastes Minimize resource consumption Minimize power consumption Meet corporate environmental goals (list five goals) Use greener R&D processes: engineering research center (ERC) developing environmental technology Design guidelines, checklists, other DFE initiatives Green index Purchasing records to monitor ODS Suppliers encouraged to discontinue use of ODS in parts manufacturing	Energy-efficient operation (operates on line power only)	Service or reconditioning operations should minimize use of solvents
Distribution		
Minimize supplier packaging Nonhazardous Packaging containing recycled material (postconsumer content specified) Reusable trays for parts in factory	Minimize product packaging Use electronic packaging guidelines Nonhazardous Optimize number of phones per package Specify packaging containing recycled material (postconsumer content specified) Use recycled paper for manual (list environmental features)	Recyclable packaging

TABLE 6.8 Legal Requirements for Business Phone[3]

Manufacture	Use or service	End-of-life management
Product		
U.S. regulations and product safety standards Clean Air Act Amendments: CFC labeling requirement (Apr. 15, 1993) Underwriter Laboratories UL 746D fabricated parts: use of regrind and recycled materials Green Seal Foreign regulations and 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 Specifications CSA C22.2 European Safety Specifications 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

General strategies for fulfilling environmental requirements are shown in Table 6.9. An explanation of each strategy is given in the *Life Cycle Design Guidance Manual* published by the EPA. Most of these strategies reach across product system boundaries; life extension, e.g., 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. 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. 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[16,17] are likely to include waste reduction, reuse, recycling, and aspects of product life extension.

TABLE 6.9 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 • Improve process layout • 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 ecolabeling and advertise environmental claims

Appropriate strategies need to satisfy the entire set of design requirements, as shown in Fig. 6.6, 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, then the benefits of environmentally responsible design are only illusory.

AT&T Life-Cycle Design Project. The AT&T life-cycle design demonstration project also offers a practical example of applying several environmental strategies to satisfy requirements. Only a few strategies pertaining to a single product component, the housing, will be discussed here. Environmental requirements for the manufacturing stage state that material for the housing must be recycled and recyclable, with toxics eliminated and waste reduced. End-of-life requirements state that the housing must be reusable or at least recyclable.

Material recyclability and toxics reduction during manufacturing were achieved by using a thermoplastic resin with good recyclability (ABS, or acrylonitrile butadiene styrene) that contained no stabilizers or colors formulated with heavy metals. The chosen resin also does not rely on polybrominated fire retardants, which are the subject of proposed bans in Europe. Manufacturing scrap was reduced by specifying a textured housing. A textured surface for external plastic parts, such as the housing, hides minor molding flaws better than a high-gloss, smooth surface, thus increasing molding yield and reducing waste from this process.

Other features were intended to ensure that at end of life, the housing can be turned into an uncontaminated and readily recyclable or reusable material by means of low-cost automatic processes. The design accomplished this by avoiding glue joints and incorporation of foreign material such as metal inserts, paints, and stick-on labels which cannot be practically separated from the base polymer.

In addition, AT&T has a network of reclamation and service centers which receives both leased telephones and trade-ins for new purchases. Depending on their condition, either the phones are refurbished and sold or leased again, or they are scrapped and recycled. Because the centers can return still-serviceable phones to another tour of duty as well as properly recycle those beyond repair, the company controls aspects of product and material life extension. Designs focusing on these strategies thus benefit the company and are easier to implement.

6.9.2 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 all potential design solutions that meet each of the criteria specified, including environmental, performance, cost, legal, and cultural criteria. Figure 6.7 illustrates this point graphically. The space in the diagram where all criteria overlap is the solution space. Strategies for satisfying design criteria are implemented after the solution space is known. At this point in development, designers select and synthesize strategies, keeping in mind concerns outlined in Table 6.9, that fulfill multicriteria design requirements.

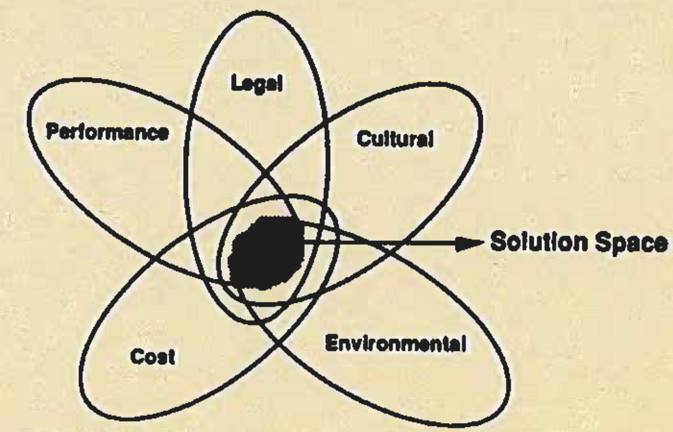

FIGURE 6.7 Design solution space.

TABLE 6.10 Difficulties and Limitations of the Current LCA Methodology[4]

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 tremendous resources to analyze.
Data collection	Data availability and access can be limiting (e.g., proprietary data); data quality including bias, accuracy, precision, and completeness is 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. 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.

6.10 DESIGN 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.

DESIGN EVALUATION

Life-cycle assessment
- EPA/SETAC framework (inventory analysis, impact and improvement assessment)
- DFEIS matrix (Allenby)
- Dow matrix
- EPS system (Federation of Swedish Industries)

General environmental metrics
- Resource productivity index (Sony)
- Waste per unit product

Specific metrics
- Energy consumed in use stage per unit product
- Percentage recycled; weight of recyclable components or weight of product

Cost assessment
- Life-cycle costing
- Environmental accounting

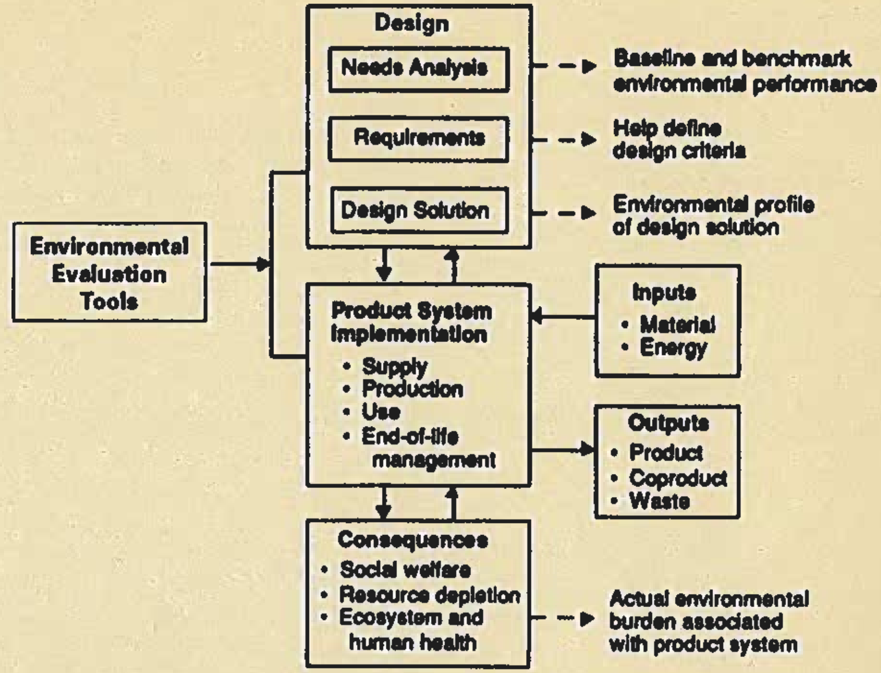

FIGURE 6.8 Environmental evaluation in the development process.

Figure 6.8 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.

6.10.1 LCA and Its Application to Design

LCA consists of several techniques for identifying and evaluating the adverse environmental effects associated with a product system.[18-23] The most widely recognized framework for LCA consists of inventory analysis, impact assessment, and improvement assessment components. At present, inventory analysis is the most established methodology of LCA.

LCA and more streamlined approaches can potentially be applied in needs analysis, requirements specification, and evaluation of conceptual through detailed design phases. Although numerous life-cycle inventories have been conducted for a variety of products,[24] only a small fraction have been used for product development. Procter & Gamble is one company that has used life-cycle inventory studies to guide environmental improvement for several products.[25] One of its 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.[26] Based on this information, opportunities for reducing impacts were identified which include designing cold water and no-rinse formulas or educating consumers to use cold water.

The *Product Ecology Report* is another example where life-cycle inventory and a valuation procedure are used to support product development.[27] For this project, the environmental priority strategies in product design (the EPS system) evaluate the environmental impact of design alternatives with 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, which 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 will be heavily dependent on the valuation procedure.

Several LCA software tools and computerized databases may make it easier to apply LCA in design. 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; and PIA, developed by the Institute for Applied Environmental Economics (TME) in the Hague, Netherlands [available from the Dutch Ministry for Environment and Informatics (BMI)]. These tools can shorten analysis time when one is exploring design alternatives, particularly in simulation studies, but data availability and quality are still limiting. In addition to these tools, a general guide to LCA for European businesses has been compiled which provides background and a list of sources for further information.[28]

Difficulties. General difficulties and limitations of the LCA methodology are summarized in Table 6.10. In principle, LCA represents the most accurate tool for design evaluation in life-cycle design and DFE. Many methodological problems, however, currently plague LCA, thus limiting its applicability to design.[4] Costs to conduct an LCA can be prohibitive, especially to small firms, and time requirements may not be compatible with short development cycles.[29,30] Although significant progress has been made toward standardizing life-cycle inventory analysis,[18–22] results can still vary significantly.[31,24] 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 present 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 to 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 are needed for proper evaluation. Simplified approaches for impact assessment, such as the *critical-volume or -mass method*[23] have fundamental 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 to a single number estimating global warming potential or ozone-depleting potential, are available for assessing global impacts.[32,33]

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 be evaluated only after 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 Fig. 6.9. 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

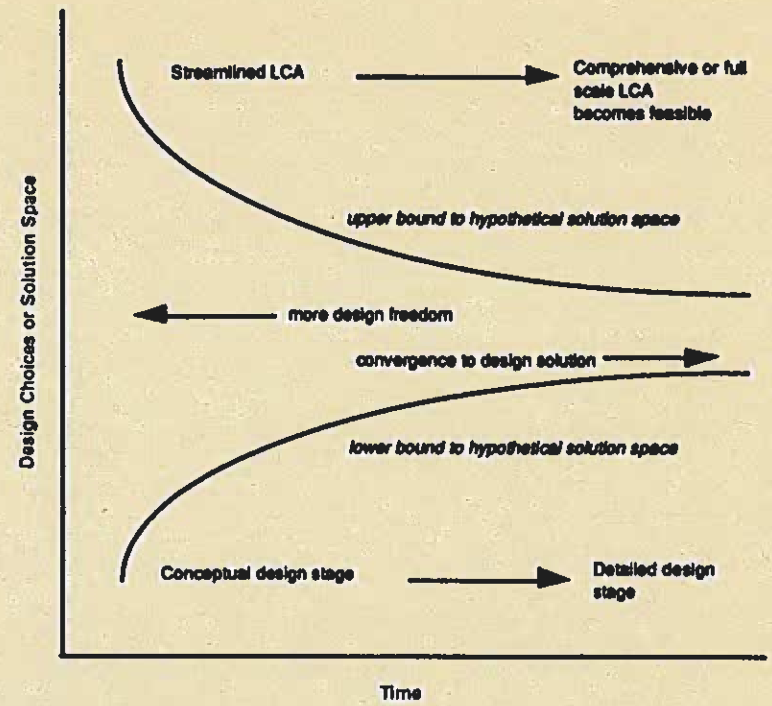

FIGURE 6.9 Design solution space as a function of time.[4]

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.

6.10.2 Other Design Evaluation Approaches

Environmental Indicators or Metrics. In contrast to a comprehensive life-cycle assessment, environmental performance parameters or metrics can be used to evaluate design alternatives. Navin-Chandra[34] introduced the following set of environmental indicators: percentage recycled, degradability, 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[35] proposes a *resource productivity* measure for evaluating "industrial performance compatible with environmental preservation." The resource productivity is defined as:

$$\frac{(\text{Economic value added}) \times (\text{product lifetime})}{(\text{Material consumed} - \text{recycled}) + (\text{energy consumed for production, recycling}) + (\text{lifetime energy used})}$$

where the individual terms in the denominator are expressed in monetary units. Longer product life, higher material recycle, and lower 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 accounts for resource depletion, which correlates with many other environmental impacts.

Matrix Approaches. DFE methods developed by Allenby[5,36] 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 nontechnical aspects of design alternatives.

Dow Chemical Company has also developed a matrix tool for assessing environmental issues across major life-cycle stages of the product system. Opportunities and vulnerabilities are assessed for core environmental issues, including 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.

Computer Tools. ReStar is a design analysis tool for evaluating recovery operations such as recycling and disassembly.[37] A computer algorithm determines an optimal recovery plan based on tradeoffs between recovery costs and the value of secondary materials or parts.

6.11 SUMMARY

Numerous companies are beginning to apply life-cycle design principles and tools. Table 6.11 highlights several examples where life-cycle design and related tools have been implemented by industry. As this chapter has demonstrated, many difficulties still must be confronted before life-cycle design tools can be more fully incorporated into product development programs. All major stakeholders, including industry, the public, and government, have a role in designing, manufacturing, and using products which are more sustainable. The following life-cycle design principles are presented to aid these stakeholders in guiding environmental improvement of product systems.

6.11.1 Life-Cycle Design Principles

Use a Systems Approach. A systems approach is essential to achieving sustainable development goals. The life-cycle system is the basis for a comprehensive framework for addressing environmental issues in design. Life-cycle design focuses on the product systems level in an 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

TABLE 6.11 Examples of Life-Cycle Design

Company	Project or Program	Activity
Xerox	Asset Recycle Management	This program has been successfully implemented for the design and manufacture of xerographic equipment. A hierarchy of strategies has been developed to optimize resource use including equipment and parts remanufacturing, repair and reuse, and materials recycling.
Dow	Life-cycle inventory	Conducted a life-cycle inventory of poultry packaging alternatives.
AT&T	Life-cycle design	Developed environmental, performance, cost, legal, and cultural requirements for a business telephone terminal. The multicriteria matrix was used to specify requirements for manufacturing, use, and end-of-life management. Various design strategies were implemented to reduce environmental burden.[15]
AlliedSignal	Life-cycle design	Developed environmental, performance, cost, legal, and cultural requirements for an engine oil filter design. A comparative analysis of cartridge and spin-on filter designs was conducted including a life-cycle cost analysis for the customer.
Volvo	EPS	Environmental priorities strategies (EPS) system uses a single metric (environmental load units) to evaluate environmental impacts. It is based on a willingness-to-pay model which accounts for biodiversity, human health, production, resources, and aesthetic values. Comparative assessments were made of alternative materials for the design of a hood and a front-end construction.
Digital	Pre-LCA	Digital applied a "pre-LCA" method to the evaluation of videodisplay shipping packaging. The pre-LCA tool consisted of a set of criteria and a numerical scoring system for evaluating environmental impacts for each criterion ranging from 1 to 9. The idea of this approach was to develop a tool for nonexperts.
Ford	Life-cycle design	Performed a comparative analysis of alternative designs, (two aluminum and a nylon composite) for an air intake manifold.[39]
Procter & Gamble	Life-cycle inventory and improvement analysis	Conducted several life-cycle inventories of various cleaners and detergents. Opportunities for design improvement were identified in several cases.
GM	Streamlined LCA	Participating in a streamlined LCA of autobody painting. This project is coordinated by the President's Council on Sustainable Development.
United Solar	Life-cycle design	Conducted a life-cycle energy analysis of an amorphous silicon photovoltaic module and studied alternative design parameters.

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 among different hierarchical levels and between the various organizational categories (e.g., economic, ecological, and sociological structures).

Take Action Early. Addressing environmental issues in the earliest stages of design is one of the most efficient ways to reduce environmental burdens.

Manage Internal and External Factors. Both internal and external factors strongly influence design. Within a company, an environmental management system that includes goals and performance measures provides the organizational structure for implementing life-cycle design. Access to accurate information about environmental impacts is also critical in achieving environmental improvement. External factors that shape design include government regulations, market forces, infrastructure, the state of the environment, and scientific understanding of human and ecological health risks and public perception of these risks.

Implement Concurrent Design. Concurrent design, a procedure based on simultaneous design of product features and manufacturing processes, includes product, process, and distribution components of the product system. Interdisciplinary participation is key to defining requirements that reflect the needs of multiple stakeholders such as suppliers, manufacturers, consumers, resource recovery and waste managers, the public, and regulators.

Specify Environmental Requirements. Specification of requirements is one of the most critical design functions. Requirements guide designers in translating needs and environmental objectives to 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.

Satisfy Multiple Objectives. Environmental issues cannot be addressed in isolation. Life-cycle design seeks to meet environmental objectives while also best satisfying cost, performance, cultural, and legal requirements. The challenge is to apply design strategies that resolve conflicting requirements.

Establish Environmental Metrics and Other Design Evaluation Tools. 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 to develop priorities for improvement.

Educate and Train Employees, Customers, and Suppliers. All members of a product realization team, including production workers and upper management, should be knowledgeable about environmental issues. Moreover, because environmental issues generally extend beyond the company boundary to customers and suppliers, attention should be given to helping all participants in the life cycle improve environmental performance.

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