A Life Cycle Approach to Product System Design

Gregory A. Keoleian, Dan Menerey, and Mary Ann Curran

Integrating environmental requirements into the earliest stages of design is a fundamental component of product life cycle management. Still, there is much work to be done to help industry practice this approach. An important new guidance manual for product life cycle design from the Environmental Protection Agency (EPA) has recently been produced by researchers at the University of Michigan and EPA. Its contents are summarized in this article.

MOST ENVIRONMENTAL IMPACTS result from design decisions made long before manufacturing or use. Yet environmental criteria often are not considered at the beginning of the design phase when it is easiest to eliminate potential negative effects through a product's life cycle. As a result, most companies continue to channel more resources to fix problems, rather than prevent them.

Although the most innovative firms are adopting ambitious environmental policies to shift their focus to prevention, translating these policies into successful action is a major challenge. In particular, without proper support, environmental design programs, which are vital to this process, may be launched without specific objectives, definitions, or principles.

EPA's Risk Reduction Engineering Laboratory (RREL) and the University of Michigan are conducting joint research to develop a life cycle design approach to integrate environmental requirements in the earliest stages of design. These requirements are chosen to minimize aggregate resource depletion, energy use, waste generation, and deleterious human and ecosystem health effects. At the same time, the environmental dimension is coupled with other key design criteria including performance, cost, cultural, and legal requirements.

Following an extensive investigation of design literature and over forty interviews with design professionals, the research team proposed a framework for life cycle design that is presented in a new report, Life Cycle Design Manual: Environmental Requirements and the Product System.[1] The report's key findings are summarized in this article.

The Life Cycle Design Project

The manual was produced as part of phase one of RREL's life cycle design project. Phase two will include corporate participation in demonstration projects to test the manual's methodologies.

The purpose of the life cycle design project is to promote environmental impact and risk reduction through design. The manual seeks to

Gregory A. Keoleian *is an assistant research scientist and manager of the National Pollution Prevention Center.* ***Dan Menerey*** *is a research assistant at the University of Michigan's School of Natural Resources and Environment in Ann Arbor, Michigan.* ***Mary Ann Curran*** *is a chemical engineer with the Pollution Prevention Research Branch of U.S. EPA's Risk Reduction Engineering Laboratory in Cincinnati, Ohio.*

- Provide guidance on reducing impacts and health risks caused by product development;
- Encourage the inclusion of environmental requirements at the earliest stage of design rather than focusing on end-of-pipe solutions; and
- Integrate environmental, performance, cost, cultural, and legal requirements into effective designs.

The Life Cycle Design Framework

The term "product life cycle" has been applied to both business activities and material balance studies. In business use, a product life cycle begins with the first phases of design and proceeds through the end of production. Businesses track costs, estimate profits, and plan strategy based on the life cycle framework.

In contrast, environmental inventory and impact analysis follows the physical system of a product. Such life cycle analyses track material and energy flows and transformations from raw materials acquisition to the ultimate fate of residuals. Life cycle design combines the standard business use of a life cycle with the physical system.

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Life cycle stages

The product life cycle can be organized into the following stages:

- Raw material acquisition
- Bulk material processing
- Engineered materials production
- Manufacturing/assembly
- Use and service
- Retirement
- Disposal

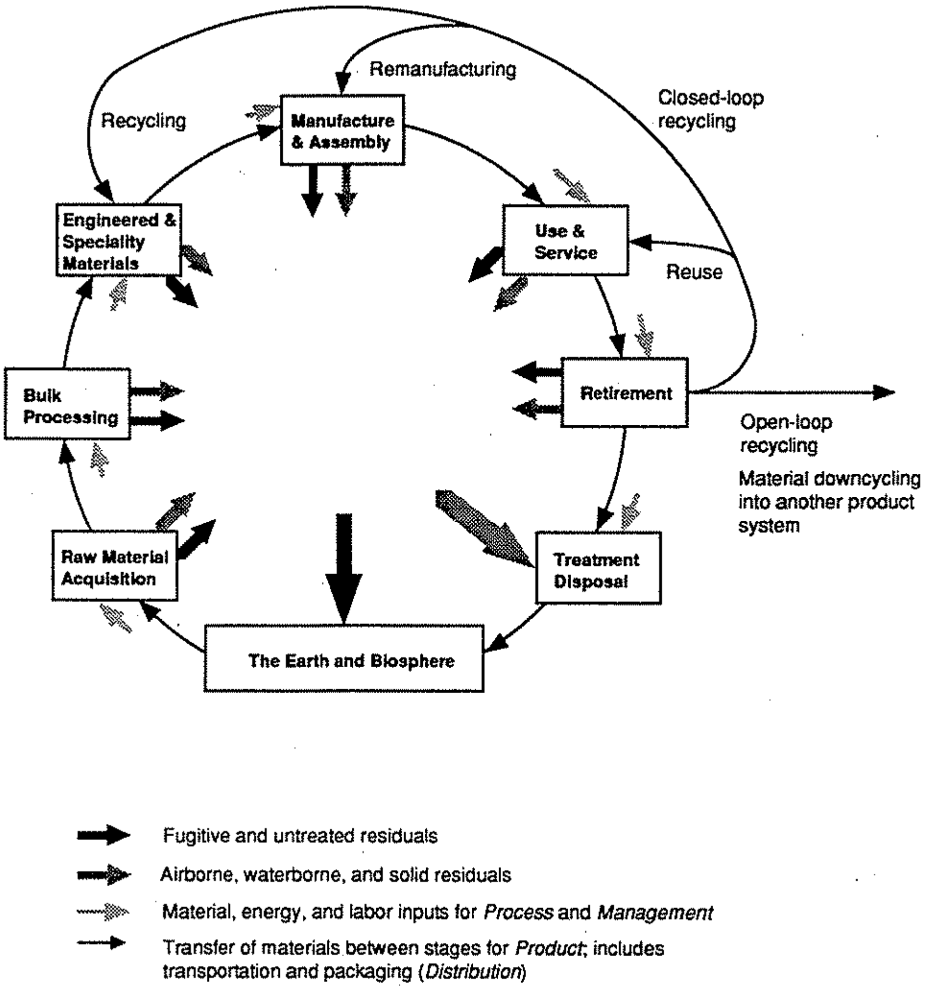
A general flow diagram of the product life cycle is presented in **Figure 1**. The net effect of each product life cycle is the consumption of resources and the conversion of these resources into residuals that accumulate in the earth and biosphere.

Product system components

Life cycle design addresses the entire product system, not just isolated components. In life cycle design, products are defined as systems that include the following components: (1) product, (2) process, (3) distribution network (packaging and transportation), and (4) management (including information provision). Incorporating these elements in the product design phase assures that every activity related to making and using products is considered.

The *product* component consists of all materials in the final

Figure 1. The Product Life Cycle System



product and includes all forms of these materials from acquisition to disposal. *Processing* transforms materials and energy into intermediary and final products. *Distribution* consists of packaging systems and transportation networks used to contain, protect, and transport items. *Management* responsibilities include administrative services, financial management, personnel, purchasing, marketing, customer services, and training and educational programs. The management component also develops information and conveys it to others.

The process, distribution, and management/information components can be further classified into the following subcomponents: facility or plant, unit operations or process steps, equipment and tools, labor, secondary material inputs, and energy.

Life cycle design can be applied to products in any number of ways:

- Improvements, or minor modifications of existing products and processes;
- New features associated with developing the next generation of an existing product or process; and
- Innovations characteristic of new designs.

No single design method or set of rules applies to all types of products. For that reason, the manual provides general guidelines rather than prescriptions. Designers should use the manual to develop tools best suited to their specific projects.

As noted earlier, the product system can be broken down into four primary components.

Goals of life cycle design

The primary objective of life cycle design is to reduce total environmental impacts and health risks caused by product development and use. This objective can only be achieved in concert with other life cycle design goals. Life cycle design seeks to

- Conserve resources;
- Prevent pollution;
- Support environmental equity;
- Preserve diverse, sustainable ecosystems; and
- Maintain long-term, viable economic systems.

Managing Life Cycle Design

Design actions translate life cycle goals into high-quality, low-impact products. As **Figure 2** shows, product development is complex. Many elements in the diagram feed back on others, emphasizing the continual search for improved products.

Life cycle goals are located at the top of the figure to indicate their fundamental importance. Unless these goals are embraced by the entire development team, true life cycle design is impossible.

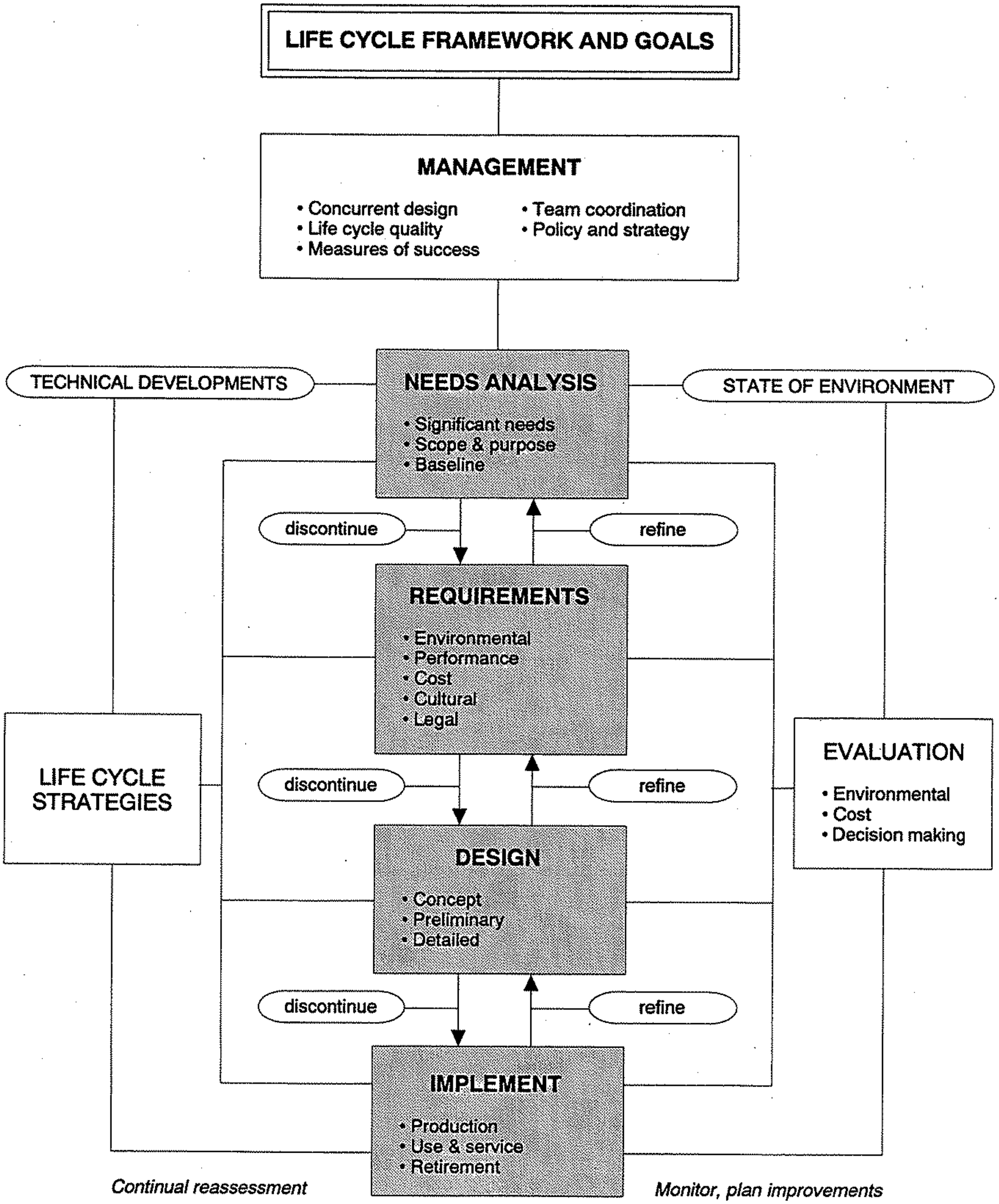
Corporate management also exerts a major influence on all phases of product development. Indeed, commitment from all levels of management is a vital part of life cycle design. For example, corporate environmental policy must be translated into specific criteria to have a significant effect on product and process design activities. Objectives and guidelines need to be established with enough detail to provide useful guidance in design decision making.

The progress of life cycle design programs should be monitored and assessed using clearly established environmental and financial measures.

The progress of life cycle design programs should be monitored and assessed using clearly established environmental and financial measures. Appropriate measures of success are necessary to motivate individuals within development teams to pursue environmental-impact and health-risk reductions.

Companies may measure progress in several ways. Verbal estimates can qualify results, or results can be calculated with numbers. In either case, life cycle design is likely to be more successful when

Figure 2. Life Cycle Design Process



environmental aspects are part of a firm's incentive and reward system. Even though life cycle design can cut costs, improve performance, and lead to greater profitability, it may still be necessary to include discrete environmental measures of an individual'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.

Both concurrent design and total quality management provide models for life cycle design, which 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. By having all actors in the life cycle participate in a project from the outset, problems that develop between different disciplines can be reduced. Efficient teamwork also reduces development time, lowers costs, and can improve quality.

Environmental considerations are also closely linked with quality in life cycle design. For example, in life cycle design, the environment is also seen as a customer. Pollution and other impacts are quality defects that reduce customer satisfaction.

Moreover, companies that look beyond quick profits to focus on customers and cooperation with suppliers have the best chance of succeeding with life cycle design. To achieve this, life cycle design depends on cross-disciplinary teams. These teams may include any of the following participants: accounting, advertising, community, customers, distribution, packaging, environmental resources staff, government regulators/standards setting organizations, industrial designers, lawyers, management, marketing and sales, process designers and engineers, purchasing, production workers, research and development staff, and service personnel. Effectively coordinating these teams, however, and balancing the diverse interests of all participants present a significant challenge.

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Incorporating Life Cycle into R&D

Research and development discovers new approaches for reducing environmental impacts, with the state of the environment providing the context. In life cycle design, current and future environmental needs are translated into appropriate designs.

A typical design project begins with a needs analysis, then proceeds through requirements formulation, conceptual design, preliminary design, detailed design, and implementation.
During these phases, the development team synthesizes various requirements into a coherent design. Because life cycle design is based on concurrent practices, activities in several phases may be occurring at the same time.

Needs analysis

Design projects customarily begin by recognizing the need for change or uncovering an opportunity for new product development. The first step in any project should be identifying customers and their needs. Avoiding confusion between trivial or ephemeral desires and actual needs is a major challenge of life cycle design.

After critical needs have been identified, the project's scope can be defined. This entails choosing system boundaries, characterizing analysis methods, and establishing a project time line and budget. In addition, development teams should decide whether the project will focus on improving an existing product, creating a new model, or developing a new product.

Initially the development team must consider the full life cycle as the boundary for design. Narrowly defined systems (e.g., partial life cycle or individual stage or activities) may also provide useful results, but the limitations of more restricted systems must be recognized and clearly stated. Certain stages of the life cycle may be omitted if they are static or not affected by a new design. In all cases, designers working on a more limited scale should be aware of potential upstream and downstream impacts.

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The development team continuously evaluates alternatives throughout design. If studies show that requirements cannot be met or reasonably modified, the project should end.

Design requirements

Formulating requirements is one of the most critical activities in life cycle design. Requirements define products in terms of functions, attributes, and constraints. *Functions* describe what a successful design does. Thus, functions should state *what* a design does, not how it is accomplished. *Attributes* are additional details that provide useful descriptions of functions. *Constraints* are conditions that the design must meet to satisfy project goals. Constraints provide limits on functions that restrict the design search to manageable areas.

Considerable research and analysis are needed to develop proper requirements. Too few requirements usually indicate that the design is ambiguous.

A well-conceived set of requirements translates project objectives into a specific solution. In life cycle design, environmental functions are critical to overall system quality. Thus, all requirements must be balanced in successful designs. A product that fails in the marketplace benefits no one. For this reason, environmental requirements should be developed at the same time as performance, cost, cultural, and legal criteria.

The manual includes a multilayer requirements matrix that provides a systematic tool to allow product development teams to carefully study the interdependencies and interactions between life cycle and traditional product requirements. (Approaches that can assist designers in defining environmental requirements and conflicts between requirements are also introduced in the manual.)

The level of detail expressed in requirements depends on the type of development project. For instance, proposed requirements for new products are usually less detailed than those set for improving an existing product.

Ranking and weighting requirements

Ranking and weighting provide designers with an understanding of the relative importance of various requirements. An example of a useful classification scheme follows.

- *"Must" requirements* are conditions that improvements and design alternatives have to meet. No design alternative is acceptable unless it satisfies all these requirements.
- *"Want" requirements* are traits used to select the most desirable alternatives from proposed solutions that meet mandatory requirements. These requirements help designers seek the best solution, not just the first alternative. These criteria can also play a critical role in customer acceptance and perception of quality.
- *Ancillary functions* are of less relative importance and can therefore be relegated to a wish list. Designers should be aware, however, that these desires exist, and try to incorporate them in designs when it can be done without compromising more critical parameters. Customers or clients should not expect to find many ancillary requirements included in the final design.

Limitations of life cycle design

Lack of data and models for determining life cycle impacts makes analysis difficult. Lack of motivation can also be a problem. When the scope of design is broadened from that portion of the life cycle controlled by individual players to other participants, interest in life cycle design can dwindle. In particular, it can be difficult for one party to take actions that mainly benefit others.

Design Strategies

Effective strategies can only be adopted after project objectives are defined by requirements. Deciding on a course of action before the destination is known can be an invitation to disaster.

Thus, a successful strategy satisfies the entire set of design requirements. No single strategy, however, should be expected to satisfy all project requirements. Most development projects should adopt a range of strategies. **Table 1** lists possible strategies discussed in the manual.

Examples of real applications described in the manual are provided here to show how various strategies have been used.

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Table 1. Life Cycle Design Strategies

Product system life extension
- appropriately durable
- adaptable
- reliable
- serviceable
- remanufacturable
- reusable

Material life extension
- recycling

Material selection
- substitution
- reformulation

Reduced material intensiveness

Process management
- process substitution
- process control
- improved process layout
- inventory control and material handling
- facilities planning

Efficient distribution
- transportation
- packaging

Improved business management
- office management
- information provision
  labeling
  advertising

Durable

A European company leases all the photocopiers it manufactures. Drums and other key components of their photocopiers are designed for maximum durability to decrease the need for replacement or repair. Because the company maintains control of the machines, materials are also selected to reduce the costs and impacts of disposal.

Adaptable

A European computer manufacturer designed a mainframe with a portable system that delinks computer hardware and software. This allows a range of previously incompatible software to be used on the same hardware.

In addition, the company guarantees competitive performance of their system over an extended period, because modular components can be replaced independently. Continual upgrading of the peripheral equipment and user programs is thus possible. Rapid technological progress can be achieved while many stable components are retained.

This design is supported by innovative marketing techniques. Stressing performance guarantees enhanced appeal of an adaptable product. Resource use and waste can be reduced in a market notorious for very short product life and rapid turnover.

Another example is a large American company that designed a telecommunications control center using a modular work station approach. Components can be upgraded as needed to maintain state-of-the-art performance. Some system components change rapidly, whereas others stay in service ten years or more.

Reliable

A large American electronics firm discovered that many plug-in boards on the digital scopes it designed failed in use. But when the boards were returned for testing, 30 percent showed no defects and were sent back to customers. Some boards were returned repeatedly, only to pass the tests every time.

Finding the problem was difficult and expensive. Preventing it during design by more thoroughly examining fit and clearance would have been much simpler and less costly.

Finally, the company discovered that a bit of insulation on each of the problem boards' capacitors was missing, producing a short when they were installed in the scope. The cause was insufficient clearance between the board and the chassis of the scope; each time the board was installed it scraped against the side of the instrument. Finding the problem was difficult and expensive. Preventing it during design by more thoroughly examining fit and clearance would have been much simpler and less costly.

Remanufacturable

A Midwestern manufacturer could not afford to replace all of its thirteen aging plastic-molding machines with new models, so it chose to remanufacture eight molders for one-third the cost of new machines. The company bought one new machine at the same time. The remanufactured machines increased efficiency by 10 to 20 percent and decreased scrap output by 9 percent compared to the old equipment; performance was equal with the new molder. Even with updated controls, operator familiarity with the remanufactured machines and use of existing foundations and plumbing further reduced costs of the remanufactured molders.

An original equipment manufacturer of jet engines also provides remanufactured engines to customers. Remanufactured engines cost $900,000 plus trade-in value, compared to $1.6 million for a new engine. Fuel efficiency in the remanufactured engine is 4 percent better than the new engine specifications, yielding an annual fuel savings of 92,000 gallons, based on average aircraft use.

Reusable

A large supplier of industrial solvents designed back-flush filters that could be reused many times. The new design replaced single-use filters for some of their on-site equipment. Installing back-flush filters caused an immediate reduction in waste generation, but further information about the environmental impacts associated with the entire multiple-use filter is necessary to properly compare it to the impacts of single-use filters.

Material substitution

An American company replaced its five-layer finish on some products with a three-layer substitute. The original finish contained nickel (first layer), cadmium, copper, nickel, and black organic paint (final layer). The new finish contains nickel, zinc-nickel alloy, and black organic paint. The substitution eliminated cadmium, a toxic heavy metal, and the use of a cyanide bath solution for plating the cadmium. The new finish was equally corrosion resistant. It was also cheaper to produce, saving the company 25 percent in operating costs (approximately $1 million annually).

Reformulation

American petroleum companies are currently reformulating gasoline sold in areas of the United States that do not comply with the new Clean Air Act (CAA). The CAA will require lower mobile source emissions of volatile organic compounds (VOCs) and nitrous oxides (NOx). Both compounds produce smog and ozone. Reduced emissions of toxic combustion products such as carbon monoxide (CO) and benzene are also mandated. Gasolines reformulated to meet these new requirements feature changes in aromatic and olefin composition. Oxygenators such as methyl tert-butyl-ether, ethanol, and methanol have also been added.

The new gasolines vary in their ability to reduce emissions of NOx, VOCs, CO, and benzene. Reformulation is further complicated, because it may reduce fuel economy and engine performance.

Reduced material intensiveness

Many single-use items have steadily reduced their material content over time, although this may not be the most effective method of reducing impacts to also meet societal needs. Even so, material reduction can be beneficial.

For example, a fast food franchise reduced material inputs and solid waste generation by decreasing paper napkin weight by 21 percent. Two store tests revealed no change in the number of new napkins used compared to the old design. Attempts to reduce the gauge of plastic straws, however, caused customer complaints; the redesigned straws were found to be too flimsy and did not draw well with milkshakes.

A systematic means of gathering and analyzing data in varying depths is needed from the very beginning of a development project through implementation.

Process substitution

A large American chemical and consumer products company switched from an organic solvent-based system for coating pharmaceutical pills to a water-based system. The substitution was motivated by the need to comply with regulations limiting emissions of VOCs. To prevent the pills from becoming soggy, a new sprayer system was designed to precisely control the amount of coating dispensed. A dryer was also installed as an additional process step. Heating requirements increased when water-based coatings were used. For a total cost of $60,000, the new system saved $15,000 in solvent costs annually and avoided $180,000 in end-of-pipe air emission controls that would have been required if the old system had been retained.

Although this process substitution is a good example of pollution prevention, the case does not demonstrate proper life cycle design practices. The water-based system has to be carefully analyzed before the impacts of the old and new systems can be compared.

Environmental Analysis Tools

A systematic means of gathering and analyzing data in varying depths is needed from the very beginning of a development project through implementation. In particular, environmental analysis is needed for benchmarking and the evaluation of design alternatives.

Life cycle environmental assessments are based on two components: (1) inventory analysis and (2) impact analysis.

Two main tasks are involved in an inventory analysis: identifying material and energy input and output streams and their constituents and quantifying these inputs and outputs. Information about material and energy inputs and waste (residual) outputs is gathered for every significant step included in the product system.

In processes with multiple useful outputs, problems may occur in allocating environmental impacts to a specific product. Proportioning impacts according to the total weight of the main product relative to the byproducts is a commonly used allocation method.

The purpose of impact assessment is to evaluate impacts and risks associated with the material and energy transfers and transformations quantified in the inventory analysis.

The purpose of impact assessment is to evaluate impacts and risks associated with the material and energy transfers and transformations quantified in the inventory analysis. The translation of inventory data into environmental effects is achieved through a wide range of impact assessment models, including hazard and risk assessment models. The final result of an impact analysis is an environmental profile of the product system. Environmental impacts can be organized into the following categories:

- Resource depletion
- Ecological degradation
- Human health effects (health and safety risks)
- Other human welfare effects

Resource acquisition has two basic environmental consequences.

One is ecological degradation from habitat disruption (e.g., physical disruption from mining). The other is reduction in the global resource base.

Ecological risk assessment includes many of the elements of human health risk assessment but is much more complex. The ecological stress agents must be identified, as well as the potentially affected ecosystem. Ecological stress agents can be categorized as chemical (e.g., toxic chemicals released to the environment), physical (e.g., habitat destruction through logging), and biological (e.g., introduction of an exotic species).

Human health risk assessment includes hazard identification, risk assessment, exposure assessment, and risk characterization. Human health and safety risks can also be assessed using models that evaluate process system reliability.

Impact analysis represents one of the most challenging analysis functions of product systems development. Although current methods for evaluating environmental impacts are incomplete, impact assessment is important, because it enables designers and planners to understand the environmental consequences of a design more fully. The development team must recognize that analysis tools for assessing environmental impacts and risks are constantly improving. Designers, however, cannot wait for the ultimate environmental assessment models.

Scope of the analysis

A full materials life cycle assessment may not be essential for many design activities. Scope can vary from complete quantification of all inputs, outputs, and their impacts to a simple verbal description of inventories and impacts. Boundaries for analysis may range from the full life cycle system to individual activities within a life cycle stage. The development team should be able to justify reducing the scope for design to a partial life cycle system.

The following factors related to analysis should also be considered when setting specific system boundaries: basis, temporal boundaries (time scale), and spatial boundaries (geographic). In general, the basis for analysis should be equivalent uses of the product. The time frame or conditions under which data were gathered should be clearly identified. A data collection period should be chosen that is representative of average system performance. Spatial boundaries should also be noted because the same activity can have radically different effects in different locations.

Life Cycle Accounting

Life cycle design will benefit from an accurate estimate of costs related to developing and using products.

Life cycle design will benefit from an accurate estimate of costs related to developing and using products. Material and energy flows provide a detailed template for assigning costs to individual products. Following the total cost assessment model, life cycle accounting adds hidden liability, and less tangible costs to those costs usually gathered. [See in this issue, *Environmentally-Smart Accounting: Using Total Cost Assessment to Advance Pollution Prevention*, pages 247-259.]

This expanded scope matches the range of activities included in life cycle design. Time scales are also expanded to include all future costs and benefits that might result from design.

Putting Life Cycle Design To Work

The framework for life cycle design presented in the EPA manual was developed to be applicable for all product domains. Individual firms are expected to interpret the manual for their own specific applications. The manual was written to assist not only design professionals, but all constituents who have an important role in life cycle design including corporate executives, product managers, production workers, distributors, environmental health and safety staff, consumers, and government regulators.

AT&T Bell Labs and Allied Signal are participating in a second phase of EPA's research on life cycle design: life cycle design demonstration projects. The purpose of these projects is to demonstrate the efficacy of life cycle design and encourage its use by other firms. These demonstrations will be completed by the end of 1993. ◆

Notes

1. The manual (EPA/600/R-92/226) can be obtained at no cost from EPA's Center for Environmental Research Information. Telephone: 513-569-7562. Photocopies can also be purchased from the National Technical Information Service by calling 703-487-4650 and asking for PB#93-164507 AS.

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about ***Pollution Prevention Review:***

contact Jean Stephenson,
Managing Editor
Phone: **212-645-7880**
Fax: **212-645-1160**

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contact John Evans
Phone: **1-800-332-8804**
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