

**Life Cycle Assessment:
Issues for the Automotive Plastics Industry**

December, 1993

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Office for the Study of Automotive Transportation
University of Michigan Transportation Research Institute

Prepared for the
Automotive Plastics Recycling Project

Report Number: UMTRI 93-40-1

Preface

The Office for the Study of Automotive Transportation (OSAT), in cooperation with researchers from other units of the University of Michigan, is undertaking a multiyear program of research titled "Effective Resource Management and the Automobile of the Future." The first project focused on recycling automotive plastics and provides an independent evaluation and review of the issues and challenges that recycling pose for this class of materials.

The Automotive Recycling Project benefited from the financial support of numerous sponsors: The American Plastics Council; The Geon Company; Hoechst Celanese; Miles, Inc.; OSAT's Affiliate Program; Owens-Corning Fiberglas; and The University's Office of the Vice President for Research. In addition, representatives of each of the Big Three automakers graciously served on the Project's advisory board, as did Suzanne M. Cole.

The project reports provide an overview and analysis of the resource conservation problems and opportunities involved in the use of plastics, and describes the factors that are likely to influence the future of automotive plastics. We develop information on the economic, infrastructure, and policy aspects of these issues, identifying the barriers to and facilitators of automotive plastics use that is less constrained by resource conservation and recycling concerns. At the same time, the Vehicle Recycling Partnership, a precompetitive joint research activity of the Big Three, is devoting its resources to the technical issues raised by recycling automotive plastics.

The Recycling Automotive Plastics project yielded six reports:

Life Cycle Assessment: Issues for the Automotive Plastics Industry (UMTRI Report #90-40-1), by Brett C. Smith and Michael S. Flynn, an overview of the LCA approach and its implications for automotive plastics (15 pages). This paper includes, as an appendix, the EPA design manual by Greg Keoleian and Dan Menerey, *Life Cycle Design Manual: Environmental Requirements and the Product System*;

Economic Issues in the Reuse of Automotive Plastics (UMTRI Report #90-40-2), by Daniel Kaplan, a general consideration of the economic barriers and issues posed by recycling automotive plastics (42 pages);

Recycling the Automobile: A Legislative and Regulatory Preview (UMTRI Report #90-40-3), by Suzanne M. Cole, Chair, Society of Plastic Engineers, International Recycling Division, describes the likely developments on the federal regulatory and legislative front that will influence the future of automotive plastics use and disposition (26 pages);

Postconsumer Disposition of the Automobile (UMTRI Report #90-40-4), by T. David Gillespie, Daniel Kaplan, and Michael S. Flynn, a review of the issues and challenges over the different disposal stages posed by postconsumer automotive plastics (54 pages);

Material Selection Processes in the Automotive Industry (UMTRI Report #90-40-5), by David J. Andrea and Wesley R. Brown, an overview of the factors and issues in vehicle manufacturers' material selection decisions (34 pages);

Automotive Plastics Chain: Some Issues and Challenges (UMTRI Report #90-40-6), by Michael S. Flynn and Brett C. Smith, a report of the OSAT survey of the automotive plastics industry (27 pages), plus appendix on types of automotive plastics.

These reports are all available from:

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**Executive Summary:
Recycling Automotive Plastics**

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The Recycling Automotive Plastics project provides an overview and analysis of the resource conservation problems and opportunities involved in the automotive use of plastics and composites, and describes the factors that are likely to influence their future. The project produced a series of six reports targeted to different aspects of the recycling challenges posed by automotive plastics. Combined with the technically oriented reports of the Vehicle Recycling Partnership, these reports should serve two purposes. First, they can serve as a broad introduction to the diverse and numerous dimensions of the recycling challenge for automotive managers whose areas of responsibility only indirectly or peripherally touch on recycling. Second, they can provide specialists with a broad panoply of contextual information, anchoring their detailed knowledge within the broad framework of recycling issues.

Automotive plastics possess numerous advantages for the automotive manufacturer and consumer. They contribute to lower vehicle weight, important for fuel conservation and emission reduction, while permitting the additional weight of new safety equipment. Plastics and composites are corrosion resistant, so their use can prolong vehicle life, and they are an important element in the paints used to protect other materials. They offer the designer greater flexibility, reducing the constraints that other materials often impose on shapes and packaging. If the difficulties of recycling automotive plastics present a potential barrier to their use, their advantages suggest that the barrier should be overcome, rather than deterring their continued automotive applications.

However, automotive plastics are visible and easily tied to the vehicle manufacturers. Hence, they may become targets for public opinion and government action out of proportion to their real role in solid waste disposal issues and potential for economic recycling.

I. The first report (Life Cycle Assessment: Issues for the Automotive Plastics Industry, UMTRI Report #90-40-1, by Brett C. Smith and Michael S. Flynn) provides an overview of the developing Life Cycle Assessment (LCA) approach and its implications for automotive plastics. An element of the emerging “design for the environment” method, LCA calls for an inventory,

impact assessment, and improvement analysis targeted to the environmental consequences of a product across its production, use, and retirement. While environmental costs are typically unavailable, LCA supports the inclusion and consideration of any such costs that can be estimated, particularly for some of the environmental factors often ignored in traditional product decisions.

A fully developed LCA for vehicles or even components presents numerous significant analytic challenges to the industry, and may never become practical. First, a full LCA would be extremely costly, and the human and financial resources it would consume may be simply unavailable. Second, the handling of the data in an LCA can critically determine its outcome. The data for factors in an LCA are often lacking, typically measured in different metrics, subject to variable weightings, and frequently aggregated in different, noncomparable ways. Third, LCAs are difficult to evaluate and compare because they often reflect differing assumptions, varying boundaries, and there are no commonly accepted standards for their execution. Finally, the comparison of environmental costs with more traditional cost factors is at best difficult and speculative.

Nevertheless, LCA offers industry a sensitizing tool, useful for ensuring consideration of some environmental effects, and consistent with an industrial ecology approach to resource conservation. Moreover, the LCA approach resonates with some other developments in the automotive industry. Thus the industry is moving to more system-based material decisions, while its accounting system is evolving to a form that would more readily provide input for an LCA. The growing emphasis on cost reduction and waste elimination is also philosophically consistent with LCA goals. The industry has gained experience in other analytic techniques, such as quality function deployment, that have value even if only partially executed.

The automotive industry must shift from a reactive to a proactive approach in the management of its environmental effects. The ability to move quickly and surely to develop environmentally acceptable products and processes will be critical to future success. Establishing environmental credibility will increasingly afford the manufacturers an opportunity to create a positive image and thus a competitive edge in the marketplace. LCA might become an important tool in the development of an environmentally friendly product. However, cost pressures in today's competitive environment will likely make the industry approach environmental issues in a cautious manner.

II. The second report (Economic Issues in the Reuse of Automotive Plastics, UMTRI Report #90-40-2, by Daniel Kaplan) presents a general consideration of the economic barriers and issues posed by recycling automotive plastics. The United States currently recycles roughly 75% of the automobile, although plastics constitute roughly one-third by weight of the landfilled residue. An important question facing the automotive plastics industry is whether a combination of economic and technical developments might occur that would permit plastics to repeat the recycling success story of automotive steel.

Recycling automotive plastics faces two major economic barriers. First, the labor cost to recover the materials in usable form is quite high, making it unlikely that recycled stock can compete with the price of virgin stock. The second is that recyclers cannot rely on a consistent and stable flow of plastic scrap, as retired automobiles vary greatly in the level and type of plastic content. This makes it difficult, if not impossible, to establish end markets. Other economic barriers to successful recycling include the costs of transportation and recovery.

There are nonrecycling options for automotive plastics disposal. The landfill option still exists, although current trends suggest that it may soon become expensive enough to promote the use of other options, such as pyrolysis. Incineration permits energy recovery, but faces some of the same undesirable side-effects as landfills.

Pressure for recycling may raise the likelihood of policy interventions, as the government tries to avert the negative consequences of automotive plastics content, such as landfilling, while preserving its benefits, such as reduced fuel consumption and vehicle emissions. Government efforts will likely focus on attempts to capture the environmental externalities in the price of materials. However, recycling may have an economic down side: at least some automotive plastics, if fully recycled, could damage the viability of both recyclers and resin producers by creating an oversupply of material.

The numerous policy tools that might be invoked by government have a predictably wide range of consequences, and these must be incorporated into a cost-benefit analysis before appropriate selections can be implemented. In any case, the industry must be prepared to respond to a wide range of possible policy developments that will shape the economic viability of recycling.

III. The third report (Recycling the Automobile: A Legislative and Regulatory Preview, UMTRI Report #90-40-3, by Suzanne M. Cole) describes the likely developments on the federal regulatory and legislative front that will influence the future of automotive plastics use and disposition. Public policy often tries to incorporate social and environmental costs in the price of goods so that markets can achieve efficient use of energy and resources. The U.S. government has typically relied on regulatory actions to achieve this aim, but may now be moving more in the direction of market-based incentives. Moreover, many key legislators are persuaded that the model of extended producer responsibility, popular in Europe, offers a mechanism for encouraging producers to heed environmental costs in the design of their products. Legislation requiring producers to “take back” their products at the end of the life cycle make them ultimately responsible for its final disposition.

The new administration appears to be committed to a course of emphasizing environmental goals within a framework that permits rational trade-offs with the need for economic growth and development. Increased government R&D spending, much of it in cooperation with private industry, provides a foundation for the search for technical solutions to environmental problems. The Clean Car program is a major example of how this approach may affect the automotive industry.

EPA appears to lack the anti-business rhetoric that many feared, and is shifting to more of a pollution prevention approach rather than a pollution clean-up response. In addition, the director now has a credible staff in place. In spite of the fears of many, Nafta is unlikely to have major adverse environmental consequences for the United States, and may actually improve Mexico’s capability to enforce its fairly stringent regulatory regime.

The give and take of politics will certainly determine exactly how the balance of environmental and economic considerations will be achieved in numerous specific decisions, from take back through recycled content legislation to the permit processes governing both new and old facilities.

IV. The fourth report (Postconsumer Disposition of the Automobile, UMTRI Report #90-40-4, by T. David Gillespie, Daniel Kaplan, and Michael S. Flynn) reviews the issues and challenges that postconsumer automotive plastics pose over the different disposal stages. The United States currently has an economically viable vehicle recycling industry, composed of dismantlers, shredders, and resin producers. Increased automotive plastics content and requirements for its recycling present enormous challenges to this industry. Developing

appropriate markets for recycled stock is a critical challenge. Mandated, rather than market-led, recycling could threaten the very existence of this recycling industry and doom recycling efforts.

Shrinking landfill capacity and rising prices threaten the recycling industry, which must dispose of superfluous material. Increased nonrecyclable plastic content threatens profits, as it often replaces material that can be sold and increases the volume of residual material for landfilling. For plastics to be profitable, the labor costs associated with recovery must be lowered and/or the price of recovered materials rise. Development of automated sorting, chemical and physical technologies for reduction, and pyrolysis all offer some hope, but the public opinion environment and automotive industry demands may force the pace of recycling beyond the infrastructure's capacity.

There are steps the industry can take to facilitate higher recycling rates for automotive plastics. First, plastic components and parts can be designed for easy disassembly and dismantling. Second, plastics can be clearly and consistently labeled, to avoid contamination in the recycle stock. Third, designers can try to limit the numbers and types of incompatible plastics in the vehicle and within any part or component. Fourth, further development of incineration and energy recycling could well support resource conservation, and ultimately higher reuse of nonplastic automotive materials. Fifth, techniques for recycling commingled plastics merit support.

V. The fifth paper (Material Selection Processes in the Automotive Industry, UMTRI Report #90-40-5), by David J. Andrea and Wesley R. Brown) discusses the factors and issues in vehicle manufacturers' material selection decisions. Material selection in the automobile industry is an artful balance between market, societal, and corporate demands, and is made during a complex and lengthy product development process.

Actual selection of a particular material for a specific application is primarily driven by the trade-off between the material's cost (purchase price and processing costs) and its performance attributes (such as strength and durability, surface finish properties, and flexibility.) This paper describes some thirty criteria used in material selection today. How critical any one attribute is depends upon the desired performance objective. The interrelationships among objectives, such as fuel economy, recyclability, and economics, are sufficiently tight that the materials engineer must always simultaneously balance different needs, and try to optimize decisions at the level of the entire system.

The vehicle manufacturers' materials engineer and component-release engineer play the pivotal role in screening, developing, validating, and promoting new materials, although initial consideration of possible material changes may be sparked by numerous players. These selection decisions are made within a material selection process that will continue to evolve. This evolution will largely reflect changes in the vehicle and component development processes to make them more responsive—in terms of accuracy, time, and cost—to market and regulatory demands. The balancing of market, societal, and corporate demands will continue to determine specific automotive material usage in the future.

VI. The sixth paper (Automotive Plastics Chain: Some Issues and Challenges, UMTRI Report #90-40-6), by Michael S. Flynn and Brett C. Smith) is a report of the OSAT survey of the automotive plastics industry (vehicle manufacturers, molders, and resin producers). This survey collected the industry's views on recycling, often contrasted with more general automotive industry views reflected in our Delphi series. This report covers four general topics: recycling and disposition challenges; regulatory challenges and responses; recycling in material selection decisions; and the future of automotive plastics.

The industry in general views a variety of economic, technical, and infrastructural recycling concerns as more important in the case of plastics than of metals. The automotive plastics industry, while perhaps viewing these concerns somewhat differently, sees a complex set of recycling challenges, varying over both the automotive plastics production chain and the stages of recycling/disposition. The manufacturers see these challenges as more severe than do molders or resin producers, and the industry generally views market development and disassembly as more critical stages. The automotive plastics industry generally favors more emphasis on open-loop recycling and the development of the disassembly infrastructure, while evidencing little support for disposal in landfills.

Government CAFE regulations are important drivers for automotive plastics use. However, government is also moderately committed to recycling. The various levels of government are somewhat likely to establish differing regulations to encourage recycling, but are less likely to impose outright bans on any current plastics/composites. Among the range of governmental incentives for recycling, tax incentives are generally seen as useful, but more restrictive and limited actions are seen as not particularly useful. The automakers are unlikely to restrict the total amount of plastics in the vehicle, although they will probably limit the use of unrecyclable plastics and restrict the number of types of plastics in the vehicle. They are also likely to pass through any recycling requirements to their suppliers, the molders and resin producers.

The recyclability of automotive plastics is not yet a major factor in automotive materials-selection decisions, ranking far below the traditional factors. Recyclability is viewed as, at most, of moderate importance to the customer and the industry. Moreover, there are concerns about the cost of recycling automotive plastics, and very real apprehension that there is little market for them, once recycled. These considerations are likely to drive up the cost of plastics, should they be recycled, and thus further discourage their use.

Our results present a somewhat mixed picture as to the future role of automotive plastics in the North American industry, although in general a promising one. There are clear drivers for their use, including their advantages for design flexibility, and these are likely to be buttressed by more stringent fuel-economy regulations in the future. However, there are concerns about their ultimate disposition when the vehicle is retired. These concerns reflect a different environmental priority, one that the automotive industry does not yet view as a customer demand, nor as a "heavyweight" materials-selection factor.

Our survey suggests that the automotive plastics industry and its vehicle producing customers are aware of and concerned about the environmental challenges that lie ahead. Moreover, they are seeking solutions to these challenges that are environmentally sound and responsive to the demands of vehicle purchasers and users. To be sure, their views are often influenced by their own position in the plastics value chain, and they reveal some tendency to prefer solutions that impose responsibility on other stages in that chain. However, they reject solutions that might relieve their own burden, but are environmentally problematic, such as landfilling.

These papers suggest that the automotive industry's adoption of plastics and composites is moving forward. The pace of adoption is responsible, and the industry treats the environmental effects of its material decisions neither lightly, nor as someone else's problem. However, that pace is cautious, reflecting many uncertainties. These include concerns that the industry may be disproportionately blamed by the public for problems in recycling disposed materials, and apprehensions that the industry may be disproportionately targeted by government to resolve such problems. Since plastics and composites confer a wide variety of benefits, including environmental advantages, the industry may be erring on the side of too much, rather than too little, caution.

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INTRODUCTION

The complexity of an automobile and its manufacturing process presents many difficult challenges and decisions to an automotive manufacturer. Traditionally, environmental factors have not weighed as heavily as other criteria in material selection decisions. However, the balance of environmental and other factors has begun to change, as the industry now faces increasing pressure from government regulations, environmental action groups, and its own internal cost constraints. These changes require a fundamental rethinking of industry's traditional methods of analyzing, allocating, and considering costs.

Life Cycle Assessment (LCA) calls for an inventory, impact assessment, and improvement analysis targeted to the environmental consequences of a product across its production, use, and retirement. While environmental costs are typically unavailable, LCA provides an approach that supports the inclusion and consideration of such costs that can be estimated, particularly for some of the environmental factors often ignored in traditional product decisions. At the very least, it offers industry a sensitizing tool, useful for ensuring the consideration of environmental effects. This paper introduces LCA and discusses some of the issues that it raises for the automotive manufacturers and their suppliers of plastic parts and components.

THE ENVIRONMENTAL CHALLENGE

Government regulation of automotive related environmental issues is rapidly becoming an issue of central importance for the industry. The Clinton administration and several important Democratic congressmen have already indicated that the future will likely see more extensive environmental legislation and regulation affecting the industry.¹ Whether these actions take the form of industry voluntary cooperation or government command and control is still an open question.

¹ Suzanne M. Cole, "The Outlook for Legislation Addressing the Environmental Impact of the U.S. Automotive Industry," (University of Michigan Transportation Research Institute report no. 93-40-3, 1993), 9-12.

A vast array of pending legislative and regulatory activity at the federal level confronts the automotive industry. The industry faces legislative challenges for its current and closed facilities and that could potentially total a \$500 billion bill for hazardous wastes cleanup alone.² It also faces environmental challenges aimed at its present actions, embodied in an expanding Resource Conservation and Recovery Act. Finally, it may well be affected by further environmental challenges in the future, possibly including product take-back legislation.

State governments are also becoming more active on the broad environmental front. In all probability, automobile manufacturers will face not only more stringent federal regulations, but also a set of stricter state laws and regulations. Moreover, the individual states are likely to pursue environmental initiatives that are varied and different, increasing the net burden on the industry. There is also reason to expect that at least some of these state initiatives will be inconsistent, reflecting various priorities, concerns, and pressures in different states. This presents a further threat to the industry. Because of the importance of scale economies, the automotive industry probably cannot manufacture affordable vehicles in quantities small enough to satisfy each state's specific requirements. If there is wide state-to-state variation, the companies may have to meet the full set of requirements at the most severe levels to preserve a national market, or pursue the unpalatable course of dropping out of the market in particular states.

A recent survey of resins manufacturers, molders, and automobile assemblers suggests that state and local governments are likely to ban some types of materials from landfills. Bans of this type could limit the manufacturers' choices of materials, effectively constraining those choices as much as would laws directly targeted to material selection. If such regulations are in fact imposed at the state and local levels, manufacturers will also face the challenge of developing products that meet a varied mix of disposal regulations. While such landfill bans are less likely to target plastics than other materials, these respondents believe that there is a fifty-fifty chance that the federal government will ban some types of automotive plastics. More generally, the industry overwhelmingly expects some requirements for recycling the automobile to emerge within this decade.³

² Jon Lowell, et al "Hazardous Waste: The Auto Industry's \$500 Billion Mess." *Ward's Auto World* 29, no. 7, (Ward's Communications, July 1993), 34.

³ See Michael S. Flynn and Brett C. Smith, "Automotive Plastics Chain: Some Issues and Challenges," (University of Michigan Transportation Research Institute report no. 93-40-6, 1993), 15-16, for further discussion.

California continues to lead in automotive air pollution legislation. The California Air Resources Board has set a requirement that calls for 2 percent of vehicles sold in California in 1998 to emit zero emissions, forcing the industry to develop new, nonpetroleum powerplants. Although this pressure has accelerated research on the technical feasibility of such zero emissions alternatives, major technological barriers remain. Electric vehicles, while perhaps closer to reality, still rely on lead acid batteries. Unfortunately, lead acid batteries of today are only slightly better than those from decades past, and current battery technology limits vehicle range to roughly 100 miles per charge—a charge that may take as long as eight hours to complete. Commercially viable electric vehicles that can secure any notable share of the private market require a major breakthrough in battery technology, an unlikely development in the next five to ten years.

Environmental advocacy groups have become increasingly vocal and influential in recent years. Groups such as the Environmental Defense Fund and Greenpeace may become more important forces in the automotive industry and market. They not only may influence legislation and regulation, but they also may effect changes in consumer sentiment that favor “green” vehicles. The situation faced by the European manufacturers, where the environmentally active Green Party has strong influence upon legislation, is even more daunting. The contribution of automotive plastics to reduce the weight of the vehicle, thus reducing emissions as well as conserving fuel, is an important one. Whether these groups recognize these environmental contributions of plastic or focus on its use of a nonrenewable resource and the challenges it poses to recycling is an open question.

The automotive industry must respond to these legislative and social challenges at a time when it is already experiencing severe financial constraints. The industry must divert funds to develop environmentally sound practices and products that meet emerging governmental and consumer demand—a potentially expensive proposition—while continuing to invest in new products to meet current consumer demand for particular types and styles of vehicles. For the automotive plastics industry, this challenge is compounded by the filtering of these demands through its automotive manufacturing customers, and the additional demands they are likely to impose.

DESIGN FOR THE ENVIRONMENT

Figure 1 illustrates the traditional resource assumptions for consumer-oriented, mass production societies. This system reflects the premise that resources are virtually unlimited and

that waste sinks (whether air, water, or land) are public goods. Many scientists and policy-makers believe that the continued reliance on this ecological model is certainly undesirable and could eventually be catastrophic. Moreover, while recent years have seen the growth of recycling and expanded reuse of materials, some critics suggest that the level of these activities is, in reality, insignificant.⁴



Figure 1 Consumer Product Resource System

Allenby suggests that society has four response options with regard to the environmental challenges, as displayed in table 1. He argues that either of the two extreme options (radical ecology or the continuation of our current practices) will inevitably lead to chaos. The intermediate options (deep ecology and industrial ecology) offer more hope. However, deep ecology, with its preference for low technology solutions, simply cannot sustain our current population levels, and that involves serious adjustment costs, if not the chaos expected under the more extreme solutions. That leaves what he terms “industrial ecology” as the preferred and viable path, largely predicated on the belief that technology has created the ability to attain our current population levels, and only through technology will we be able to sustain those levels. Industrial ecology requires engineers to exercise care and caution, recognizing environmental constraints and guiding technical evolution within its boundaries. The adoption of the design for environment as the standard practice is the major route to achieving this goal.

Design for environment (DFE) is an overall strategy to develop products that are more environmentally acceptable, yet continue to meet customer demands. Design for recycling (DFR), design for disassembly (DFD), and life cycle assessment (LCA) are all important elements of DFE, and each is undergoing further refinement and definition. These three elements are currently in varying stages of adoption in the automotive industry, and are critical if the industry is to develop products that consumers view as environmentally friendly.

⁴ R. Braden Allenby, "Industrial Ecology: The Materials Scientist in an Environmentally Constrained World." *MRS Bulletin*, March 1992, 48-49.

Table 1 Ecological Options, Technical Effects, and Social Costs

Options	Effect on Technology	Costs
Radical Ecology	Return to low technology	Probable unmanaged population crash; economic, cultural, technical chaos
Deep Ecology	Appropriate technology; "low tech" where possible	Probable lower population; substantial adjustments to economic, cultural, technical status quo
Industrial Ecology	Reliance on technical evolution within environmental constraints; develop Design for Environment as standard practice; no bias for low tech unless environmentally preferable	Substantial adjustments to economic, cultural, technical status quo
Continuation of Status Quo	Ad hoc adoption of specific mandate; little effect on overall trendline	Probable unmanaged population crash; economic, cultural, technical chaos

Automobile manufacturers are now actively incorporating strategies to increase the recyclability of their products. Efforts include the development of more easily recyclable materials and their incorporation into the vehicle and its constituent components. Research and development targeted on recycling techniques and processes is also part of the strategy. By recognizing and pursuing the application of DFR practices now, the industry can ensure a stream of recyclable cars in the future.

The ease of component removal and separation is an important factor in the recycling of materials from an automobile.⁵ The goal of DFD is to design the product in ways that will make the disassembly of vehicles more efficient and cost-effective. The effort to design products that disassemble more easily, thus facilitating the separation of components, will make materials recycling less economically constrained. The incorporation of snap-fit designs, rather than using chemical adhesives or metal fasteners subject to corrosion, to join parts is an example of DFD. Such joining is more readily and less expensively reversible at the disassembly stage.

Life cycle assessment constitutes a third major approach supporting vehicle designs that better meet environmental constraints, including recycling. LCA provides a structured approach

⁵ See T. David Gillespie, Daniel Kaplan, and Michael S. Flynn, "Post-Consumer Disposition of the Automobile," (University of Michigan Transportation Research Institute report no. 93-40-4, 1993).

to defining and quantifying all the environmental costs associated with the entire life of a product, by extending the definition of the life cycle beyond the normal boundaries of engineering, manufacturing, and customer use. We now turn our attention to a description and discussion of that approach.

LIFE CYCLE ASSESSMENT⁶

Over the course of the past decade, North American automotive engineers have become familiar with the principles of design for manufacture and/or assembly (DFM/A)—a design approach that emphasizes making a component or part easier to make and/or assemble. Just as the gains from DFM/A are becoming evident and perhaps even commonplace, designers, engineers, and managers must begin to consider the environmental risks and effects associated with their products. The primary mechanism for this is the recognition and inclusion of these factors (as costs, when feasible) in an LCA approach that encompasses the expanded product life cycle. The LCA approach recognizes seven distinct stages of the product's life cycle, as illustrated in Figure 2.⁷

LCA focuses on the environmental effects associated with each stage of the product life cycle and targets the eventual evaluation of environmental costs at every stage. Thus, factors such as energy consumption during processing and distribution, as well as waste streams during material acquisition and manufacturing, are important inputs to the full LCA evaluation. These effects are considered together with the more traditional factors of material, labor, and capital.

The EPA suggests that a proper accounting system for an LCA should include an inventory analysis, with each material and energy input/output identified and quantified. To be sure, this poses serious difficulty when a product or process is itself a complex system that must be reduced to smaller subsystems for analysis. After the subsystems' effects are identified, they must be quantified in a meaningful way, perhaps initially by reporting the levels of released hazardous or dangerous wastes.⁸

⁶ Our discussion draws heavily on Gregory Keoleian and Dan Menerey, "Life Cycle Design Manual: Environmental Requirements and the Product System." The United States Environmental Protection Agency, 1993. The Project Summary is attached as Appendix I.

⁷ Ibid., 13.

⁸ Keoleian and Menerey, *op. cit.*, 102.

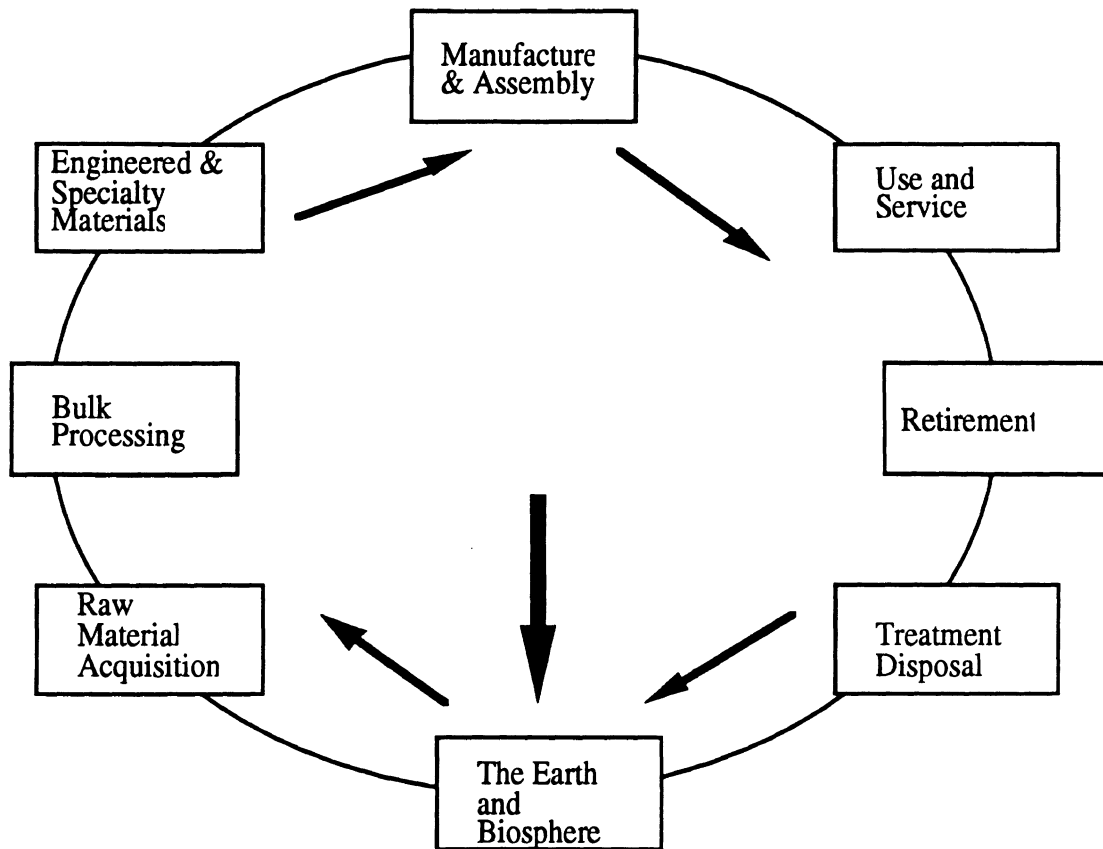


Figure 2 The product life cycle system

A further challenge is the development of standards for the environmental impact of a system, including resource depletion, ecological effect, as well as human health and safety effects.⁹ These areas have received little attention until recently and have traditionally been treated as an externality—costs borne by society rather than by the individuals involved in the transaction.¹⁰ As the number of accepted measurement standards increases, reporting of wastes and externalities will become more complete and useful inputs to material selection and product design decisions.

⁹ Ibid., 108-109.

¹⁰ See Daniel Kaplan, "Economic Issues in the Reuse of Automotive Plastics," (University of Michigan Transportation Research Institute report no. 93-40-2, 1993), 27-34, for a discussion of externalities in the automotive industry.

Each of these seven stages can include thousands of variables and events that affect the final decision. A complete LCA requires quantifying and ranking each potential material with regard to its potential waste streams at each stage—a difficult and challenging, if not impossible, task. However, partial LCAs can yield valuable information, and frequently can improve the overall quality of the design. A partial LCA may focus on a critical subset of components, rather than the entire product, or it may reflect differing levels of precision in measuring the costs included in the analysis. Thus the evaluation of two designs may include precise dollar estimates of the labor costs to manufacture the product, but include only rank-ordered estimates of associated adverse ecological effects.

A significant challenge for industry is the development of a measurement system that will permit the evaluation of environmental costs and their comparison with more traditional cost factors. For a product as complex as an automobile, the challenge is extreme. The complexity of the industry makes such an undertaking a daunting, not to say expensive one. However, the industry cannot wait until all inputs to an LCA are as reliably and accurately measured as more traditional costs, nor until all such measures are convertible to a common scale, such as dollars. Such action would be no more sensible than ignoring market share estimates in traditional product evaluations simply because such estimates are less certain and well grounded than are estimates of labor costs. LCA analysis, for all its limitations and the difficulties it presents, is a useful tool, and its application should improve the overall environmental performance of the vehicle and its component systems.

To be sure, an LCA, even for smaller and simpler products than vehicle parts and components, can be lengthy and expensive, especially when those products include multiple materials. Norsk Hydro, a Norwegian chemical company, recently published a 220 page LCA for polyvinyl chloride.¹¹ To put this in perspective, a North American automobile may contain 20-30 different types of plastic.

Although LCAs have seen some applications to simpler products, no full LCA for an automobile has been undertaken. However, there have been initial attempts to begin a structured LCA for automobiles. Volvo AB is developing a streamlined approach to permit the more affordable application of LCA methodology to the vehicle. Nevertheless, the complexity of even this streamlined process has led Volvo to join with the Federation of Swedish Industries and the Swedish Environmental Research Institute in pursuing this goal. While the group has made

¹¹ Emma Chynoweth and Michael Roberts, "Green Pressures Force PVC to Take LCA Lead in Europe," *Chemical Week*, November 18, 1992, 41.

some progress in summarizing the environmental impact of design choices, several large barriers remain.¹²

In addition to the sheer size of the project, there are other, more fundamental problems in the development of an automotive LCA. Benda, Narayan, and Stickler suggest that generally accepted standards for resolving eight issues or problems must be developed if LCA is to be accepted as a standard design evaluation methodology.¹³ These problems include:

Data limitations Key data may often be unavailable or of questionable reliability.

Varying assumptions These can tilt the LCA outcomes, and often must be arbitrary.

Lack of standards The many LCAs that are beginning to appear must be subject to comparative evaluation against some commonly accepted standard.

Cost LCAs can require substantial human and financial resources, and until costs can be brought down, are unlikely to see wide application.

Lack of common measurement units This makes it difficult to have confidence in the comparison of different factors.

Boundary definitions Defining the system limits for an LCA, whether full or partial, can be extremely difficult, and this decision can determine its ultimate value.

Weighting factors How the evaluator weights the various factors in an LCA is critical to its results, and there is little experience to guide the proper assignment of weights.

Data aggregation How data is combined across factors can influence the resulting estimates of environmental effects.

These authors suggest that until these issues achieve resolution and some broad consensus, it will be difficult to conduct an LCA that yields generally accepted results. Nevertheless, we feel that until LCAs become a more common feature of design decisions, and there is an accumulated experience base in the use of the method, few of these issues will be resolved.

¹² Steven Ashley, "Designing for the Environment," *Mechanical Engineering*, March 1993, 55.

¹³ James Benda, Ramani Narayan, and Jon Sticklen, "Use of Expert Systems for Life Cycle Analysis," Society of Automotive Engineers, Paper 930558.

INDUSTRY PARALLELS TO LCA

If a full LCA for an automobile, or even a partial LCA of a significant component such as an instrument panel poses a daunting challenge, it is useful to recognize that the LCA approach is not completely foreign to the industry's decisional framework and experience. First, the automotive industry increasingly is relying on a systematic approach to materials selection.¹⁴ In the case of the automobile, the positive and negative traditional attributes of individual components and materials are fairly well understood, at least at each of the traditional stages. The industry has also recognized that decision that optimizes performance on one dimension or at one stage frequently suboptimizes performance over all criteria and stages. LCA extends this systems approach to decisions by broadening the system under consideration to include all aspects of the product's environmental risks and effects over an expanded conception of the product life cycle.

Second, LCA presents a major challenge in quantifying costs on each criterion and within each stage, and then developing metrics that permit the comparison of costs across stages. While this calls for a major shift in the traditional accounting system, such shifts are already underway. Pollution and wastes have typically been accounted for at the factory level—grouped into an overhead account, and then applied to all products produced at that plant, making it virtually impossible to allocate these costs to any particular product line. However, activity-based costing (ABC) is gaining acceptance, and this approach makes it possible to track more finely pollution and waste costs, as well as important traditional cost factors.

Third, LCA is not offered as some environmental panacea that demands elimination of all waste, effectively condemning any design as bad, because all products result in waste to the same degree, such as energy expenditures and generation of scrap materials. Rather, LCA is firmly embedded in the industrial-ecology worldview, and recognizes that all products pose environmental risks and detrimental effects and that careful analysis is necessary to make the appropriate trade-offs and balance the outcomes of our decisions. LCA's goal is the classification of the environmental costs of designs to support the selection of those designs that minimize waste.¹⁵ This is consistent with the cost reduction and waste elimination efforts of the industry that have been focused within the more traditional and restrictive life cycle stages and encompassing the more traditional cost factors.

¹⁴ David J. Andrea and Wesley Brown, "Material Selection Processes in the Automotive Industry," (University of Michigan Transportation Research Institute report no. 93-40-5, 1993).

¹⁵ "ECN Environmental Technology--Life Cycle Analysis: Dispelling the Myth." *European Chemical News*, February 15, 1993, 18.

Fourth, LCA is similar in some ways to quality function deployment (QFD). QFD faces all of the eight problems discussed above, and few full QFDs have been performed on complex products. QFD also relies on speculative data, wrestles with noncomparable measurements, and often requires extensive resources. Yet it has proved a valuable design tool, and its application has often improved the quality of specific designs as it provides a method of assuring that the desires of the customer are translated into the design criteria of the engineer. An LCA can also provide input to a QFD. Environmental quality characteristics can be added to the QFD house of quality, treating the environment as the final customer. Extending the definition of quality beyond the product to include the environmental impact of the product and processes inevitably leads to a better product. However, just as quality cannot be added to a car after developing it, environmental quality cannot be added after the design. Environmental quality must be designed-in from the outset.¹⁶

Fifth, the North American automotive industry has adopted a cross functional team (CFT) approach to developing new products. Teaming the many functions within a company early in the process, before costly capital and labor decisions are made, makes problems easier and less expensive to resolve. An LCA expands the use of CFTs, using members from all stages of the product life cycle to better define the challenge.

As with any new process, one of the more important conditions for the success of an LCA is the support and acceptance of management. Without the complete support of management, the results of an LCA may be questioned, resisted, and ultimately ignored, and the entire approach could fall into disfavor and disuse.

Ford Motor Company provides an interesting example of how the drivers and concerns of LCA integrate into the strategic objectives of an automotive manufacturer, and results in management support for the development of new approaches and tools to better measure environmental quality. Ford has identified five strategic imperatives for achieving the quality, safety, performance, and value that ensure success in the market. These five imperatives are displayed in table 2. The integration of these imperatives with environmental concerns suggests the industry's growing recognition of the importance of tying business strategy to environmental issues.¹⁷

¹⁶ See Gillespie, Kaplan, and Flynn, *op. cit.*, for a discussion of the importance of design to one environmental outcome, recycling of automotive plastics.

¹⁷ H. O. Petraskas, "Manufacturing and the Environment: Implementing Quality Environmental Management at Ford Motor Company" The University of Michigan Manufacturing Forum, November 20, 1992, (Speech).

Table 2 Strategic imperatives and environmental issues: Ford Motor Company

Customer satisfaction	The customer is becoming more environmentally conscious. The ability to exceed customers' expectations with respect to quality, safety, performance, and value will always be requirements. Environmentally friendly products will give the company an advantage.
World class timing	Anticipate new environmental requirements and plan for these early in the process. Achieving compliance with environmental regulations will be a critical timing element.
Investment efficiency	Pollution prevention can be less expensive than pollution control. The company must efficiently invest, early in the development stages, in products and processes that prevent, rather than control pollution
Organization structure	Management must empower cross-functional teams to integrate environmentally responsive decisions into the products and processes.
Supply base structure	Rely on suppliers to develop processes and products that are world class, and also environmentally responsive.

LIFE CYCLE STAGES FOR THE AUTOMOBILE

Each stage of an automobile's life is a direct concern for the automotive industry. Even though the industry has moved away from the massive vertical integration of the early years (an era best typified by the massive Ford Motor Company's River Rouge facility), the assemblers and their suppliers must still accept the environmental burden for the materials and manufacturing processes that yield their product, the energy used during the vehicle's useful life, and the final disposition of the vehicle.

Considering the automobile across the seven stages of the product life cycle adds interesting insight to the EPA flow chart, displayed above in figure 2. An industry as complex as the manufacture of automobiles leads to many tradeoffs, and, not surprisingly, the present decision process often leads to less than optimal environmental solutions.

Raw material acquisition The acquisition of raw material for the automotive industry is a major source of external wastes and are usually not included in industry decisions. These wastes are frequently overlooked, perhaps because the mining activity is so far removed, both geographically and psychologically, from the automobile manufacturing process. Consider the mining of iron ore to make steel. Environmental costs such as the damage done to the earth from

the mining, the energy used to mine, the pollution in surrounding water supplies caused by the runoff, and the energy used in transporting the ore are simply not considered. Such costs enter automotive decisions only to the extent that they are appropriately reflected in the price of steel. While steel is viewed as an inexpensive material at the manufacturing stage, the traditional financial accounting system may not accurately reflect these several environmental costs. The ability to measure these wastes properly and include them in the total cost of the material is critical to a comprehensive LCA.

Bulk Processing Bulk Processing, similar to raw material acquisition, is far enough upstream from the manufacturing process that the wastes associated with it are sometimes overlooked. Making aluminum from bauxite is an example of bulk processing. The realistic measurement of the energy used to make the transformation is critical in measuring environmental costs. The transformation of bauxite to aluminum is energy (i.e., electricity) intensive. While the price of the electricity captures some of this cost, local electric companies subsidize many aluminum conversion facilities. Although aluminum is attractive for its fuel saving capabilities, the present system may not permit all of its environmental costs to be appropriately considered in a material selection decision.

Engineered specialty materials Automotive plastics provide many examples of the transformation of raw materials into engineered material. The development of thermosets and engineered plastics has proven to be an asset to the automotive industry. These materials offer the industry low weight and flexibility, yet the complexity of the chemical reactions needed to manufacture the materials increases the challenge of recycling these polymers.¹⁸

Manufacture and assembly This stage is traditionally the focal decision point for the automotive industry. Over the decades, the industry has developed favored materials and processes. Decisions, traditionally based on cost, focused mainly on factors that affected manufacturing, assembly and the next stage—the use of the vehicle. The traditional materials and processes are now undergoing reexamination. Manufacturing processes deemed appropriate for decades are now understood to cause potential significant wastes. The industry must now pay for the damage caused by practices that at the time were not considered negligent.¹⁹

¹⁸ See Gillespie, Kaplan, and Flynn, op. cit..

¹⁹ Stephen Plumb, "A Field of Dreams Turns into a Field of Waste," *Ward's Auto World* 29, no. 7, Ward's Communications, July 1993, 34

Use and service Like manufacturing, this stage has been an important and emphasized part of the traditional business analysis of the product life cycle. Recently this stage has gained an even more prominent role in the decision process. As pressure to increase fuel economy has grown, a greater emphasis has been given to lightweight materials. Plastics have excelled as lightweight materials. Yet the increase in plastics has, to a certain extent, shifted the waste stream from the useful life of the vehicle (through reduced gasoline consumption) to the retirement stage (landfilling or incineration of plastics).

Retirement The retirement of a vehicle raised a major solid waste disposal issue in the 1960s, but with the development of minimills it became less critical. Nearly all automobiles are recycled through an efficient and profitable infrastructure of dismantlers and shredders. However, this recycling infrastructure is now under threat, as the increased use of plastics and the increased costs—both financial and social—of landfilling automotive residue make the basic economics of vehicle recycling less attractive.²⁰

Treatment and disposal The last stage in an automobile's life cycle is the final disposal of the materials, including the materials that are returned to the earth and biosphere. Landfilled materials and residue from pyrolysis and heat recovery represent typical ends of the automotive materials life cycle. Numerous costs occur at this stage that traditionally have been treated as externalities in automotive industry decisions.

The task of defining the environmental costs of a single material on a single component through the life cycle is a lengthy and laborious venture. If the entire range of alternative materials is included in the analysis, the venture is potentially overwhelming. Even so, it is becoming increasingly critical for product development teams to begin incorporating the environmental impacts of materials in their selection criteria.

²⁰ See Gillespie, Kaplan, and Flynn, *op. cit.*

SUMMARY

The automotive industry must shift from a reactive to a proactive approach in the management of its environmental effects. The ability to move quickly and surely to develop environmentally acceptable products and processes will be critical to future success. Establishing environmental credibility will increasingly afford the manufacturers an opportunity to create a positive image and thus a competitive edge in the marketplace.

Design for the environment is a developing strategy that encompasses a broad range of actions. Each of these actions, perhaps especially LCA, will be a critical tool in the development of an environmentally friendly product. However, cost pressures in today's competitive environment will likely make the industry approach environmental issues in a cautious manner.

Appendix I

Project Summary

“Life Cycle Design Manual: Environmental Requirements and the Product System.”

Gregory Keoleian and Dan Menerey

The United States Environmental Protection Agency, 1993



Project Summary

Life Cycle Design Manual: Environmental Requirements and the Product System

Gregory A. Keoleian and Dan Menerey

The U.S. Environmental Protection Agency's (EPA) Risk Reduction Engineering Laboratory and the University of Michigan are cooperating in a project to reduce environmental impacts and health risks through product system design. The resulting framework for life cycle design is presented in *Life Cycle Design Manual: Environmental Requirements and the Product System*. Environmental requirements in life cycle design are chosen to minimize aggregate resource depletion, energy use, waste generation, and deleterious human and ecosystem health effects.

The manual adopts a systems-oriented approach based on the product life cycle. A product life cycle includes raw materials acquisition, bulk and engineered materials processing, manufacturing/assembly, use/service, retirement, and disposal. Design activities address the product system, which includes product, process, distribution, and management/information components.

Integrating environmental requirements into the earliest stages of design is a fundamental tenet of life cycle design. Concepts such as concurrent design, total quality management, cross-disciplinary teams, and total cost assessment are also essential elements of the framework. A multilayer requirements matrix is proposed to balance environmental, performance, cost, cultural, and legal requirements. The following design strategies for pollution prevention and resource conservation are presented: product life extension, material life extension, material selection, reduced material intensiveness, process

management, efficient distribution, and improved business management (which includes information provision). Environmental analysis tools for developing requirements and evaluating design alternatives are outlined.

This Project Summary was developed by the University of Michigan for the EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Overview

The purpose of the *Life Cycle Design Project* is to promote environmental impact and risk reduction through design. This project complements the EPA's *Life Cycle Assessment Project* which is developing guidelines for life cycle inventory analysis. The framework developed in this project guides designers to reduce aggregate impacts associated with their products. Successful low-impact designs must also satisfy performance, cost, cultural, and legal criteria.

Investigation of the design literature and interviews with 40 design professionals contributed to the development of a basic framework for life cycle design. The interviews were conducted to identify barriers and the information and tools needed to achieve environmental objectives. Life Cycle Design Demonstration Projects are being conducted with AT&T Bell Labs and Allied Signal to test the design framework.

A summary of the seven chapters contained in *Life Cycle Design Manual: Environ-*

mental Requirements and the Product System follows.

Chapter 1. Introduction

Most environmental impacts result from design decisions made long before manufacture or use. Yet environmental criteria often are not considered at the beginning of design when it is easiest to avoid impacts. As a result, many companies channel resources into fixing problems rather than preventing them.

In the past 15 yr, companies began to focus more on pollution prevention and resource conservation. Innovative firms are now adopting ambitious environmental policies in response to changing public perceptions. But translating these policies into successful action is a major challenge. Without proper support, environmental design programs may be launched without specific objectives, definitions, or principles.

Such practices demonstrate the need for a design framework that helps reduce total environmental impacts while satisfying other criteria. When design considers all stages of the life cycle from raw material acquisition to final disposal of residuals, the full consequences of product development can be understood and acted on.

Purpose

The manual seeks to:

- 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
- integrate environmental, performance, cost, cultural, and legal requirements in effective designs

Scope

Environmental requirements for product design are the main focus of the manual. In life cycle design, products are defined as systems that include the following components: product, process, distribution network (packaging and transportation), and management (including information provision). Life cycle design can be applied to:

- *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.

Audience

Each participant in product system development has an important role to play in achieving impact reduction. The manual is primarily targeted for the following decision makers:

- product designers
- industrial designers
- process design engineers
- packaging designers
- product development managers
- staff and managers in: accounting, marketing, distribution, corporate strategy, environmental health and safety, law, purchasing, and service

Chapter 2. Life Cycle Design Basics

Several key elements form the foundation of life cycle design. First, design takes a systems approach based on the life cycle framework. Every activity related to making and using products is included in design. As a result, the product is combined with processing, distribution, and management to form a single system for design. When the full consequences of development are identified, environmental goals can be better targeted.

The Life Cycle 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 this type of product life cycle.

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. By taking a systems approach, life cycle design seeks to avoid the cross-media transfer of pollutants or the shifting of impacts from one life cycle stage to another.

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 which accumulate in the earth and biosphere.

Product System Components

Life cycle design addresses the entire product system, not just isolated components. This is the most logical way to reduce total environmental impacts. The product system can be decomposed into four primary components:

- product
- process
- distribution network
- management

The *product* component consists of all materials in the final product and includes all forms of these materials from acquisition to their ultimate fate. *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.

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
- maintain long-term, viable economic systems

Resource conservation, pollution prevention, and the equitable distribution of resources and risks are essential to preserve the sustainable ecosystems that comprise the planet's life support system. For this reason, product systems must be developed that balance human resources, natural resources, and capital while preserving healthy ecosystems.

Chapter 3. The Development Process

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

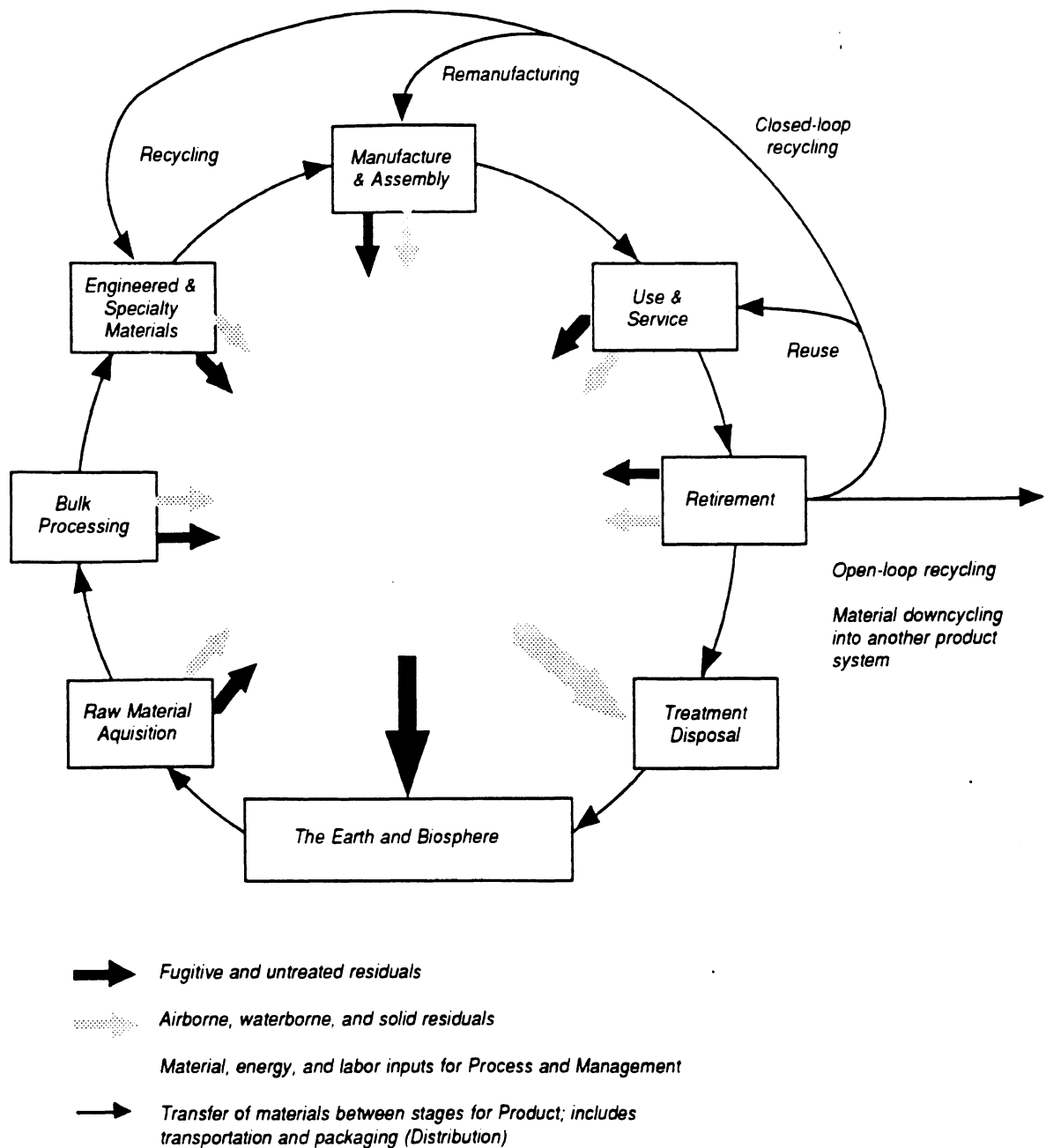


Figure 1. The product life cycle system.

back on others. This emphasizes the continual search for improved products.

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

Management exerts a major influence on all phases of development. Both concurrent design and total quality management provide models for life cycle design. In addition, appropriate corporate policy, strategic planning, and measures of success are needed to support design projects.

Research and development discovers new approaches for reducing environmental impacts. The state of the environment provides a context for design. 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 formulating requirements, conceptual design, preliminary design, detailed design, and implementation. During the needs analysis, the purpose and scope of the project are defined, and customers are clearly identified.

Needs are then expanded into a full set of design criteria that includes environmental requirements. Successful designs balance environmental, performance, cost, cultural, and legal requirements. Design alternatives are proposed to meet these requirements. The development team continuously evaluates alternatives throughout design. If studies show that requirements cannot be met or reasonably modified, the project should end.

Finally, designs are implemented after final approval and closure by the development team.

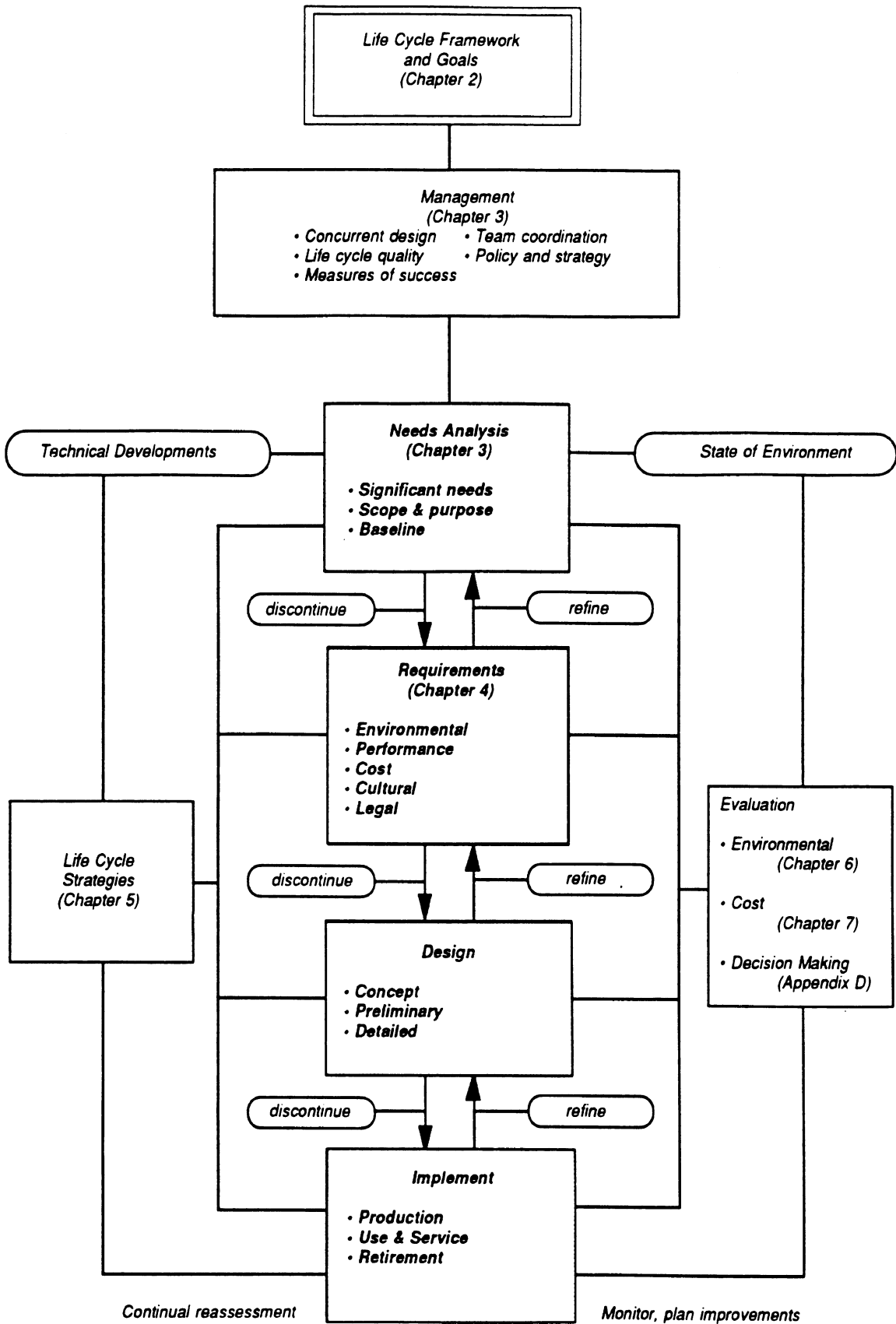


Figure 2. Life cycle design process.

Management

Commitment from all levels of management is a vital part of life cycle design. 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 in 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. Appropriate measures of success are necessary to motivate individuals within development teams to pursue environmental impact and health risk reductions.

Concurrent Design

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. 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.

Life Cycle Quality

Environmental aspects are closely linked with quality in life cycle design. Companies who look beyond quick profits to focus on customers, multidisciplinary teamwork, and cooperation with suppliers provide a model for life cycle design. The life cycle framework expands these horizons to include societal and environmental needs. Life cycle design may thus build on total quality management, or be incorporated in a TQM program. In life cycle design, the environment is also seen as a customer. Pollution and other impacts are quality defects that must be reduced. Ultimate success depends on preserving environmental quality while satisfying traditional customers and employees.

Team Building

Life cycle design depends on cross-disciplinary teams. These teams may include any of the following life cycle participants: accounting, advertising, community, customers, distribution/packaging, environmental resources staff, government regulators/standards setting organizations, industrial designers, lawyers, management, marketing/sales, process designers and engineers, procurement/purchasing, production workers, research and development staff, and service personnel. Effectively coordinating these teams and balancing the diverse interests of all participants presents a significant challenge.

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.

Once significant 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 the next generation model, or developing a new product.

In choosing an appropriate system boundary for design, the development team must initially consider the full life cycle. More restricted system boundaries must be properly justified. 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 environmental impact reduction.

Narrowly bounded systems may provide useful results, but the limitations must be recognized and clearly stated. Stages 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.

Comparative analysis, also referred to as benchmarking, is necessary to demonstrate that a new design or modification is an improvement over competitive or alternative designs.

Requirements

Requirements define the expected design outcome. Design alternatives are evaluated on how well they meet requirements. Whenever possible, requirements should be stated explicitly to help the design team translate needs into effective designs.

Successful development teams place requirements before design. Rushing into design before objectives are defined often results in failed products.

Design Phases

The following phases of development are not significantly altered by life cycle design: 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.

Limitations

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. It can be difficult for one party to take actions that mainly benefit others.

Chapter 4. Requirements

Formulating requirements is one of the most critical activities in life cycle design. A well-conceived set of requirements translates project objectives into a defined solution space for design.

In life cycle design, environmental functions are critical to overall system quality. For this reason, environmental requirements should be developed at the same time as performance, cost, cultural, and legal criteria. All requirements must be balanced in successful designs. A product that fails in the marketplace benefits no one.

Key Elements

Requirements define products in terms of functions, attributes, and constraints. *Functions* describe what a successful design does. Functions should state *what* a design does, not how it is accomplished. *Attributes* are further details that provide useful description 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 indicates that the design is ambiguous.

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

Use of Requirements Matrix

A multilayer requirements matrix provides a systematic tool for formulating a thorough set of environmental, performance, cost, cultural, and legal requirements. A schematic of this multilayer matrix is shown in Figure 3.

A practical matrix should be formed by further subdividing the rows and columns of this conceptual matrix. Matrices allow product development teams to carefully study the interdependencies and interactions between life cycle requirements. They also provide a convenient tool for identifying conflicts between requirements and clarifying trade-offs that must

be made. Issues that can assist designers in defining environmental requirements are introduced in the manual.

Ranking and Weighing Requirements

Ranking and weighing requirements 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 *must* requirements.
- *Want* requirements are desirable traits used to select best alternatives from proposed solutions that meet *must* requirements. *Want* requirements help designers seek the best solution, not just the first alternative that satisfies mandatory conditions. These criteria can play a critical role in customer acceptance and perceptions of quality.
- *Ancillary* functions are low ranked in terms of relative importance and can therefore be relegated to a wish list. Designers should be aware 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.

Chapter 5. 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. Strategies flow from requirements, not the reverse.

A successful strategy satisfies the entire set of design requirements, thus promoting integration of environmental requirements into design. No strategy is exclusive. Most development projects should adopt a range of strategies to satisfy requirements. For this reason, no single strategy should be expected to satisfy all project requirements.

The following strategies are outlined in the manual:

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

Chapter 6. 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.

Environmental assessments are based on the following two components:

- Inventory analysis
- Impact analysis

An inventory analysis identifies and quantifies all inputs and outputs for a product system. Information about material and energy inputs and waste (residual) outputs for every significant step included in the system under study are compiled during 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.

Scope of the Analysis

A full 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 use. 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 perfor-

mance. Spatial boundaries should also be noted because the same activity can have radically different effects in different locations.

Inventory Analysis

The inventory analysis should be conducted to satisfy requirements of the impact analysis. Two main tasks are involved in an inventory analysis:

- Identifying material and energy input and output streams and their constituents
- Quantifying these inputs and outputs

Allocation problems can occur in processes with multiple useful outputs. Proportioning impacts according to the total weight of the main product relative to the coproducts is a commonly used allocation method.

The EPA publication, *Life Cycle Assessment: Inventory Guidelines and Principles* (EPA/600/R-92/036) provides more detailed instructions for conducting an inventory assessment.

Impact Assessment

The final result of an impact analysis is an environmental profile of the product system. The translation of inventory data into environmental effects or impacts is achieved through a wide range of impact assessment models, including hazard and risk assessments models.

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. Decisions should be based on the best available data and methods of assessment.

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:

- ecological degradation from habitat disruption (e.g., physical disruption from the mining)
- a reduction in the global resource base that affects sustainability

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

	Raw Material Acquisition	Bulk Processing	Engineered Materials Processing	Assembly & Manufacturing	Use & Service	Retirement	Treatment & Disposal
Product • Inputs • Outputs							
Process • Inputs • Outputs							
Distribution • Inputs • Outputs							
Management • Inputs • Outputs							

Figure 3. Conceptual requirements matrix.

well as the ecosystem potentially impacted. 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 (introduction of an exotic species) agents.

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.

Chapter 7. Life Cycle Accounting

Traditional accounting practices need to be modified to more fully reflect the total costs of pollution and resource depletion. Improved accounting practices can be a key element in facilitating life cycle design. Accounting methods outlined in this chapter are based on the total cost assessment model.

At present, most cost systems used in business are based on financial accounting. Because these systems are designed to serve reporting rather than management functions, environmental costs are usually gathered on the facility level. These costs are added to overhead and then assigned to specific products for management purposes. Allocation methods vary in accuracy, but future advances may allow gathering of much more accurate product-specific costs.

Life cycle design benefits 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. 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.

Usual Costs

Life cycle accounting first identifies traditional capital and operating expenses and revenues for product systems. Many low-impact designs offer benefits when evaluated solely by usual costs. Such cost savings can be achieved through material and energy conservation, elimination or reduction of pollution control equipment, nonhazardous and hazardous waste disposal costs, and labor costs.

Hidden Costs

Hidden costs consist mainly of regulatory costs associated with product system development. Many hidden costs incurred by a company are gathered for entire facilities and assigned to overhead.

Hidden regulatory costs include the following (this is only a partial list):

Capital costs

- monitoring equipment
- preparedness and protective equipment
- additional technology

Expenses

- notification
- reporting
- monitoring/testing
- record keeping
- planning/studies/modeling

- training
- inspections
- manifesting
- labeling
- preparedness and protective equipment
- closure/post closure care
- medical surveillance
- insurance/special taxes

Liability Costs

Liability costs include fines due to noncompliance and future liabilities for remedial action, personal injury, and property damage. Avoiding liability through design is the wisest course. Because estimating potential environmental liability costs is difficult, these costs are often understated.

Less Tangible Costs

Many less tangible costs and benefits may be related to usual costs, hidden regulatory costs, and liabilities. Estimating intangibles such as corporate image or worker morale is difficult, as is projecting improvements in market share or benefits derived from improved customer loyalty.

Limitations

The main difficulties in life cycle accounting arise in estimating costs for many nontraditional items and properly allocating those costs to specific products/processes. Liability and less tangible costs are the most difficult to estimate.

Some low-impact designs have probably not been implemented because life cycle costs were not accurately calculated.

Externalities (costs borne by society rather than the responsible parties) also present problems. These costs are beyond the scope of accounting at present. As long as costs for pollution, resource depletion, and other exter-

nalities do not accrue to firms, accounting systems will not reflect these costs, and life cycle accounting will remain incomplete.

The full report was submitted in fulfillment of Cooperative Agreement No. 817570 by

the University of Michigan under the sponsorship of the U.S. Environmental Protection Agency.

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The complete report, entitled "Life Cycle Design Manual: Environmental Requirements and the Product System" (Order No. PB93-164507AS; Cost: \$27.00, subject to change) will be available from:

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