Industrial Pollution Prevention Handbook

Harry M. Freeman

McGraw-Hill, Inc.

New York San Francisco Washington, D.C. Auckland Bogotá
Caracas Lisbon London Madrid Mexico City Milan
Montreal New Delhi San Juan Singapore
Sydney Tokyo Toronto

Library of Congress Cataloging-in-Publication Data

Freeman, Harry
Industrial pollution prevention handbook / Harry M. Freeman.
p. cm.
Includes bibliographical references and index.
ISBN 0-07-022148-0
1. Industry—Environmental aspects. 2. Pollution. I. Title.
TD194.F74 1995
363.73'1—dc20 95-7979
CIP

1 2 3 4 5 6 7 8 9 0 DOH/DOH 9 0 9 8 7 6 5 4

ISBN 0-07-022148-0

The sponsoring editor for this book was Gail F. Nalven, the editing supervisor was Kimberly A. Goff, and the production supervisor was Donald F. Schmidt. This book was set in Palatino. It was composed by McGraw-Hill's Professional Book Group composition unit.

Printed and bound by R. R. Donnelley & Sons Company.

This book is printed on recycled, acid-free paper containing a minimum of 50% recycled de-inked fiber.

18
Pollution Prevention through Life-Cycle Design

Gregory A. Keoleian, Ph.D.
National Pollution Prevention Center
School of Natural
Resources and Environment
University of Michigan
Ann Arbor, Michigan

18.1 Introduction

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The design of a product system can be represented logically as a series of decisions and choices made individually and collectively by design participants. These choices range from the selection of materials and manufacturing processes to choices relating to shape, form, and function of the product. A design team represents a wide range of functional responsibilities including industrial design, process engineering, product development management, accounting, purchasing, marketing, human and ecosystem health, safety, and

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The design of a product system can be represented logically as a series of decisions and choices made individually and collectively by design participants. These choices range from the selection of materials and manufacturing processes to choices relating to shape, form, and function of the product. A design team represents a wide range of functional responsibilities including industrial design, process engineering, product development management, accounting, purchasing, marketing, human and ecosystem health, safety, and regulatory compliance. Each decision or choice made by these team members during development and implementation will shape the overall environmental profile of the product system.

Existing knowledge and experience guide individual and group design decisions. Both new information and new approaches to synthesizing and evaluating this information are essential to achieve pollution prevention through design. Recognizing that no single design method has universal appeal, this chapter offers guidelines rather than prescriptions. These guidelines are based on the life-cycle design framework developed by the author for the Pollution Prevention Branch of the U.S. Environmental Protection Agency (EPA).[1] Individual designers and design teams that recognize the benefits of pollution prevention are invited to adapt the ideas and guidelines for their own specific applications.

18.2 Definition of the Product System

18.2.1 Life-Cycle Stages

The product life cycle provides a logical system for addressing pollution prevention because the full range of environmental consequences associated with the product can be considered. By focusing on this system, designers can prevent the shifting of impacts between media (air, water, land) and between stages of the life cycle. In addition, this framework encompasses the many stakeholders (suppliers, manufacturers, consumers/users, resource recovery and waste managers) whose involvement is critical to successful design improvement. The life-cycle system is complex due to its dynamic nature and its geographical scope. Stages of the life cycle are changing continuously and changes often occur independently. Life-cycle stages are also widely distributed on a geographical basis, and environmental consequences occur on global, regional, and local levels.

Figure 18-1 is a general flow diagram of the product life cycle. As this figure shows, a product life cycle is circular. On an elementary level resources are consumed and residuals will eventually accumulate in the earth and biosphere. The product life cycle can be organized into the following stages:

1. Raw material acquisition
2. Bulk material processing
3. Engineered and specialty materials production
4. Manufacturing and assembly
5. Use and service
6. Retirement
7. Disposal

Raw material 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

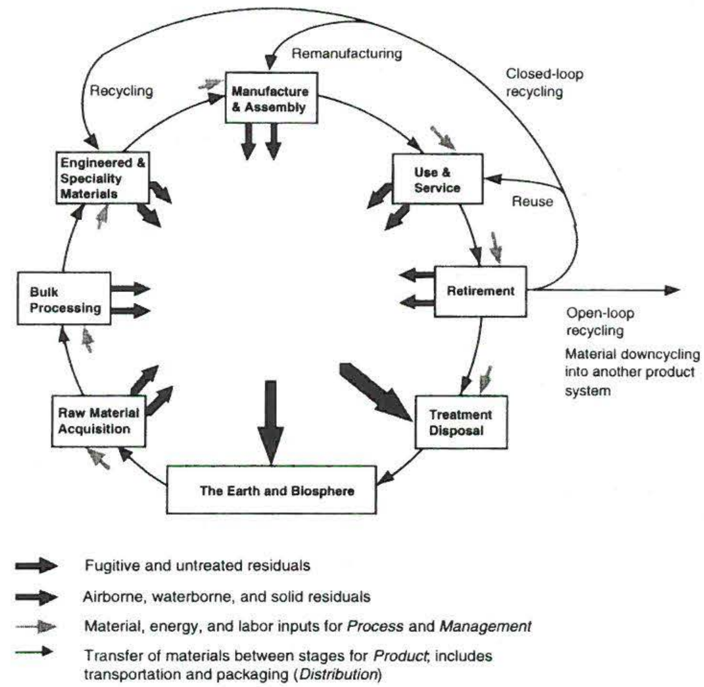

Figure 18-1. The product life-cycle system. (*Courtesy of U.S. EPA, Life Cycle* Design Guidance Manual: Environmental Requirements and the Product System *EPA 600/R-92/226.*)

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 some processes, 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 of residuals depends on how they degrade after release.

18.2.2 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. In addition to life-cycle stages, this system can be organized into four basic components: product, process, distribution, and management. As much as possible, life-cycle design seeks to integrate these components.

Product. The *product component* consists of all materials constituting the final product and includes all forms of those materials in each stage of the life cycle. 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 invested in new or used replacement parts are also included in the product component.

The remaining three components of the product system, process, distribution, and management, each share the following subcomponents:

- Facility or plant
- Unit operations or process steps
- Equipment and tools
- Labor
- Direct and indirect material inputs
- Energy

Process. Processing transforms materials and energy into a variety of intermediate and final products. The *process component* includes direct and indirect materials used to make a product. Catalysts and solvents are examples of direct process materials. They 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.

Specific process-oriented pollution prevention design strategies are addressed in Chaps. 21–26.

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 environmental impacts. Packaging accounted for 31.6 percent of municipal solid waste generated in the United States in 1988.[2] Transportation networks include modes and routes. Trains, trucks, ships, airplanes, and pipelines are some major modes of transport. 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.

Storage facilities such as vessels and warehouses are necessary for distribution. The selling of a product is also considered part of distribution. This includes both wholesale and retail activities.

Management. The *management component* includes the entire information network that supports decision making throughout the life cycle. Within a corporation, management responsibilities include administrative services, financial management, personnel, purchasing, marketing, customer services, legal services, and training and education programs. Each of these has a strong influence on product development. In addition, significant pollution is generated and substantial resources are consumed in support of the management function.

18.3 Goals of Life-Cycle Design

The fundamental goal of life-cycle design is to promote sustainable development at the global, regional, and local level. In simple terms, sustainable development seeks to meet current needs without compromising the ability of future generations to satisfy their needs. Essential elements of sustainable development include pollution prevention, resource conservation, environmental equity, human health, and maintenance of ecosystem structure and function. Stated succinctly, life-cycle design seeks to minimize environmental impacts and utilize resources efficiently in meeting basic societal needs.

A major challenge in sustainable development is achieving environmental equity, both intergenerational and intersocietal. Enormous inequities in the distribution of resources continue to exist between developed and less-developed countries. Inequities also occur within national boundaries. Pollution and other impacts from production are also unevenly distributed.[3] Studies show that low-income communities in the United States are often exposed to higher health risks from industrial activities than are higher-income communities.[4] Inconsistent regulations in the United States also have led to different definitions of acceptable risk levels for workers and consumers.[5]

Life-cycle design goals are articulated through a corporation's environmental management system, to be discussed in the next section. This system then provides the structure for the product development team to specify environmental requirements which shape the design.

18.4 Development Activities

Figure 18-2 demonstrates the complexity in integrating environmental issues into design. The goal of sustainable development is located at the top to indicate its fundamental importance. This goal should be embraced by the entire development team. Various forces shape the creation, synthesis, and evaluation of a design by a product manufacturer, including both internal and external factors.

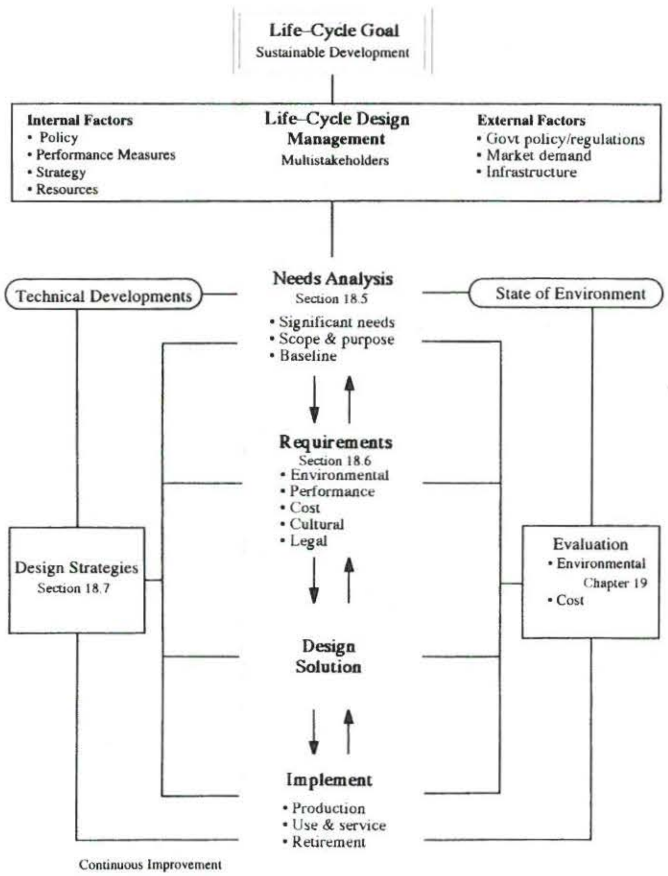

Figure 18-2. The product development process.

External factors include government regulations and policy, market demand, infrastructure, state of the economy, state of the environment, scientific understanding of environmental risks, and public perception of these risks. Many of these issues are addressed elsewhere in this handbook and are also discussed in Ref. 6. Within a company, both organizational and operational changes must take place to effectively implement life-cycle design.

Of the internal factors, management exerts a major influence on all phases of development. Both concurrent design and total quality management (TQM) provide models for life-cycle design. In addition, appropriate corporate policy, goals, and performance measures, as well as adequate resources, are needed to support design projects.

Research and technology development uncovers new approaches for reducing environmental impacts, while the state of the environment provides a context for design. Recognition and prioritization of global, regional, and local environmental problems by the scientific community and the general public should be used to guide improvement. Accordingly, current and future environmental needs are translated into appropriate designs.

A typical design project begins with a needs analysis, then proceeds through formulating requirements, conceptual design, preliminary design, detailed design, and implementation. During the needs analysis, 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 that includes environmental requirements, which are discussed in Secs. 18.5 and 18.6. Design alternatives are proposed to meet these requirements. Strategies for satisfying environmental requirements are presented in Sec. 18.7.

The development team continuously evaluates alternatives throughout the design process. Environmental analysis tools include *life-cycle assessment* (LCA), which is outlined in Chap. 19. Several barriers and limitations must be overcome for LCA to be applied to design on a widespread basis.[7] Successful designs must ultimately balance environmental, performance, cost, cultural, and legal requirements.

18.4.1 Design Management

Environmental Management System. Successful life-cycle design projects depend on commitment from all employees and all levels of management. The result is a corporation's environmental management system, which supports environmental improvement through design. Key components of this system include an environmental policy and goals, performance measures, and a strategic plan. This system must also provide access to accurate information about environmental impacts. A well-managed environmental information system is critical to guiding the design process in the direction of environmental improvement. Ideally the environmental management system is well integrated within the corporate structure and not treated as a separate function.

Environmental Policy and Goals. Company policies that support pollution prevention, resource conservation, and other life-cycle principles foster life-cycle design. Although a step in the right direction, vague environmental policies may not be much help. To benefit design projects, a firm's environmental policies must be specific and clearly stated. Management should offer objectives and guidelines that are detailed enough to provide a practical framework for the actions of designers and others in the company. Examples of environmental goals include phasing out the use of specific chemicals under a specific time line, 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 level.

Environmental Performance Measures. The progress of design projects should be clearly assessed with appropriate measures to help members of the design team pursue 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 efficiency of resource use (materials and energy utilization), and waste generation (multimedia), as well as measures to assess human health and ecosystem sustainability. Life-cycle assessment provides a framework for establishing corporate performance measures that address these issues.

Companies may 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. 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 people for reducing impacts, managers and workers will naturally focus on other areas of the business.

Environmental Strategy. Strategic planning is essential to manage the complex and dynamic life-cycle system. This activity can seem overwhelming given the different time cycles affecting product system components. Time scales of different events that can influence design include:

Business cycle (recovery, inflation, recession)
Product life cycle (R&D, production, termination, service)
Useful life of the product
Facility life
Equipment life
Process
Cultural trends (fashion obsolescence)
Regulatory change
Technology cycles
Environmental impacts

Shorter-term and longer-term environmental goals should be defined based on these cycles. Although challenging, understanding and coordinating time scales can be a key element in improved design. For life-cycle design to be effective corporations must make long-term investments which will also promote sustainability of the corporation. Such actions include

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

Effective planning requires correctly assessing company strengths, capabilities, and resources. Many companies are under pressure to shorten development times. This is due in part to competition to continuously bring new products to market. Strategic planning must balance these factors with the need to meet and even exceed life-cycle goals.

18.4.2 Concurrent Design

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 using process-oriented pollution prevention and waste minimization approaches. Product-oriented approaches are also now gaining recognition. Life-cycle design seeks to integrate product and process design functions to more effectively reduce environmental impacts associated with the entire product system.

Life-cycle 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 single team.[8] By having all actors in the life cycle participate in a project from the outset, problems that often develop between different disciplines can be reduced. Product quality can be improved through such cooperation. Efficient teamwork can also reduce development time and lower costs. Table 18-1 shows how various members of the design team can participate.

18.5 Needs Analysis

A development project should first clearly identify customers and their needs. Design can then focus on meeting those needs. Ideas that lead to design pro-

Table 18-1. Role of Participants in Life-Cycle Design

Life-cycle participant	Duties and responsibilities
Accounting	Assign environmental costs to products accurately; calculate hidden, liability, and less tangible costs.
Advertising	Inform customers about environmental attributes of product.
Community	Understand potential impacts and benefits; define and approve acceptable plans and operations.
Distribution and packaging	Design distribution systems that limit packaging and transportation while ensuring protection and containment.
Environmental, health, and safety staff	Ensure occupational, consumer, and community health and safety; provide environmental information for other participants.
Government regulators and standards organizations	Develop policy, regulations, and standards that support life-cycle design goals.
Industrial designers	Create a design concept that meets environmental criteria while also satisfying all other important functions.
Legal	Interpret statutes and promote pollution prevention to minimize cost of regulation and possible future liability.
Management	Establish corporate environmental policy and translate into operational programs; establish measures for success; develop corporate environmental strategy.
Marketing and sales	Give designers feedback on existing products and demand for alternatives; promote design of low-impact products.
Process engineers	Design processes to limit resource inputs and pollutant outputs.
Procurement and purchasing	Select suppliers with demonstrated low-impact operations; assist suppliers in reducing impacts of their operations to ensure steady supply at lower costs.
Production workers	Maintain process efficiency; ensure product quality; minimize occupational health and safety risks.
Purchasers and/or customers	Provide information about needs and environmental preferences; offer feedback on design alternatives.
Research and development staff	Perform basic and applied research on impact reduction technology or product innovations.
Service	Help design product system to facilitate maintenance and repair.
Suppliers	Provide manufacturers with an environmental profile of their goods.
Waste management professionals	Offer information about the fate of industrial waste and retired consumer products and propose options for improved practices.

jects come from many sources, including customer focus groups, and research and development. Environmental assessment of existing products may uncover opportunities for design improvement. One such approach, life-cycle improvement analysis, is discussed in Chap. 19. One improvement strategy involves targeting major environmental impacts for reduction or elimination.

Life-cycle development projects properly 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, projects may not create low-impact products. By including the environmental requirements in the set of customer requirements that must be satisfied, designers will be motivated to focus on environmental improvement.

Product development managers should first recognize that environmental impacts can be substantially reduced by ending production of high-impact product lines for which lower-impact alternatives are available.

18.5.1 Define Scope of Design Project

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, or individual stages or activities. Choice of the full-life-cycle system will provide the greatest opportunities for 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 a project has been well defined and is 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 dividends in avoided costs and added benefits that outweigh the initial investment.

18.5.2 Establish Baseline Life-Cycle Data

Comparative analysis and benchmarking are used to establish a basis for environmental improvement. "Benchmarking" is used to compare cost and performance of best-in-class competitors; in life-cycle design environmental performance is also compared.

18.6 Requirements

Formulating requirements may well be the most critical phase of design. Requirements define the expected outcome and are crucial for translating needs and environmental goals into 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.

This discussion focuses on environmental requirements. Incorporating environmental requirements into the earliest stage of design can reduce the need for later corrective action. This proactive approach enhances the likelihood of developing a lower-impact product. Pollution control, liability, and remedial action costs can be greatly reduced by developing environmental requirements at the outset of a project.

Life-cycle design seeks to integrate environmental requirements with traditional performance, cost, cultural, and legal requirements. All requirements must be properly balanced in a successful product. A low-impact product that fails in the marketplace benefits no one.

Regardless of the project's nature, the expected design outcome should not be overly restricted or too broad. Requirements defined too narrowly eliminate attractive designs from the "solution space." On the other hand, vague requirements lead to misunderstandings between potential customers and designers while making the search process inefficient.[9]

When too little time is devoted to developing excellent requirements, a design project can proceed along a mistaken path. Such false starts delay the discovery of critical elements. Mistaken assumptions may also shape design until it is too late or too expensive to develop the proper product.[9,10] Surprises are unavoidable in any development project, but they are far more common and likely to be disastrous when requirements are compiled too hastily.

Activities through the requirements phase typically account for 10 to 15 percent of total product development costs.[11] Yet decisions made at this point can determine 50 to 70 percent of costs for the entire project.[11,12]

18.6.1 Requirements Matrix

Different methods are available to assist the design team in establishing requirements, including requirements matrices and design checklists. This chapter describes a matrix approach. Matrices allow product development teams to study the interactions between life-cycle requirements.

Figure 18-3 shows a multilayer matrix for developing requirements. The matrix for each type of requirement contains columns that represent life-cycle stages. Rows of each matrix are formed by the product system components described in Sec. 18.2: product, process, distribution, and management. Each row is subdivided into inputs and outputs. Elements can then be described and tracked in as much detail as necessary.

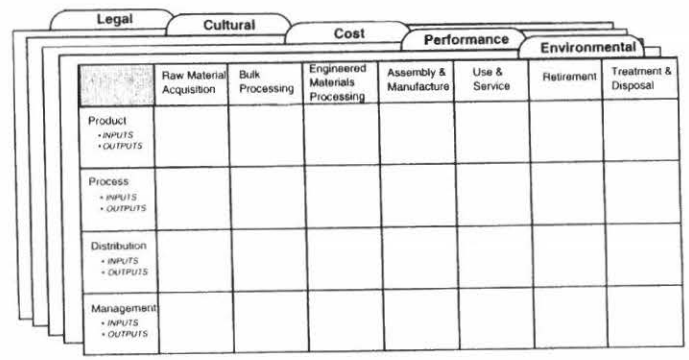

Figure 18-3. Conceptual requirements matrices. (*Courtesy of U.S. EPA. Life Cycle Design Guidance Manual: Environmental Requirements and the Product System. EPA 600/R-92/226.*)

The requirements matrices shown in Fig. 18-3 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 into the distribution component of the use phase.

There are no absolute rules for organizing matrices. Development teams should choose a format that is appropriate for their project.

Table 18-2 is a further illustration of how categories in the matrix can be subdivided. This example shows how each row in the environmental matrix can be expanded to provide more detail for developing requirements.

18.6.2 Types of Requirements

Environmental. Environmental requirements should be developed to minimize

- Use of natural resources (particularly nonrenewables)
- Energy consumption
- Waste generation
- Health and safety risks
- Ecological degradation

Through translation of these goals into clear functions, environmental requirements help identify and constrain environmental impacts and health risks.

Table 18-2. Example of Subdivided Rows for Environmental Requirements Matrix

Product

Inputs
  Materials
  Energy (embodied)
Outputs
  Products, coproducts, and residuals

Process

Inputs
  Materials
    Direct: process materials
    Indirect: first level (equipment and facilities)
        second level (capital and resources to produce first level)
  Energy: process energy (direct and indirect)
  People (labor)
Outputs
  Materials (residuals)
  Energy (generated)

Distribution

Inputs
  Materials
    Packaging
    Transportation
      Direct (e.g., oil and brake fluid)
      Indirect (e.g., vehicles and garages)
  Energy
    Packaging (embodied)
    Transportation (Btu/ton · mile)
  People (labor)
  Outputs
    Materials (residuals)

Management

Inputs
  Materials, office supplies, equipment and facilities
  Energy
  People
  Information
Outputs
  Information
  Residuals

SOURCE: U.S. EPA, *Life Cycle Design Guidance Manual: Environmental Requirements and Product System*, EPA 600/R-92/226.

Table 18-3 lists issues that can help development teams define environmental requirements. This chapter cannot provide detailed guidance on environmental requirements for each business or industry. Although the lists in Table 18-3 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 discovered in the needs analysis or benchmarking, government policies can also be used to set requirements. For example, the

Table 18-3. Issues to Consider When Developing Environmental Requirements

	Materials	

Amount
  Material intensiveness
Type
  Direct
    Product related
    Process related
  Indirect
    Fixed capital (building and equipment)
Source
  Renewable
    Forestry
    Fishery
    Agriculture
  Nonrenewable
    Metals
    Nonmetals
	Character
	  Virgin
	  Recovered (recycled)
	  Reusable/recyclable
	  Useful life
	  Resource base factors
	    Location
	    ▪ Locally available
	    ▪ Regionally available
	    Scarcity
	    ▪ Threatened species
	    ▪ Reserve base
	    Quality
	    ▪ Composition
	    ▪ Concentration
	    Management/restoration practices
	    ▪ Sustainability
		Impacts associated with extraction, processing, and use
		  Residuals
		  Energy
		  Ecological factors
		  Health and safety

	Energy	

Amount
  Energy efficiency
Type
  Purchased
  Process by-product
  Embodied in materials
	Source
	  Renewable
	    Wind
	    Solar
	    Hydro
	    Geothermal
	    Biomass
	  Nonrenewable
	    Fossil fuel
	    Nuclear
		Character
		  Resource base factors
		    Location
		    Scarcity
		    Quality
		    Management/restoration practices
		Impacts associated with extraction, processing, and use
		  Materials
		  Residuals
		  Ecological factors
		  Health and safety
		  Net energy

Table 18-3. Issues to Consider When Developing Environmental Requirements (*Continued*)

Residuals		
Type	Characterization	Environmental fate
Solid waste Solid Semisolid Liquid Air emissions Gas Aerosol Particulate Waterborne Dissolved Suspended solid Emulsified Chemical Biological	Nonhazardous Constituents Amount Hazardous Constituents Toxicity Concentration Amount Radioactive Potency/half life Amount Concentration	Containment Degradability (physical, biological, chemical) Bioaccumulation Mobility/transport mechanisms Atmospheric Surface water Subsurface/groundwater Biological Treatment/disposal Impacts • Residuals • Energy • Materials • Health and safety effects
Ecological Factors		
Ecological stressors	Type of ecosystems impacts	Scale
Physical (disruption of habitat) Biological Chemical	Diversity Sustainability Rarity Sensitive species	Local Regional Global
Human Health and Safety		
Population at risk	Toxicological characterization	Nuisance effects
Workers Users Community	Morbidity Mortality Exposure Routes • Inhalation • Skin contact • Ingestion Duration Frequency	Odors Noise Accidents Type

Integrated Solid Waste Management Plan developed by the EPA in 1989 targets municipal solid waste disposal for a 25 percent reduction by 1995.[13] Other initiatives, such as the EPA's 33/50 Program, are aimed at reducing toxics. It may benefit companies to develop requirements that match the goals of these programs.

It can also be wise to set environmental requirements that exceed government statutes. 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. Performance requirements define 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 protect 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." Absolute limits that products may strive to achieve 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 also need to be understood. In many cases, process design is constrained by existing facilities and equipment. This affects many aspects of process performance. It can also limit product performance by restricting possible materials and features. When this occurs, 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 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. However, gasoline consumption in the United States 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 therefore can contribute to excess waste generation and resource use.

Cost. 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 fully reflect environmental costs and benefits are important to life-cycle design. With more complete accounting, many low-impact designs may show financial advantages. Chapter 15 discusses methods of financial analysis that can help companies make better decisions in developing requirements.

Cost requirements should help designers add 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 state 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. In this way, quality products are not always judged on least first cost, which addresses only the initial purchase price or financing charges.

Cultural. Cultural requirements define the shape, form, color, texture, and image that a product projects. Low-impact designs must satisfy cultural requirements to be successful. Material selection, product finish, color, and size are guided by consumer preferences. These choices have direct environmental consequences.

However, because customers usually do not know about the 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 those in other categories. 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 thus determine whether demand for perceived convenience and environmental requirements conflict.

Legal. 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. In 1991, people convicted of violating environmental regulations served prison terms totaling 550 months.[14] Firms may also be liable for punitive damages.

Environmental professionals, health and safety staff, legal advisors, and government regulators can identify legal issues for life-cycle design. Principal local, state, federal, and international regulations that apply to the product system provide a framework for legal requirements. Laws and regulations relating to pollution prevention are discussed in Chaps. 4 and 6.

Federal regulations are administered and enforced by agencies such as the EPA, the Food and Drug Administration (FDA), and the Consumer Product Safety Commission (CPSC). In addition to such federal authorities, many other political jurisdictions enforce 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 account 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.

18.6.3 Example of Partial Matrix

The following example illustrates how part of a requirements matrix might be filled in. Requirements in this hypothetical example are proposed for the next generation of a consumer refrigerator. Only requirements for the use stage of the life cycle are shown in Tables 18-4 through 18-8.

This is just a sample of possible requirements. In this example, requirements are stated generally, without specific numerical constraints. An actual project would likely set more requirements in greater detail.

The requirements outlined here demonstrate some of the conflicts and trade-offs that arise in design. For example, increasing insulation in the walls and door reduces energy use, but it can also increase material use and waste at the time of disposal while reducing usable space. If cultural requirements dictate that refrigerators must fit in existing kitchens and maintain a certain usable space, energy-saving actions that increase wall thickness might be precluded. Also, CFCs are usually more efficient than alternatives that do not deplete ozone. Replacing CFCs might increase energy use.

18.6.4 Ranking and Weighing

Organizing. Ranking and weighting distinguishes 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 follows:

1. *Must* requirements are conditions that designs have to meet. No design is acceptable unless it satisfies all must requirements.
2. *Want* requirements are desirable traits that are not mandatory. 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.
3. *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 should only be expressed in design when they do not compromise more critical functions. Customers or clients should not expect designs to reflect many ancillary requirements.

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 of the design team must be used to arrive at priorities.

The process of making trade-offs between types of requirements is familiar to every designer. Asking "How important is this function to the design?" or

Table 18-4. Some Use and Service Requirements for Refrigerators
Environmental Matrix

Product

Material type—Based on a materials inventory of components/parts (refrigerator/freezer compartments, refrigeration system, compressor, condenser, evaporator, fans, electric components).
Eliminate high-impact materials: substitute for CFC-12 with lower ozone-depleting-potential and global-warming-potential alternatives.

Material amount
Reduce material intensiveness: specify pounds of material.
Residuals—Specified in Retirement stage.

Process

Energy
Reduce energy use: specify energy consumption for compressor, fans, antisweat heaters (average yearly energy use).

People
Noise: specify frequency and maximum loudness.

Residuals
Reduce waste: specify systems for recovering refrigerant during service; specify level of refrigerant loss during normal use and service; requirements for reuse, remanufacture, recycle of components are stated in Retirement stage.

Distribution

Material type
Reduce impacts associated with packaging materials: specify low-impact materials.

Material amount
Reduce material intensiveness of packaging: specify pounds of material.

Energy
Conserve transportation energy: specify constraints on energy associated with delivery.

Residuals
Reduce packaging waste: specify reusable, recyclable packaging.
Reduce product waste: specify maximum amount of damaged products during distribution.

Management

Information
Provide consumers with information on energy use: meet DOE labeling requirements for energy efficiency.

"What is this function worth (to society, customers, suppliers, others)?" is a necessary exercise in every successful development project.

Resolving Conflicts. Development teams can expect conflicts between requirements, as was demonstrated in the refrigerator design example. If conflicts cannot be resolved between must requirements, there is no solution space

Table 18-5. Some Use and Service Requirements for Refrigerators
Performance Matrix

Product

Material
Dimensions: H × W × D; capacity in cubic feet; shelf area; usable storage space.
Features: ice making; meat keeping; crisper humidity.

Process

Material
Identify best available technology for refrigeration system components as a practical limit to performance.
Specify useful life of product and components
Specify reliability.
Specify durability.

Energy
Identify thermodynamic limits to performance (e.g., maximum efficiency determined by temperatures inside and outside the refrigerator).
Specify temperature control: balance, uniformity, compensation.

Distribution

Material
Specify product demand.
Specify installation time and equipment requirements.
Specify packaging requirements for protection and containment.

Energy
Specify location of retail outlets relative to market.

Management

Information
Specify minimum information requirements for owner's manual.
Specify warranty period.

for design. When a solution space exists but 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.

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.

Table 18-6. Some Use and Service Requirements for Refrigerators
Cost Matrix

Product
Material
Retail price.
Cost for replacement parts.
Process
Material and labor
Service costs (cost for service and parts).
Energy
Electricity ($/kWh × kWh/yr).
Distribution
Material, energy, and labor
Delivery and installation cost.
Residuals
Packaging disposal cost.
Management
Information
Manufacturer's guarantee.
Payback period to user for purchasing more expensive energy-efficient unit.

Table 18-7. Some Use and Service Requirements for Refrigerators
Cultural Matrix

Product
Material
Color preferences.
Size (dependent on frequency of shopping and on convenience).
Finishes and materials (affects cleaning, appearance).
Process
Material
Manual vs. automatic defrost.
Compartmentalization—ability to organize food.
Residuals
Food spoilage—ability to control temperature.
Management
Information
Instructions clearly written.

Table 18-8. Some Use and Service Requirements for Refrigerators
Legal Matrix

Product
Material
Consumer Product Safety Commission.
Montreal Protocol for discontinuing the use of CFCs.
TSCA (Refrigerants meet regulations for use).
Process
Energy
National Appliance Energy Conservation Act—January 1, 1993 [maximum energy consumption rate = E = 16.0 AV + 355 kWh/yr (AV = adjusted volume of top-mounted refrigerator)].
Distribution
Residuals
Packaging: German take-back legislation; community recycling ordinance.
Management
Information
FTC guidelines on environmental claims.
DOE labeling requirements for energy efficiency.

18.7 Design Strategies

This section will focus on design strategies relating to product and distribution components of the product system. Process- and management-oriented strategies for achieving pollution prevention are addressed elsewhere in this handbook.

Appropriate strategies satisfy the entire set of design requirements, 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 degraded, the benefits of environmentally responsible design may be illusory.

General strategies that may be followed to fulfill environmental requirements are presented in Table 18-9. Most of these strategies reach across product system boundaries. Product life extension strategies can also be applied to equipment used in processing, distribution, and management. Similarly, process design strategies are not limited to manufacturing operations. They are also useful when product use depends on processes. For example, the drive train of an automobile functions like a miniature industrial plant with a reactor, storage tanks, electric power generator, and process control equipment. Process strategies can thus lower environmental impacts caused by automobile use.

The following sections present impact and risk reduction strategies. It is unlikely that a single strategy will be best for meeting all environmental require-

Table 18-9. Design Strategies

General strategy	Specific strategy
Product life extension	Appropriately durable Adaptable Reliable Serviceable Remanufacturable Reusable
Material life extension	Recycling
Material selection	Reformulation Substitution
Reduced material intensiveness	
Process improvement (see Chaps. 21–26)	Process substitution Process control Improved process layout Inventory control and material handling Facility planning (Chap. 12)
Efficient distribution	Transportation Packaging
Improved management practices	Office management (Chap. 30) Total quality management (Chap. 9) Accounting (Chap. 16)
Improved information provision	Product labeling (Chap. 20)

ments. One strategy is even less likely to satisfy the full set of requirements. For that reason, most development projects should adopt a range of strategies.

18.7.1 Product System Life Extension

Extending the life of a product can directly reduce environmental impacts. In many cases, longer-lived products save resources and generate less waste, because fewer units are needed to satisfy the same needs. Before pursuing this strategy, designers should understand the concept of useful life.

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.[15] Measures of useful life vary with function. Some common measures and examples are listed below:

Measures for useful life	*Product examples*
Number of uses or duty cycles	Clothes washers, switches
Length of operation (i.e., operating hours, months, years, or miles)	Automobiles, light bulbs
Shelf life	Food, unstable chemicals

Retirement is the defining event of useful life. Reasons why products are no longer in use include

- Technical obsolescence
- Fashion obsolescence
- Degraded performance or structural fatigue caused by normal wear over repeated uses
- Environmental or chemical degradation
- Damage caused by accident or inappropriate use

A product may be retired for fashion or technical reasons, even though it continues to perform its design functions well. Clothing and furniture are often retired prematurely when fashions change. Technical obsolescence is common for electronic devices.

Users may also be forced to retire a product for functional reasons. Normal wear can degrade performance until the product no longer serves a useful purpose. Repeated use can also cause structural deformation and fatigue that finally result in loss of function.

Some products are exposed to a wide variety of environmental conditions that cause corrosion or other types of degradation. Such biological or chemical stresses can reduce performance below a critical level. This type of deterioration may also cause products to be retired for aesthetic reasons, even though they continue to perform adequately.

Accidents or incorrect use also cause premature retirement. Poor design or failure to consider unlikely operating conditions may lead to accidents. Some of these events can be avoided through better operating instructions or warnings.

Understanding why products are retired helps designers extend product system life. To achieve a long service life, designs must successfully address issues beyond simple wear and tear. A discussion of specific strategies for product life extension follows.

Appropriately Durable. *Durable* items can withstand wear, stress, and environmental degradation over a long useful life.

A durable product continues to satisfy customer needs over an extended life. Some design actions may make a product more durable without the use of additional resources. However, enhanced durability may depend on increased resource use. When this happens, design alternatives should be compared on a normalized basis (total impacts/useful life).

Development teams should enhance durability only when appropriate. Designs that allow a product or component to last well beyond its expected useful life can be wasteful.

Products based on rapidly changing technology may not always be proper candidates for enhanced durability. If a simple product will soon be obsolete, making it more durable could be pointless. In complicated products subject to rapid change, adaptability is usually a better strategy. For example, modular construction allows easy upgrading of fast-changing components without replacing the entire product. In such cases, useful life is expected to be short for certain components, so they should also not be designed for extreme durability.

Durable designs must also meet other project requirements. When least first cost is emphasized, durable products may encounter market resistance. Even so, durability is often associated with high-quality products. For example, garden tools with reinforced construction can withstand higher stresses than lower-quality alternatives and thus generally last longer. Although these tools are initially more expensive, they may be cheaper in the long run because they do not need to be replaced as frequently.

Enhanced durability can be part of a broader strategy focused on marketing and sales. For some durable products, leasing may be more successful than sale to customers. Leasing can be viewed as selling services while maintaining control over the means of delivering those services. Durability is an integral part of all profitable leasing. Original equipment manufacturers who lease their products usually have the most to gain from durable designs.

Adaptable. *Adaptable* designs either allow continual updating or they perform several different functions. *Modular components* allow single-function products to evolve and improve as needed.

As previously mentioned, adaptability can extend the useful life of products that quickly become obsolete. Products with several parts are the best candidates for adaptable design. To reduce overall environmental impacts, a sufficient portion of the existing product must usually remain after obsolete parts are replaced.

Adaptable designs rely on interchangeable components. Interchangeability controls dimensions and tolerances of manufactured parts so that components can be replaced with minimal adjustments or on-site modifications.[15] Thus, fittings, connectors, or information formats on upgrades are consistent with the original product. For example, an adaptable strategy for a new razor blade design would ensure that blades mount on old handles so the handles don't become part of the wastestream.

Adaptable design may be particularly beneficial for processes and facilities. This strategy allows rapid response to changing conditions through continual upgrades. Such adaptable manufacturing may make it much easier to offer low-impact products that meet customer demands. A well-designed system helps save suitable plant and equipment for continued use.

Reliable. *Reliability* is often expressed as a probability. It measures the ability of a system to accomplish its design mission in the intended environment for a certain period of time.

Environmental impacts are influenced by reliability. Unreliable products or processes, even if they are durable, may be retired prematurely. Customers will not tolerate untrustworthy performance, inconvenience, and expense for long. Unreliable designs can also present safety and health hazards.

The number of components, the individual reliability of components, and configuration are important aspects of reliability. Parts reduction and simplified design can increase both reliability and manufacturability. Simpler designs may also be easier to service. All these factors can reduce resource use and waste. Aside from environmental benefits, producers and customers can save money with reliable products.

Reliability cannot always be achieved by reducing the number of parts or making designs simple. In some cases, redundant systems must be added to provide needed backup. When a reliable product system requires parallel systems or fail-safe components, costs may rise significantly.

Reliability should be designed into products rather than achieved through later inspection. Screening out potentially unreliable products after they are made is wasteful because such products must either be repaired or discarded. In both cases, environmental impacts and costs increase.

Serviceable. A *serviceable* system can be adjusted for optimum performance under controlled conditions. This capacity is retained over a specified life.

Many complex products designed to have a long useful life require service and support. When designing serviceable products, the team should first determine who will provide the service. Any combination of original equipment manufacturers, dealers, private business, or customers may service a product. Types of tools and the level of expertise needed to perform tasks strongly influence who is capable of providing service. In any case, simple procedures are an advantage.

Design teams should also recognize that equipment and an inventory of parts are a necessary investment for any service network. Service activities may be broken into two major categories: maintainability and repairability.

Maintainable. The relative difficulty or time required to maintain a certain level of system performance determines whether that system can be practically *maintained*.

Maintenance includes periodic, preventative, and minor corrective actions. Proper maintenance helps to conserve resources and prevent pollution. For example, tuning an automobile engine improves fuel economy while reducing toxic tailpipe emissions. On the other hand, delaying or ignoring maintenance can damage a product and shorten its useful life.

Designers wishing to create product systems that are easy to maintain should address the following topics:

Downtime, tool availability, personnel skills

Complexity of required procedures

Potential for error

Accessibility to parts, components, or system to be maintained

Frequency of design-dictated maintenance

This is not an exhaustive list, but it identifies some key factors affecting maintenance. Most of these criteria are interrelated. If maintenance is complex, specialized personnel are required, downtime is likely to be long, and the potential for error increases. Specialty tools also make maintenance less convenient.

Similarly, if parts or components are not readily accessible, complexity and costs can increase. Spatial arrangement is the key to easy access. Critical parts and assemblies within a piece of equipment should be placed so they can be reached and the necessary procedures performed. Simpler designs are usually easier to maintain.

Maintenance schedules should balance a variety of requirements. For an automobile, changing motor oil every 500 miles would obviously be wasteful, but changing oil every 50,000 miles would damage the engine. Customers usually believe that the less often maintenance is required the better, so designs that preserve peak performance with minimal maintenance are likely to be more popular. In addition, low-maintenance designs are more likely to stay in service longer than less robust designs. Products dependent on continual readjustments for an acceptable level of performance are generally considered low-quality. Such products can be wasteful, and they are not likely to gain much market share.

Repairable. *Repairability* is determined by the feasibility of replacing dysfunctional parts and returning a system to operating condition.

A two-step process is usually followed when a product needs repair. First, a diagnosis identifies the defect. Then, several questions critical to resource management should be asked:

Should the product be repaired or retired?

Are other components near the end of their useful life and likely to fail soon?

Should the defective component be replaced with a new, remanufactured, or used part?

Answers to these questions should take into account life-cycle consequences.

Factors relating to downtime, complexity, and accessibility are as important in repair as they are in maintenance. Easily repaired products also rely on interchangeable and standard parts. *Interchangeability* usually applies to parts produced by one manufacturer. *Standardization* refers to compatible parts made by different manufacturers. Standardization makes commonly used parts and assemblies conform to accepted design standards.[15]

Use of standard parts designed to codes established by numerous manufacturers greatly aids repair. Designs that feature unique dimensions for common parts can confound normal repair efforts. Specialty parts usually require expanded inventories and extra training for repair people. In the burgeoning global marketplace, following proper standards enables practical repair.

Cost also determines repairability. If normal repair is too expensive, practical repairability does not exist. Labor, which is directly related to complexity and accessibility, is a key factor in repair costs. When labor is costly, only items of relatively high value will be repaired. However, a substantial purchase price is not enough to promote repairability. Designs that impede repair may be retired prematurely regardless of initial investment. As with maintenance, infrequent need, ease of intervention, and a high probability of success lower operating costs, increase customer satisfaction, and translate directly into perceptions of higher quality.

Repairable designs need proper after-sale support. Firms should offer information about troubleshooting, procedures for repair, tools required, and the expected useful life of components and parts.

Remanufacturable. *Remanufacturing* is an industrial process that restores worn products to like-new condition. In a factory, a retired product is first completely disassembled. Its usable parts are then cleaned, refurbished, and put into inventory. Finally, a new product is assembled from both old and new parts, creating a unit equal in performance and expected life to the original or a currently available alternative. In contrast, a *repaired* or *rebuilt* product usually retains its identity, and only those parts that have failed or are badly worn are replaced.[16]

Industrial equipment or other expensive products not subject to rapid change are the best candidates for remanufacture. Typical remanufactured products include jet engines, buses, railcars, manufacturing equipment, and office furniture. Viable remanufacturing systems rely on the following factors:[17]

A sufficient population of old units ("cores")

An available trade-in network

Low collection costs

Storage and inventory infrastructure

Design teams must first determine if enough old units will exist to support remanufacturing. Planning for proper marketing and collection after retirement helps ensure a sufficient population of cores. To remain competitive with new products, the cost of cores must be low. Costs for collecting cores include transport and a trade-in to induce customer return.

Systems for collecting and storing the needed number of cores at competitive prices support remanufacturing. But no remanufacturing program can succeed without design features and strategies such as

Ease of disassembly

Sufficient wear tolerances on critical parts

Avoiding irreparable damage to parts during use

Interchangeability of parts and components in a product line

Designs must be easy to take apart if they are to be remanufactured. Adhesives, welding, and some fasteners can make this impossible. Critical parts must also be designed to survive normal wear. Extra material should be present on used parts to allow refinishing. Care in selecting materials and arranging parts also helps avoid excessive damage during use. Design continuity increases the number of interchangeable parts between different models in the same product line. Common parts make it easier to remanufacture products.

Reusable. *Reuse* is the additional use of an item after it is retired from a clearly defined duty. Reformulation is not reuse. However, repair, cleaning, or refurbishing to maintain integrity may be done in transition from one use to the next.

The environmental impacts of reusable products are often contrasted with those of single-use alternatives. Examples include diapers, cameras, razors, and clothing. Which designs are environmentally superior is controversial in some cases. In others, reuse offers a clear advantage.

Reusable products are returned to the same or less demanding service without major alterations. They may undergo some minor processing, such as cleaning, between services. For example, dishware or glass bottles can be washed before reuse.

The environmental profile of a reusable product does not always depend on the number of expected uses. If the major impacts occur in manufacturing and earlier stages, increasing the number of uses will reduce total environmental impacts. However, when most impacts are caused by cleaning or other steps between uses, increasing the number of duty cycles may have little effect on overall impacts.

Convenience is often cited as a major advantage of single-use products. However, customers usually fail to consider the costs and time of purchasing, storing, and disposing single-use products. Single-use products often cost more per use than reusable products.

Several environmental comparisons between reusable and single-use products have been made. These are mostly confined to life-cycle inventories, which are discussed in the next chapter.

18.7.2 Material Life Extension

Recycling. *Recycling* is the reformation or reprocessing of a recovered 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."[18]

Many designers, policymakers, and consumers believe recycling is the best solution to a wide range of environmental problems. Recycling does divert discarded material from landfills, but it also causes other impacts. Before designers focus on making products easier to recycle, they should understand several recycling basics. A discussion of types of recovered material, pathways, and infrastructure will provide a framework for understanding recycling.

Types of Recycled Material. Material available for recycling can be grouped into the following three classes: home scrap, preconsumer, and postconsumer.

Home scrap consists of materials and by-products generated and commonly recycled within an original manufacturing process.[18] Many materials and products contain home scrap that should not be advertised as recycled content. For example, mill broke (wet pulp and fibers) is easily added to later batches of product at paper mills. This material has historically been used as a pulp substitute in paper making rather than discarded, so it is misleading to consider it recycled content.

Preconsumer material consists of overruns, rejects, or scrap generated during any stage of production outside the original manufacturing process.[18] It is generally clean, well-identified, and suitable for high-quality recovery. Preconsumer material is now recycled in many areas.

Postconsumer material has served its intended use and been discarded before recovery. Unfortunately, in many cases postconsumer material is a relatively low-quality source of input for future products.

Recycling Pathways. Development teams choosing recycling as an attractive way to meet requirements should be aware of the two major types of pathways recycled material can follow: closed-loop pathways and open-loop pathways.

In *closed-loop systems*, recovered materials and products are suitable substitutes for virgin material. They are thus used to produce the same part or product again. Some waste is generated during each reprocessing, but in theory a closed-loop model can operate for an extended period of time without virgin material. Of course, energy, and in some cases process materials, are required for each recycling.

Solvents and other industrial process ingredients are the most common materials recycled in a closed loop. Postconsumer material is much more difficult to recycle in a closed loop, because it is often degraded or contaminated. Designs that anticipate closed-loop recycling of such waste may thus overstate the likely benefits.

Open-loop recycling occurs when recovered material is recycled one or more times before disposal. Most postconsumer material is recycled in an open loop. The slight variation or unknown composition of such material usually causes it to be downgraded to less demanding uses.

Some materials also enter a *cascade open-loop model* in which they are degraded several times before final discard. For example, used white ledger paper may be recycled into additional ledger or computer paper. If this product is then dyed or not de-inked, it will be recycled as a mixed grade after use. In this form, it could be used for paperboard or packing, such as trays in produce boxes. At present, the fiber in these products is not valuable enough to recover. Ledger paper also enters an open-loop system when it is recycled into facial tissue or other products that are disposed after use.

Infrastructure. Types of recycled materials, and the major routes they follow, provide an introduction to recycling. Infrastructure is the key to understanding how recycling actually occurs. Suitable programs must be in place or planned to ensure the success of any recycling system. Key considerations include

Recycling programs and participation rates

Collection and reprocessing capacity

Quality of recovered material

Economics and markets

Economic and market factors ultimately determine whether a material will be recycled. Markets for some secondary materials may be easily saturated. Recycling programs and high rates of participation address only collection; unless recovered material is actually used, no recycling has occurred.

In addition, if a material is not one of the few now targeted for public collection, recovery could be difficult. It may not be possible to create a private collection and reprocessing system that competes with virgin materials. However, if demand for recovered material increases in the future, this will greatly aid collection efforts.

Design Considerations. Recycling can be a very effective resource management tool. Under ideal circumstances, most materials would be recovered many times until they became too degraded for further use. Even so, design for recyclability is not the ultimate strategy for meeting all environmental requirements. For example, studies show that refillable glass bottles have a much lower life-cycle energy usage than single-use recycled glass to deliver the same amount of beverage.[19]

When suitable infrastructure appears to be in place, or the development team is capable of planning it, recycling is enhanced by

Ease of disassembly

Material identification

Simplification and parts consolidation

Material selection and compatibility

Products may have to be taken apart after retirement to allow recovery of materials for recycling. However, easy disassembly may conflict with other project needs. For example, snap-fit latches and other joinings that speed assembly can severely impede disassembly. In some products, easy disassembly may also lead to theft of valuable components.

Material identification markings greatly aid manual separation and the use of optical scanners. Standard markings are most effective when they are well-placed and easy to read. Symbols have been designed by the Society of the Plastics Industry (SPI) for commodity plastics. The Society of Automotive Engineers (SAE) has developed markings for engineered plastics. Of course, marked material must still be valuable and easy to recover or it will not be recycled. In addition, labeling may not be useful in systems that rely on mechanical or chemical separation, although it can be a vital part of collection systems that target certain materials or rely on source separation.

Simplification and parts consolidation can also make products easier to recycle. This is an attractive strategy for many other reasons. As previously mentioned, simple designs also ease assembly and may lead to more robust, higher-quality products.

In many design projects, material selection has not been coordinated with environmental strategies. As a result, many designs contain a bewildering number of materials chosen for combined cost and performance attributes. There may be little chance of recovering material from such complex products unless they contain large components made of a single, practically recyclable material.

Even without separation, some mixtures of incompatible or specialty materials can be "downcycled." At present, several means are available to form incompatible materials into composites. However, the resulting products, such as plastic lumber, may have limited appeal.

Designers can aid recycling by reducing the number of incompatible materials in a product. For example, a component containing parts composed of different materials could be designed with parts made from the same material. This strategy also applies within material types. Formulations of the same material might have such different properties that they are incompatible during recycling. Designers will usually have to make trade-offs when selecting only compatible materials for a product. Making single-material or compatible components may be possible in some cases but not in others.

18.7.3 Material Selection

Material selection, which is fundamental to design, offers many opportunities for reducing environmental impacts throughout a product life cycle. In life-cycle design, material selection begins with identification of the nature and source of raw materials. Then environmental impacts caused by material acquisition, processing, use, and end-of-life product management are evaluated. Finally, proposed materials are compared to determine best choices.

When modest improvements of existing products or the next generation of a line are designed, material choice may be constrained. Designers may also be restricted to certain materials by the need to use existing plant and equipment. This type of process limitation can even affect new product design. Substantial investment may then be needed before a new material can be used. On the other hand, material substitutions may fit current operations and actually reduce costs. In either case, material choice must meet all project requirements.

Reformulation is also an option when materials are selected. Most materials or products may be reformulated to reduce impacts, even when material choice is constrained.

Substitution. Substitution is a strategy available for improvement of existing designs. The challenge with substitution is to reduce life-cycle environmental impacts without compromising performance, cost, or other requirements. These material substitutions can address a wide range of issues, such as replacing rare tropical woods in furniture with native species.

Material substitutions can be made for product as well as process materials, such as solvents and catalysts. For example, water-based solvents or coatings can sometimes be substituted for high-VOC alternatives during processing. On the other hand, materials that don't require coating, such as some metals and polymers, can be substituted in the product itself.

Reformulation. Reformulation is a less drastic alternative than substitution. It is an appropriate strategy when a high degree of continuity must be maintained with the original product. Consumables and other products that must fit existing standards may limit design choices. Rather than entirely replace one material with another, designers can alter percentages to achieve the desired result. Some materials can also be added or deleted if characteristics of the original product are still preserved. Gasoline is one product that has undergone many reformulations to reduce fugitive emissions as well as emissions from combustion. In this case, reformulation is further complicated because it can reduce fuel economy or engine performance.

18.7.4 Reduced Material Intensiveness

Resource conservation can reduce waste and directly lower environmental impacts. A product that is less material intensive may also be lighter, thus saving energy in distribution or use. Designing to conserve resources is not always simple. Reduced material use may affect other requirements in complex ways.

In some cases, using less material affects no other requirements and thus clearly lowers impacts. When the reduction is very simple, benefits can be determined without a rigorous life-cycle assessment. However, careful study may be needed to ensure that significant impacts have not been created elsewhere in the life cycle. In addition, impacts might have been reduced further by use of another material rather than less of the current choice.

18.7.5 Efficient Distribution

Both transportation and packaging are required to transfer goods between locations. A life-cycle design project benefits from distribution systems that are as efficient as possible.

Transportation. Life-cycle impacts caused by transportation can be reduced by several means. Approaches that can be used by designers include:

Choose an energy-efficient mode

Reduce air pollutant emissions from transportation

Maximize vehicle capacity where appropriate

Backhaul materials

Ensure proper containment of hazardous materials

Choose routes carefully to reduce potential exposure from spills and explosions

Trade-offs between various modes of transportation will be necessary. Transportation efficiencies are shown in Table 18-10. Time and cost considerations, as well as convenience and access, play a major role in the choice of the best transportation. When selecting a transportation system, designers should also consider infrastructure requirements and their potential impacts.

Packaging. Packaging must contain and protect goods during transport and handling to prevent damage. Regardless of how well designed an item might be, damage during distribution and handling may cause it to be discarded before use. To avoid such waste, products and packaging should be designed to complement each other.

The concurrent practices of life-cycle design are particularly effective in reducing impacts from packaging. As a first step, products should be designed to withstand both shock and vibration. When cushioned packaging is required, members of the development team need to collaborate to ensure that cushioning does not amplify vibrations and thus damage critical parts.[20] Cooperation between design specialties can greatly reduce such product damage.

The following strategies may be used to design packaging within the life-cycle framework. Most of these strategies also result in significant cost savings.

Packaging reduction

- Elimination: distribute appropriate products unpackaged
- Reusable packaging
- Product modifications
- Material reduction

Material substitution

- Recycled materials
- Degradable materials

Packaging Reduction. Shipping items without packaging is the simplest approach to impact reduction. In the past, many consumer products, such as screwdrivers, fasteners, and other items, were offered unpackaged. They can still be hung on hooks or placed in bins that provide proper containment while allowing customer access. This method of merchandising avoids use of unnecessary plastic wrapping, paperboard, and composite materials. Wholesale

Table 18-10. 1990 Transportation Fuel Requirements

	Fuel consumed per 1000 ton-miles	Energy consumed* (Btu/ton-mile)
Combination truck (tractor trailer)		
Diesel	11.8 gal	1945
Gasoline	11.8 gal	1782
Single-unit truck		
Diesel	19.1 gal	3136
Gasoline	20.8 gal	3132
Rail		
Diesel	3.1 gal	514
Barge†		
Diesel	2.0 gal	330
Residual	0.6 gal	96
Total		426
Ocean freighter†		
Diesel	0.1 gal	16
Residual	1.0 gal	173
Total		190
Pipeline—natural gas		
Natural gas	2300 ft^3	2657
Pipeline—petroleum products		
Electricity	22 kWh	236
Pipeline—coal slurry		
Electricity	235 kWh	2517

*Includes precombustion energy for fuel acquisition.
†An average ratio of diesel and residual fuels is used to represent barge and ocean freighter transportation energy.

SOURCE: Franklin Associates, Ltd.

packaging can also be eliminated. For example, furniture manufacturers commonly ship furniture uncartoned. Uncartoned furniture is protected with blankets that are returned after delivery to the distribution center.

Reusable packaging systems are also an attractive design option. Wholesale items that require packaging are commonly shipped in reusable containers. Tanks of all sizes, wire baskets, wooden shooks, and plastic boxes are frequently used for this purpose.

Necessary design elements for most reusable packaging systems include

Collection or return infrastructure

Procedures for inspecting items for defects or contamination

Repair, cleaning, and refurbishing capabilities

Storage and handling systems

Unless such measures are in place or planned, packaging may be discarded rather than reused. Manufacturers and distributors cannot reuse packaging unless infrastructure is in place to collect, return, inspect, and restore packaging for another service. Producers can reduce these infrastructure needs by offering their product in bulk. Some system will still be required for reusable wholesale packaging, but it should be much less complex than that needed to handle consumer packaging. When products are sold in bulk, customers control all phases of reuse for their own packaging.

Even so, waste generation and other environmental impacts are only reduced when customers reuse their container several times. Customers who use new packaging for each bulk purchase generally consume more packaging than customers who buy prepackaged products. This is particularly true of items distributed in single-use bulk packaging.[21]

Product modification is another approach to packaging reduction. Sturdy products may require less packaging and may also prove more robust in service. Depending on the delivery system, some products may safely be shipped without packaging of any kind. Even when products require primary and secondary packaging to ensure their integrity during delivery, product modifications may decrease packaging needs. Designers can further reduce the amount of packaging used by avoiding unusual product features or shapes that are difficult to protect.

Reformulation is another type of product modification that may be possible for certain items. Products that contain ingredients in diluted form may be distributed as concentrates. In some cases, customers can simply use concentrates in reduced quantities. A larger, reusable container may also be sold in conjunction with concentrates. This allows customers to dilute the product as appropriate. Examples of product concentrates include frozen juice concentrates and concentrated versions of liquid and powdered detergent.

Material reduction may also be pursued in packaging design. Many packaging designers have already managed to reduce material use while maintaining performance. Reduced thickness of corrugated containers (board grade reduction) provides one example. In addition, aluminum, glass, plastic, and steel containers have continually been redesigned to require less material for delivering the same volume of product.

Material Substitution. As discussed, material substitution can reduce impacts in other areas of design. One common example of this strategy in packaging is the substitution of more benign printing inks and pigments for those containing toxic heavy metals or solvents. The less harmful inks are usually just as effective for labels and graphic designs. When some properties depend on toxic constituents, designers can develop new images that are compatible with sounder pigments, inks, and solvents.

Whenever possible, designers can create packaging with a high recycled content. Many public and private recycling programs currently focus on collecting packaging. As a direct consequence, firms are being encouraged to increase the recycled content of their packaging.

However, using recycled material in packaging design cannot be thought of as a complete strategy in itself. Opportunities for material reduction and packaging reduction or elimination should still be investigated. Recycling and recycled materials were discussed in more detail earlier in this chapter.

Degradable materials are capable of being broken down by biological or chemical processes or exposure to sunlight. At first glance, package designs based on degradable material appear to be an attractive solution to the mounting problem of waste disposal. But the lack of sunlight, oxygen, and water in modern landfills severely inhibits degradation. Degradable materials thus provide only limited benefits in packaging that will be properly disposed. This may change if composting of municipal waste becomes more widespread.

In any event, degradability is a desirable trait for litter deposited in aesthetically pleasing natural areas. In particular, polymers or other materials that are normally resistant to decay are less of a nuisance if they can be formulated to quickly break down. Degradable materials may also benefit some aquatic species that encounter litter. Various mammals, birds, and fish can die from entrapment in such items as six-pack rings and plastic sacks. Even so, it may be difficult to determine whether degradable packaging is an asset or just encourages irresponsible behavior.

Previously resistant materials that are now designed to decay may also cause unanticipated problems. Degradable polymers can impede recycling efforts by acting as a contaminant in recovered materials. Questions have also been raised about the environmental impacts of degraded polymers. Degradation can liberate dyes, fillers, and other potentially toxic constituents from a material that was previously inert.

18.8 Summary of Life-Cycle Design Principles

Life-cycle design principles for achieving pollution prevention and guiding the environmental improvement of the product system are summarized here.

1. Addressing environmental issues in the earliest stages of design is one of the most efficient approaches to achieving pollution prevention. Other related benefits include enhancing resource efficiency, reducing liabilities, and achieving competitiveness.
2. The ultimate goal of life cycle design is to achieve sustainable development. Sustainable development seeks to satisfy basic societal needs of today without compromising future generations' ability to meet their needs. Maintenance of ecosystem structure and function (the planet's life support system) is critical to achieving this goal.
3. The product life cycle is a useful framework for evaluating and reducing adverse environmental impacts associated with the manufacture, use, and end-of-life management of a product. Designers can prevent the shifting of adverse impacts between media and life-cycle stages.
4. Both internal and external factors strongly influence design. Internally, the environmental management system, which includes goals and performance measures, provides the organizational structure within a company to implement pollution prevention by design. Access to accurate information about environmental impacts is also critical for achieving environmental improvement. External factors that shape design include government regulations, market forces, infrastructure, and state of the environment, as well as scientific understanding and public perception of risks.
5. The concurrent design of product system components (product, process, distribution, and information/management) is an important principle in life-cycle design management. Interdisciplinary participation is key to defining requirements that reflect the needs of multiple stakeholders: suppliers, manufacturers, consumers, resource recovery and waste managers, the public, regulators.
6. 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.
7. Life-cycle design seeks to optimize environmental objectives while also optimizing cost, performance, cultural, and legal requirements. The challenge is to apply value-added design strategies that resolve conflicting requirements.

Two industry demonstration projects of the life-cycle design framework are being conducted by the EPA's Pollution Prevention Branch and National Pollution Prevention Center based at the University of Michigan. Results from demonstration projects with AT&T and Allied Signal are currently being documented and will be published by the EPA. The author has also recently completed a critical review of life cycle design.[22]

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