Selected Reading Materials

- **Braden R. Allenby:**
  "Achieving Sustainable Development Through Industrial Ecology." *International Environmental Affairs* 4, no. 1 (1992): 56–68.

- **Robert U. Ayres:**
  "Industrial Metabolism: Theory and Policy." In *The Greening of Industrial Ecosystems,* edited by Braden R. Allenby and Deanna J. Richards, 23–37. Washington: National Academy Press, 1994.

- **Robert A. Frosch:**
  "Industrial Ecology: A Philosophical Introduction." *Proceedings of the National Academy of Sciences, USA* 89 (February 1992): 800–803.

- **Greg Keoleian and Dan Menerey:**
  "Sustainable Development by Design: Review of Life Cycle Design and Related Approaches." *Air and Waste* (Journal of the Air and Waste Management Association) 44 (May 1994): 645–668.

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COMMENTARY

Achieving Sustainable Development through Industrial Ecology

BRADEN R. ALLENBY

Introduction

It has become apparent to thoughtful observers that current economic, population, and associated cultural patterns are not sustainable; that is, they cannot be continued indefinitely as they are. Abundant data support this point.[1] The logical question is then obvious: what now?

The concept of "sustainable development," first developed in a study by the World Commission on Environment and Development (the Brundtland Report), is the response.[2] The concept, however, remains somewhat vague and ill-defined. In part, of course, this is simply a reflection of the nascent state of the dialogue on sustainable development. In part it is because the concept of sustainable development is, to several established disciplines and political authorities, somewhat revolutionary and thus subject to misunderstanding.

In large part, however, it results from the human desire to define an end state—"sustainable development"—and then to determine how to get there. Sustainable development, however, is not an end state; indeed, complex systems such as the global economic system and human cultures don't reach static end states (although they may indeed end). Rather, sustainable development will be a dynamic, continuous process; a verb, not a noun. It cannot, therefore, be defined absolutely as a thing in itself, but must be defined in terms of the process by which it is achieved and promulgated, and the principles that inform that process.

Those principles and that process constitute industrial ecology.

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What is Industrial Ecology?[3]

Somewhat teleologically, "industrial ecology" may be defined as the means by which a state of sustainable development is approached and maintained. It consists of a systems view of human economic activity and its interrelationship with fundamental biological, chemical, and physical systems with the goal of establishing and maintaining the human species at levels that can be sustained indefinitely—given continued economic, cultural, and technological evolution.[4]

It is perhaps useful in clarifying this somewhat oxymoronic term to resort to a biological analogy. Use of biological analogies is always tricky; nonetheless in this case I believe they advance understanding (at the inevitable cost of oversimplifying the biology).

Classic ecology has been defined as "the study of the relation of organisms or groups of organisms to their environment . . . the science of the interrelations between living organisms and their environment . . . the study of the structure and function of nature."[5] It is a discipline that studies quintessentially complex biological systems. It is the focus on interrelationships and complex systems, in particular, that makes this biological analogy so suggestive, since it is the failure to focus on the interrelationships between human activity and fundamental global support systems that creates many of the current environmental perturbations.

In developing this idea further, consider a postulated primitive biological system, where the biological component is a small subsystem compared to its supporting environmental systems.[6] Under such circumstances, a quasi-linear biology might well be appropriate, perhaps even more efficient from the organisms' perspective. In such a protosystem, which I will term a "Type I" system, resources and sinks are for all practical purposes unlimited.[7] Accordingly, the flows of materials from "resource" through "organism" to "waste" are essentially independent, and there is no need for an organism or groups of organisms to expend the energy to create mechanisms for economizing or cycling any input or output (see figure 1).

As external constraints on unlimited resources and unlimited sinks begin to develop—that is, as the biomass of the organic subsystem begins to reach a scale where its activities affect the functioning of the supporting environmental systems—a Type II system evolves, where the flows within the biological domain may be large, but the flows into and out of the domain are limited (see figure 2). The biomass is now evolving as a system in its own right; it is no longer simply a disconnected set of linear flows. Driven by competition for scarce resources, feedback loops begin to develop; with scarcity comes more rapid evolution.

While the Type II system is more efficient in its use of now-scarce resources, it is not yet sustainable in an absolute sense, given continued reliance on lim-

Fig. 1. Type I system

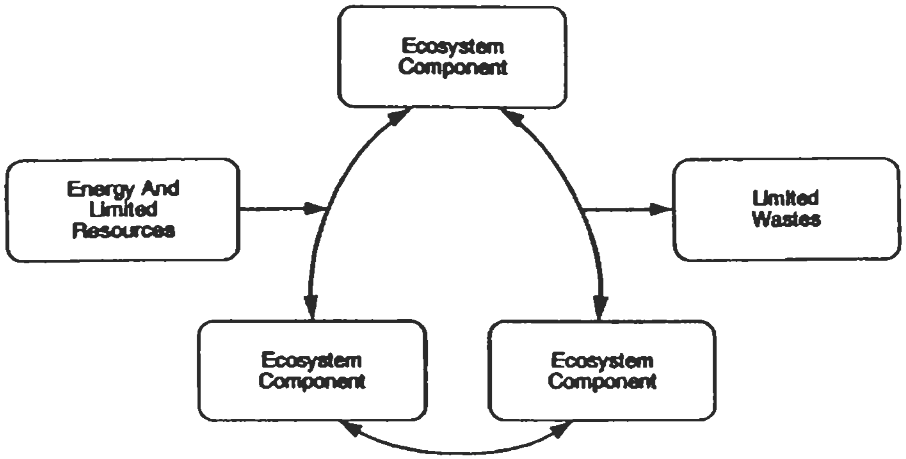

Fig. 2. Type II system

ited resources and limited sinks. To the extent growth continues and biomass accumulates, a Type III system exhibiting complete cyclicity will have to evolve for strict sustainability, as shown in figure 3.[8]

Type III systems are characterized by complete cycling of all materials, with no demand for inputs and no waste. Such systems are, however, energetically open, in that they depend on a continuous flow of solar radiation to maintain energy flows throughout the system. Obviously, these three systems are simplifications of a complex reality—and highly idealized at that. Nonetheless, these simplified biological paradigms illustrating complex systems can be applied to human economic activity as well. Like a biological community or ecosystem, human economic activity is a complex system embedded in supporting physical, chemical, and biological systems, which are also absolute constraints on the behavior of the embedded system. Materials flow through both systems in complex temporal and spatial patterns, and the structure of these patterns can have significant implications for the relationship between the embedded biological or economic system, and its suppo[illegible] environmental systems. While individual parts of a biological or economic system—a specie[illegible] firm, or a national economy [illegible] be studied in isolation, it is obvious

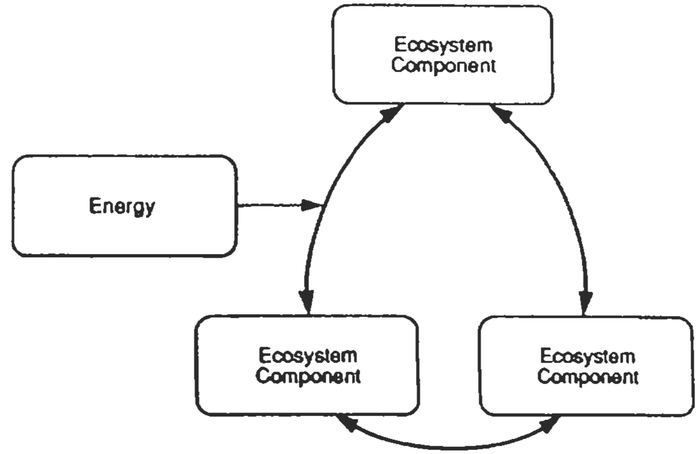

Fig. 3. Type III system

that each system must also be understood on its own terms, as a complex system. This is especially true where impacts of the embedded system on its support structure are involved.[9]

Let us explore in a little more depth some of the interesting implications of the proposed analogy. Consider, for example, the fundamental principle that the evolution of more complex systems—moving from a Type I to a Type III model—was necessary if continued growth in biomass was to occur, given the limited resources of the earth. In other words, the magnitude of the biomass subsystem that can be supported at a given level of resources is directly dependent on the efficiency with which that subsystem can maximize internal cycling and reduce resource and sink consumption.

Now consider the human condition. We unquestionably have a large and growing population that demands to be supported at a certain minimal economic level, thereby implying a certain minimal level of capital stock, given current technology. However, the human economy today is predominantly a Type I system. Many raw materials and resources do not cycle through the economy, but are simply mined or manufactured, put into a consumer article, and disposed of at the end of their useful life. This phenomenon of dissipation of materials in the modern consumer economy obviously is not compatible with a sustainable, cyclical pattern of resource use.[10] Although public and industrial recycling is increasing,[11] basic resources—especially inputs of air and water—and sinks—especially the atmosphere and receiving waters—are still treated as if they were essentially limitless.[12]

From a systems perspective, this is clearly unsustainable. What we are doing is attempting to support a biomass appropriate for Type III conditions with a linear Type I economy and culture. This is not a new insight,[13] but [illegible] ndustrial ecology approach helps frame the alternatives: we can simply continue as we are, and let the inevitable global constraints reduce the human biomass to a level appropriate to Type I economic and cultural practices, or we can evolve towards a Type III structure.

There is another important insight to be gleaned from the biological analogy, one with serious implications for the size of the task facing us. It is well known that a biological population with no constraints will display essentially a sigmoid growth curve characterized by exponential growth until limiting conditions are met, then level off at a carrying capacity.[14] The leveling-off process may be more or less graceful; but in our model system, it amounts to a transition from the Type I system (exponential growth) to the Type III system (carrying capacity).

Not only human population, but human consumption of many important inputs (energy, fresh water, and raw materials) have displayed exponential-like growth curves since the Industrial Revolution (and the associated agricultural and population revolutions).

Fundamentally, the Industrial Revolution created a Type I, essentially unlimited, growth environment for our species. There is no question that localized environmental degradation could be severe, but the effect on global support systems was not perceived as a problem, in part due to temporal lags exhibited by these complex systems.[15] Now, of course, it is apparent that we have begun to degrade our global support systems badly, particularly the critical sinks of the atmosphere and the oceans. The exponential free ride is over as far as the earth is concerned. Unfortunately, our institutions have not yet responded to those signals. Thus, in many ways, current human economic activity is still shaped by the implicit model of continuing exponential growth, not the reality of encroaching fundamental biological, chemical, and physical limits. The shift from this growth phase to a state of sustainable development culture will be profound, affecting most human institutions.

Current trends in the evolution of technology, for example, tend to be unsustainable precisely because they fuel, and are fueled by, an increasingly dissipative economy. Telephones in the United States, for instance, used to be recycled by the Bell System for years. Now, telephones exhibit more functionality, but have much shorter lifetimes and tend to end up in landfills instead of being recycled back into the economy. In part, such examples also illustrate our failure to develop, and to apply, a systems understanding of the interrelationship between our economy and the underlying global support systems.[16]

Virtually all critical academic and intellectual disciplines today are still predicated on assumptions appropriate to an exponential growth phase, not a sustained development phase. The intoxication of mainstream economics with growth at any cost, and the virtually universal use of discount rates for resource consumption decisions, are examples. The failure of law to recognize any rights of future generations is another example. The strongly pronatalist policies of many faiths and governments, frequently grounded in the belief that a larger population of believers or citizens makes for increased strength, are yet another example. The simple fact is that, as a species, we are in a Type III world with Type I institutions. The many indications that resource and sink limitations are becoming more critical, however, indicate that the current economic system and cultural institutions will be under increasing pressure to evolve toward a more cyclical stage or, alternatively, human activity will be forced back to a system size where the impacts on fundamental environmental support systems are reduced to sustainable forms and magnitudes. As it is evident that this latter course could include substantial economic and social disruption, as well as a significant collapse in human population, it is desirable to encourage evolution of the human economy on a relatively stable path toward a Type III system. Industrial ecology is the discipline that will inform this effort.

At the outset, it is necessary to emphasize that industrial ecology must subsume *all* human economic activity, including forestry, agriculture, extractive industries, energy production and use, manufacturing, service operations and processes, and sustenance activities. In doing so, it will also have to address significant cultural, technological, and political institutional issues. In fact, part of the reason we find ourselves in our current dilemma is that our systems thinking has, to date, been too limited in both the spatial and temporal dimensions.

Developing the ability to conceptualize and define the industrial ecology metasystem on this level is, however, currently beyond the state of the art. Thus it may be useful to provide a subsystem example of the kind of cyclical activity towards which we should be moving. For example, the modern manufacturing system is relatively well understood, so we can begin to understand in broad terms the appropriate model to work towards. Schematically, a Type III industrial subsystem of the industrial ecology metasystem might look something like that in figure 4. While this appears simplistic, it is not: for example, in some nations, hazardous waste laws are written in such a way as to actively discourage the kind of cyclical material flows one would wish, in fact, to encourage.[17]

More broadly, a failure to apply the kind of systems approach inherent in figure 5 lies behind much of the apparently inappropriate behavior of modern institutions. Any study of industrial ecology must recognize its metasystem attributes in comparison to the subsystem scale of current institutions. Indeed, many of the dysfunctional aspects of current institutions—political, legal, economic, scientific, or otherwise—arise not from inherent fallacies within the institution, but the application of the principles of the institution beyond the scale to which they are valid.[18] Schematically, these institutions properly are seen as subsystems of the industrial ecology metasystem (see figure 5).

Human beings are, of course, familiar with the institutions with which they interact. At this point, much less can be said for the industrial ecology metasystem. Some things are, however, apparent. For example, it is clear that the

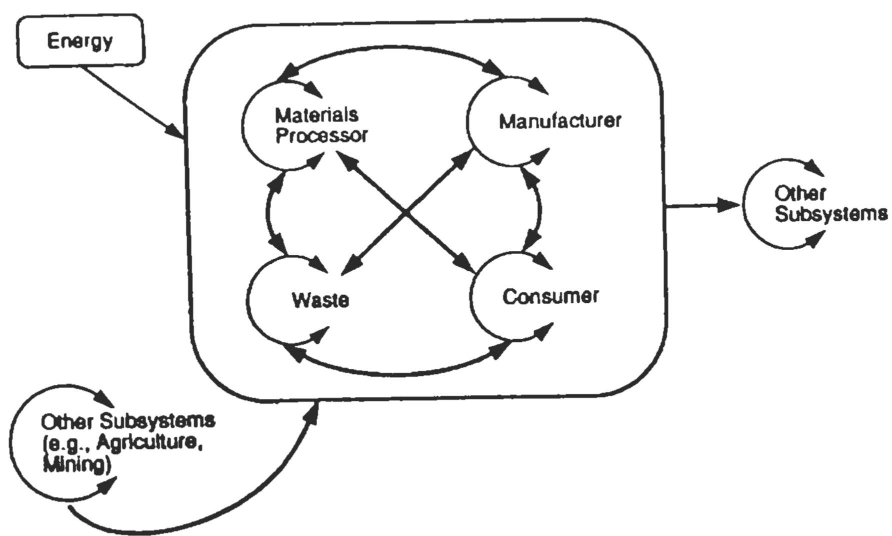

Fig. 4. Type III global economy

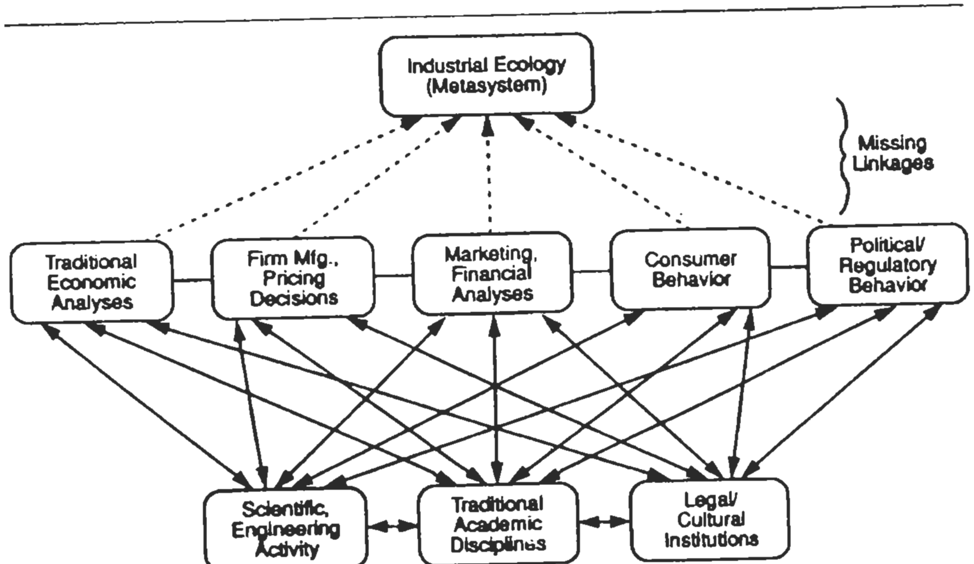

Fig. 5. Industrial ecology as a metasystem

scale of the industrial ecology metasystem must be global, so as to include all economies, developed and undeveloped—in the closed system. This does not mean that local traditions, cultures, and economies are precluded. To the contrary, they should be encouraged, as local responses to environmental constraints will be a valuable source for adaptive cultural mutations. Equally as important, different local and regional patterns may well constitute an important element of the quality of life in a sustainably developed world.[19]

Given these preliminary thoughts on the nature and scope of the industrial ecology metasystem, it is apparent that understanding this system, much less attempting to manipulate it, is a daunting task. Where should one begin?

Developing the Study of Industrial Ecology

There are several immediate and practical steps that can be taken by individual nations to initiate the study and practice of industrial ecology. Some of these steps are already being taken, albeit often without a full recognition of the scope of the metasystem involved. The most obvious need is to raise the visibility of industrial ecology as a legitimate area of study, and to begin to define the parameters of the metasystem more accurately. In the United States, the National Academy of Engineering has already done some work in this area. The work has resulted in a book on the interrelationship between technology and the environment.[20] The concept of life-cycle analysis, which is currently being developed by several groups, contains elements of an industrial ecology approach,[21] as does the nascent practice of integrating environmental considerations and constraints into product and process design, called Design for Environment, or DFE.[22] Similar efforts using different terminology, and focusing on what we would call "subsystems of the industrial ecology metasystem," are becoming increasingly common around the world.

There are other, more specific, efforts that must be undertaken, however, if industrial ecology is to flourish as a new international field of study. This suggests not only the need to establish an international society for industrial ecology, but international institutes for industrial ecology as well.

An international society for industrial ecology is a logical longer-term result of preliminary workshops and meetings. Such a society would serve as a critical information and networking resource for practitioners of industrial ecology, as well as a supportive peer group. Input from existing international organizations, such as the United Nations Environment Programme or the UN Center for Transnational Corporations, would be useful in ensuring that the necessary international scope is maintained.

The institutes for industrial ecology would also be pivotal in initiating the study of industrial ecology. In particular, they could be given several tasks:

1. The institutes should develop graduate and undergraduate curricula in facets of industrial ecology. This function could be performed independently, or in partnership with interested academic institutions. The institutes could also serve as an information clearinghouse for academic institutions experimenting with such curricula.
2. The institutes could identify and maintain data bases regarding existing organizations and data resources which are performing complementary work. This information would be available to academic institutions, industry, and others. The institutes would also integrate this material—much of which deals only with certain aspects of industrial ecology, such as pollution prevention, waste minimization, recycling, and energy conservation—in light of industrial ecology principles.

   As a corollary, the institutes should define the data necessary to perform industrial ecology-type analyses of industrial issues, and collect or fund the collection of such data. While there are several sources of raw data on production, sales import, and export activities involving the industrial, forestry, agricultural, mining, and other sectors in various countries, the data tend to be of uneven quality. Moreover, there are also significant data gaps which could impede understanding and analyses of industrial ecology issues.
3. The institutes should sponsor or participate in multidisciplinary, multinational conferences, seminars, and workshops on industrial ecology, with industrial, academic, government, and other appropriate partners.
4. The institutes should encourage, support, and fund research in industrial ecology. As the field grows, this activity should be coordinated with other private, industrial, academic, and national and international official funding sources to ensure efficient use of scarce research dollars.
5. The institutes should develop, manage, and (if appropriate and possible) fund an internship program involving academic and industrial participants. Internships should be offered at both academic and industrial locations.

   More broadly, the institutes must encourage the development of new forms of organizations linking multinational organizations, governments, and private and academic institutions. Because part of the cause of regional and global environmental perturbations is dysfunctional economic and cultural subsystems, part of the solution must be to evolve new organizations of the appropriate scope and scale. There are a few initial efforts in this direction, such as the Industry Cooperative for Ozone Layer Protection, but much more is necessary.[23] Determining how to encourage and implement such efforts, and how they may be made effective, would appear to be an important mission for the institutes.

If they are to be effective, the institutes should have some fundamental characteristics. Perhaps most important, they must be objective, and be perceived as being objective. This will not be trivial for organizations that, to carry out their mission, will have to work closely with industry and government entities having significant financial and bureaucratic interest in the way industrial ecology principles are implemented. The institutes may also be partially funded by industry or industry-related sources, raising additional potential for biases. Nonetheless, they will have to be in the world of industry, but not *of* it.

It also is absolutely essential that the institutes be multidisciplinary. Each discipline or profession carries with it an implicit and explicit set of biases, methodologies and assumptions that, taken alone, are inadequate to address the problem. Addressing metasystem issues will require contributions from numerous fields, including anthropology, economics, law, engineering, systems ecology, biology, and the physical sciences. Specialized institutes will obviously have additional expertise requirements. Moreover, the institutes will require people with industrial experience, whose areas of expertise may be impossible to categorize.

Additionally, the institute must insist on the highest professional and academic standards, without falling into the trap of disregarding new or multidisciplinary work because it does not conform to existing preconceptions or dogmas. This may prove difficult: there is a lot of unreviewed, second-rate material in the environmental field; yet traditional, narrow, discipline-based academic standards will frequently not be appropriate. Indeed, to some extent they are part of the problem, not part of the solution.[24]

Why institutes instead of just one institute? Simply put, it will probably be necessary as a practical matter to limit each institute to certain subsystems of industrial ecology, at least initially, to achieve any meaningful benefits. The industrial ecology metasystem is simply too big to tackle head-on. Thus, there will be a need for a linked series of regional—or perhaps—national institutes, each focusing on a specific subsystem within the industrial ecology metasystem, while recognizing the need to interact and integrate activities among fellow institutes to the extent possible.

A more subtle reason to begin with regional or, if necessary, national institutes is to reinforce the need for a unified global approach to industrial ecology, while demonstrating a concern for indigenous cultures and practices. Moreover, it is presumptuous in the extreme, particularly at this point, to assume that any specific culture will hold the key to industrial ecology. Indeed, some of the countries moving most rapidly toward certain elements of industrial ecology, such as waste minimization, are precisely those countries where one would expect psychological loyalty to the Industrial Revolution and the exponential-growth mindset to be greatest.

Conclusions

Current economic patterns and supporting cultural and political structures have, by and large, evolved during the exponential growth phase of human history, generally termed the Industrial Revolution. It is now apparent that the levels of human population and economic activity traditionally associated with that phase are not sustainable. A primary reason is that existing cultural, economic, and technical systems are only subsystems of a metasystem I have defined as "industrial ecology." Optimizing or satisficing behavior at the subsystem level has clearly failed to create conditions under which the industrial ecology metasystem functions to support sustainable development. Our species will reach sustainable levels, of course. It is our choice as to whether this occurs through natural population control mechanisms (starvation, epidemics) and social collapse, or planned evolution toward sustainable development. If we choose the latter course, we must begin now to explore and understand the industrial ecology metasystem.

Notes

1. While there are excellent general sources on global environmental perturbations, the two *Scientific American* special issues, ***Managing Planet Earth,*** 261, no. 3, September, 1989, and ***Energy for Planet Earth,*** 263, no. 3, September 1990, are noteworthy.
2. The World Commission on Environment and Development, ***Our Common Future*** (the Brundtland Report), (Oxford: Oxford University Press, 1987).
3. Portions of the discussion in this section are based on background papers prepared by the author alone and in conjunction with T. E. Graedel and P. B. Linhart of AT&T Bell Laboratories, in support of a joint AT&T–National Academy of Sciences workshop on industrial ecology, held in Washington, D.C., in May, 1991.
4. Some readers will detect the concept of "carrying capacity"—a biological term denoting the maximum population a given environment can sustain for an extended time—latent in this broad formulation. While the carrying capacity concept has some descriptive power regarding what may constitute a state of sustainable development, it is difficult to apply this idea to a species such as ours that exhibits significant cultural and technological evolution. Indeed, it is our capacity for such evolution that offers a modicum of hope for the future.
5. E. P. Odum, ***Fundamentals of Ecology,*** (Philadelphia: W. B. Saunders Company, 1959), p. 4.
6. Whether the postulated quasi-linear community structure characterized the early stages of the actual evolution of life is as yet undetermined; there is much controversy about how life originally evolved. See J. Horgan, "Trends in Evolution: In The Beginning," *Scientific American* (February 1991): 116–125.
7. This structure is analogous to the energy models developed by H. T. Odum. In studying those systems, he found that, at low energy, the linear pathway in the models carried the most energy flow, while at higher energies, the energy competition was dominated by autocatalytic, higher exponent, pathways. See H. T. Odum, "Self-Organization, Transformity, and Information," *Science* 242 (November 25, 1988): 1132–1139.
8. By "strict sustainability" I mean sustainability that can be maintained indefinitely over time in the absence of significant exogenous shocks in the external environment, such as a meteor impact. The concept of sustainability must, of course, allow for evolution, be it biological or, in the case of humanity, cultural and technical.

9. A similar approach is taken by R. A. Frosch and N. E. Gallopoulos in "Toward an Industrial Ecology," a paper presented to the Royal Society, London, February 21, 1990.
10. See R. U. Ayres, "Industrial Metabolism," in *Technology and Environment,* J. H. Ausubel and H. E. Sladovich, eds. (Washington, D.C.: National Academy Press, 1989), pp. 23–49.
11. Both mandated and voluntary recycling initiatives have sprung up in Europe and the United States. In many cases, these are tied to the price of the recovered product. It is no surprise, for example, to find that precious metals are relatively highly conserved in the economy. See R. A. Frosch and N. E. Gallopoulos, "Strategies for Manufacturing," *Scientific American* 261, no. 3 (September 1989): 144–152. Recently, however, more attention is being paid to recycling of articles: in Germany, BMW has developed a "recyclable car," while in the United States the Office of Technology Assessment is investigating the degree to which companies factor environmental considerations into their design processes.
12. See Garrett Hardin, "The Tragedy of the Commons," *Science* 162 (December 13, 1968): 1243–1248; and the differentiation between "common property" (private property used by a group with attendant duties which tend to preserve the property) and "open access regimes" (where the tragedy of the commons may occur) drawn by D. W. Bromley and M. M. Cernea, "The Management of Common Property Natural Resources," World Bank Discussion Paper No. 57, 1989.
13. See, for example, Donella H. Meadows, Dennis L. Meadows, Jrgen Randers,and William W. Behrens, III, ***The Limits to Growth*** (New York: Universe Books, 1972).
14. There are obviously variations on this basic theme in the somewhat-messy real world. See for example Odum, note 5, p. 184.
15. The most obvious example is the increase in carbon dioxide with associated forcing of global climate change, albeit on a temporal scale. Humans find this hard to intuit. See R. A. Joughton and G. M. Woodwell, "Global Climate Change," *Scientific American* 260, no. 4, (April 1989): 36–43.
16. This example also illustrates the importance of appropriate scale for economic and political organizations if environmentally desirable behavior is to be encouraged. Because the Bell System in the United States controlled much of the physical plant it used from creation to destruction, economic savings effected by substantial recycling of cable, switches, public telephones, and other materials could be captured by one entity. With divestiture, however, the existing system was broken into subsystems, none of which could capture sufficient benefits to maintain the same level of recycling. This scale dysfunction factor, which is generally characteristic of industrial organization throughout the world, has contributed to the increasingly dissipative materials trends characteristic of modern economies.
17. The Resource Conservation and Recovery Act (RCRA), 42 U.S.C. Sec. 6901 et seq., is an example in the United States. While proper handling of hazardous materials, including wastes, is obviously necessary, this statute assumes a linear manufacturing paradigm by defining anything that falls from a manufacturing line as waste, and imposing burdensome paperwork and regulatory requirements on such materials, thereby discouraging recycling and reuse of such materials. It

thus becomes a self-fulfilling process: materials become hazardous waste because RCRA defines them so.

18. See Daly and Cobb, *For the Common Good* (Boston: Beacon Press, 1989), for an application of this principle to the discipline of economics.
19. See note 18; the book contains a stimulating discussion of this point.
20. *Technology and Environment,* J. H. Ausubel and H. E. Sladovich, eds., (Washington, D.C.: National Academy Press, 1989).
21. See, for example, The Society of Environmental Toxicology and Chemistry, "A Technical Framework for Life-Cycle Analysis," (Washington, D.C.: SETAC Foundation, 1991).
22. See Braden R. Allenby, "Design for Environment: A Tool Whose Time Has Come," *55A Journal* (September 1991).
23. The Industry Cooperative for Ozone Layer Protection, or ICOLP, was planned by AT&T, the U. S. Environmental Protection Agency, and Northern Telecom as an organization which would provide information to facilitare the implementation of alternatives to chlorofluorocarbon use by electronics firms around the world. ICOLP has been spectacularly successful: it has already sponsored international conferences on CFC elimination, published six technical manuals on CFC alternatives, and implemented a worldwide data base, called "Ozonet," on CFC alternatives. The unique nature of the organization is demonstrated by the fact that it was conceptualized by a troika consisting of two bitter commercial rivals—AT&T and Northern Telecom—and a government agency, the U.S. Environmental Protection Agency, which is frequently in an adversarial legal posture against private industry. Moreover, ICOLP's current membership, which includes not only major companies from around the world but such organizations as the Japan Electrical Manufacturers Association, the State Institute of Applied Chemistry (the former USSR), and the U. S. Air Force, illustrates the eclecticism which will be required to meet the challenges of regional and global environmental constraints.
24. See note 18, especially their discussions of "misplaced concreteness" and "disciplinolatry."

Industrial Metabolism: Theory and Policy

ROBERT U. AYRES

The word *metabolism*, as used in its original biological context, connotes the internal processes of a living organism. The organism ingests energy rich, low-entropy materials (food), to provide for its own maintenance and functions, as well as a surplus to permit growth or reproduction. The process also necessarily involves excretion or exhalation of waste outputs, consisting of degraded, high-entropy materials. There is a compelling analogy between biological organisms and industrial activities—indeed, the whole economic system—not only because both are materials-processing systems driven by a flow of free energy (Georgescu-Roegen, 1971), but because both are examples of self-organizing "dissipative systems" in a stable state, far from thermodynamic equilibrium (Ayres, 1988).

At the most abstract level of description, then, the metabolism of industry is the whole integrated collection of physical processes that convert raw materials and energy, plus labor, into finished products and wastes in a (more or less) steady-state condition (Figure 1). The production (supply) side, by itself, is not self-regulating. The stabilizing controls of the system are provided by its human component. This human role has two aspects: (1) direct, as labor input, and (2) indirect, as consumer of output (i.e., determinant of final demand). The system is stabilized, at least in its decentralized competitive market form, by balancing sup-

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NOTE: Figure 2 has been corrected

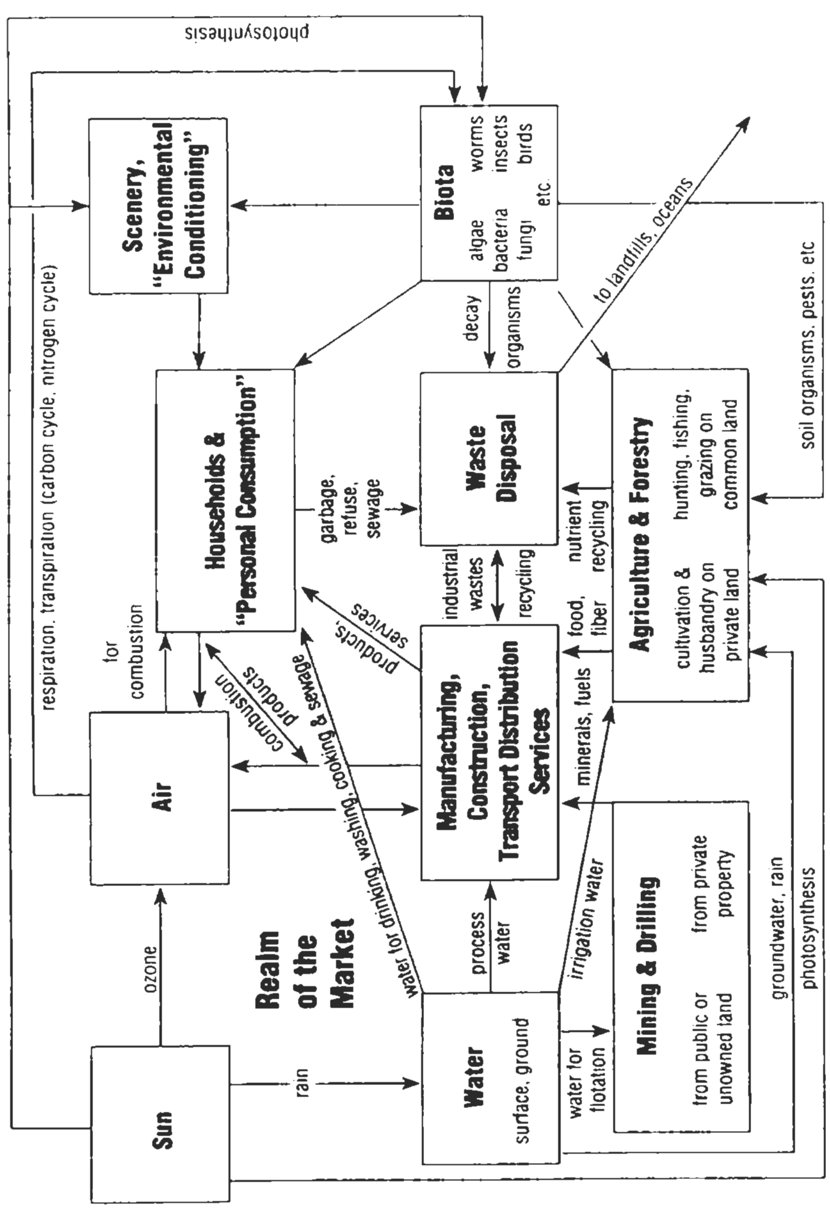

FIGURE 1 What is industrial metabolism?

ply of and demand for both products and labor through the price mechanism. Thus, the economic system is, in essence, the metabolic regulatory mechanism.

Industrial metabolism can be identified and described at a number of levels below the broadest and most encompassing global one. Thus, the concept is obviously applicable to nations or regions, especially "natural" regions such as watersheds or islands. The key to regional analysis is the existence of a well-defined geographical border or boundary across which physical flows of materials and energy can be monitored.

The concept of industrial metabolism is equally applicable to another kind of self-organizing entity, a manufacturing enterprise or firm. A firm is the economic analogue of a living organism in biology.[1] Some of the differences are interesting, however. In the first place, biological organisms reproduce themselves; firms produce products or services, not other firms (except by accident). In the second place, firms need not be specialized and can change from one product or business to another. By contrast, organisms are highly specialized and cannot change their behavior except over a long (evolutionary) time period. In fact, the firm (rather than the individual) is generally regarded as the standard unit of analysis in economics. The economic system as a whole is essentially a collection of firms, together with regulatory institutions and worker-consumers, using a common currency and governed by a common political structure. A manufacturing firm converts material inputs, including fuels or electric energy, into marketable products and waste materials. It keeps financial accounts for all its external transactions; it is also relatively easy to track physical stocks and flows across the "boundary" of the firm and even between its divisions.

THE MATERIALS CYCLE

A third way in which the analogy between biological metabolism and industrial metabolism is useful is to focus attention on the "life cycle" of individual "nutrients." The hydrological cycle, the carbon cycle, and the nitrogen cycle are familiar concepts to earth scientists. The major way in which the industrial metabolic system differs from the natural metabolism of the earth is that the natural cycles (of water, carbon/oxygen, nitrogen, sulfur, etc.) are *closed*, whereas the industrial cycles are *open*. In other words, the industrial system does *not* generally recycle its nutrients. Rather, the industrial system starts with high-quality materials (fossil fuels, ores) extracted from the earth, and returns them to nature in degraded form.

This point particularly deserves clarification. The materials cycle, in general, can be visualized in terms of a system of compartments containing *stocks* of one or more nutrients, linked by certain *flows*. For instance, in the case of the hydrological cycle, the glaciers, the oceans, the freshwater lakes, and the groundwater are stocks, while rainfall and rivers are flows. A system is *closed* if there are no

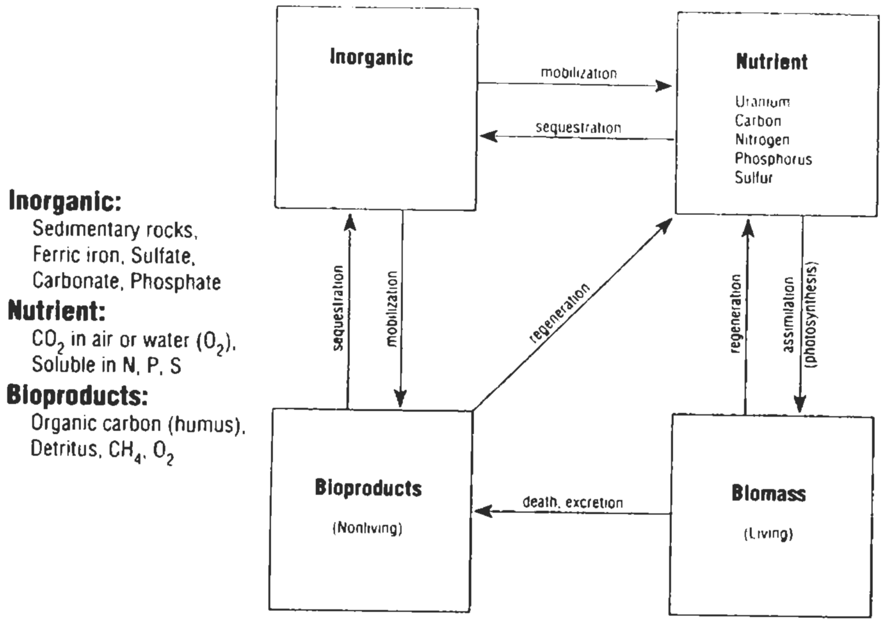

FIGURE 2 Box scheme for bio-geo-chemical cycles.

external sources or sinks. In this sense, the Earth as a whole is essentially a closed system, except for the occasional meteorite.

A closed system becomes a *closed cycle* if the system is also in steady-state, that is if the stocks in each compartment are constant and unchanging, at least on the average. The materials balance condition implies that the material inputs to each compartment must be exactly balanced (on the average) by the outputs. If this condition is not met, for a given compartment, then the stock in one or more compartments must be increasing, while the stocks in one or more other compartments must be decreasing.[2]

It is easy to see that a closed cycle of flows, in the above sense, can be sustained indefinitely only by a continuous flow of free energy. This follows immediately from the second law of thermodynamics, which states that global entropy increases in every irreversible process. Thus, a closed cycle of flows can be sustained as long as its external energy supply lasts. An open system, on the contrary, is inherently unstable and unsustainable. It must either stabilize or collapse to a thermal equilibrium state in which all flows, that is, all physical and biological processes, cease.

It is sometimes convenient to define a generalized four-box model to describe materials flows. The biological version is shown in Figure 2, while the analogous industrial version is shown in Figure 3. To revert to the point made at the beginning of this section, the natural system is characterized by closed cycles, at least

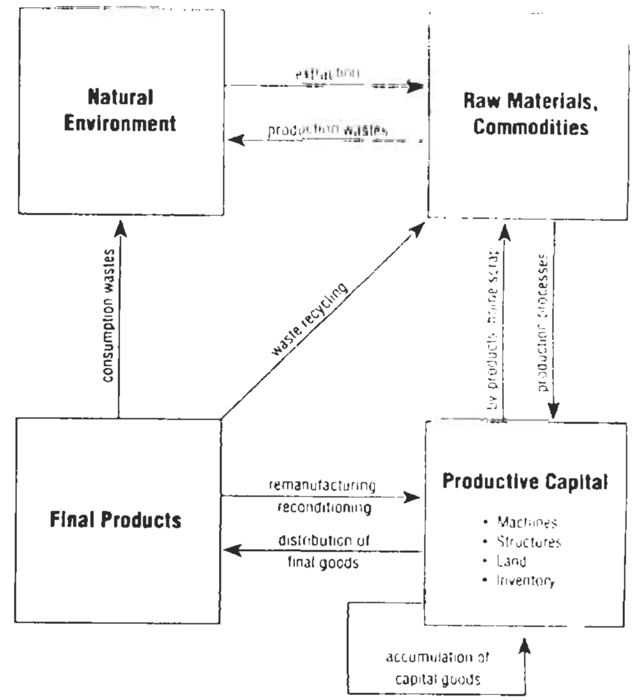

FIGURE 3 Box scheme for industrial material cycles

for the major nutrients (carbon, oxygen, nitrogen, sulfur)—in which biological processes play a major role in closing the cycle. By contrast, the industrial system is an open one in which "nutrients" are transformed into "wastes" but are not significantly recycled. The industrial system of today is therefore unsustainable.

At this stage, it should be noted that nothing can be said about open cycles (on the basis of such simple thermodynamic arguments, at least) with respect to any of the really critical questions. These are as follows: (1) Will the industrial system stabilize itself without external interference? (2) If so, how soon, and in what configuration? (3) If not, does there exist any stable state (i.e., a system of closed materials cycles) short of ultimate thermodynamic equilibrium that could be reached with the help of a feasible technological "fix"? (4) If so, what is the nature of the fix, and how costly will it be? (5) If not, how long do we have until the irreversible collapse of the bio-geosphere system makes Earth uninhabitable? (If the time scale is a billion years, we need not be too concerned. If it is a hundred years, civilization, and even the human race, could already be in deep trouble.) It is fairly important to try to find answers to these questions. Needless to say, we do not aspire to answer all these questions in the present paper.

It should also be pointed out that the bio-geosphere was not always a stable system of closed cycles. Far from it. The earliest living cells on Earth obtained their nutrients, by fermentation, from nonliving organic molecules whose origin is still not completely understood. At that time the atmosphere contained no free oxygen or nitrogen; it probably consisted mostly of water vapor plus some hydrogen and hydrogen-rich gases such as methane, hydrogen sulfide, and ammonia. The fermentation process yields ethanol and carbon dioxide. The system could have continued only until the fermentation organisms used up the original stock of "food" molecules or choked on the carbon dioxide buildup. The system stabilized temporarily with the appearance of a new organism (blue-green algae, or cyanobacteria) capable of recycling carbon dioxide into sugars and cellulose, thus again closing the carbon cycle. This new process was anaerobic photosynthesis.

However, the photosynthesis process also had a waste product: namely, oxygen. For a long time (over a billion years) the oxygen generated by anaerobic photosynthesis was captured by dissolved ferrous iron molecules, and sequestered as insoluble ferric oxide or magnetite, with the help of another primitive organism, the stromatolites. The resulting insoluble iron oxide was precipitated on the ocean bottoms.[3] (The result is the large deposits of high-grade iron ore we exploit today.) The system was still unstable at this point. It was only the evolutionary invention of two more biological processes, aerobic respiration and aerobic photosynthesis, that closed the oxygen cycle as well. Still other biological processes—nitrification and denitrification, for instance—had to appear to close the nitrogen cycle and others.

Evidently biological evolution responded to inherently unstable situations (open cycles) by "inventing" new processes (organisms) to stabilize the system by closing the cycles. This self-organizing capability is the essence of what has been called Gaia. However, the instabilities in question were slow to develop, and the evolutionary responses were also slow to evolve. It took several billion years before the biosphere reached its present degree of stability.

In the case of the industrial system, the time scales have been drastically shortened. Human activity already dominates natural processes in many respects. While cumulative anthropogenic changes to most natural nutrient stocks still remain fairly small, in most cases,[4] the *rate* of nutrient mobilization by human industrial activity is already comparable to the natural rate in many cases. Table 1 shows the natural and anthropogenic mobilization (flow) rates for the four major biological nutrients, carbon, nitrogen, phosphorus, and sulfur. In all cases, with the possible exception of nitrogen, the anthropogenic contributions exceed the natural flows by a considerable margin. The same is true for most of the toxic heavy metals, shown in Table 2.

Based on relatively crude materials cycle analyses, at least, it would appear that industrialization has already drastically disturbed, and therefore destabilized, the natural system.

TABLE 1 Anthropogenic Nutrient Fluxes, Teragrams/year (Tg/yr)

	Carbon		Nitrogen		Sulfur		Phosphorus	
	Tg/yr	%	Tg/yr	%	Tg/yr	%	Tg/yr	%
To atmosphere, total	7,900	4	55.0	12.5	93	65.5	1.5	12.5
Fossil fuel combustion and smelting	6,400		45.0		92			
Land clearing, deforestation	1,500		2.6		1		1.5	
Fertilizer volatilization[a]			7.5					
To soil, total			112.5	21	73.3	23.4	15	7.4
Fertilization			67.5		4.0		15	
Waste disposal[b]			5.0		21.0			
Anthropogenic acid deposition			30.0		48.3			
Anthropogenic (NH_3, NH_4) deposition			10.0					
To rivers and oceans, total			72.5	25	52.5	21	5	10.3
Anthropogenic acid deposition			55.0		22.5			
Waste disposal			17.5		30.0		5	

[a]Assuming 10% loss of synthetic ammonia-based fertilizers applied to land surface (75 Tg/yr).
[b]Total production (= use) less fertilizer use, allocated to landfill. The remainder is assumed to be disposed of via waterways.

TABLE 2 Worldwide Atmospheric Emissions of Trace Metals (1,000 tonnes per year)

Element	Energy Production	Smelting, Refining, and Manufacturing	Manufacturing Processes	Commercial Uses, Waste Incineration, and Transportation	Total Anthropogenic Contributions	Total Contributions by Natural Activities
Antimony	1.3	1.5	—	0.7	3.5	2.6
Arsenic	2.2	12.4	2.0	2.3	19.0	12.0
Cadmium	0.8	5.4	0.6	0.8	7.6	1.4
Chromium	12.7	—	17.0	0.8	31.0	43.0
Copper	8.0	23.6	2.0	1.6	35.0	28.0
Lead	12.7	49.1	15.7	254.9	332.0	12.0
Manganese	12.1	3.2	14.7	8.3	38.0	317.0
Mercury	2.3	0.1	—	1.2	3.6	2.5
Nickel	42.0	4.8	4.5	0.4	52.0	29.0
Selenium	3.9	2.3	—	0.1	6.3	10.0
Thallium	1.1	—	4.0	—	5.1	—
Tin	3.3	1.1	—	0.8	5.1	—
Vanadium	84.0	0.1	0.7	1.2	86.0	28.0
Zinc	16.8	72.5	33.4	9.2	132.0	45.0

NOTE: Based on relatively crude materials cycle analyses, at least, it would appear that industrialization has already drastically disturbed, and *ipso facto* destabilized, the natural system.

SOURCE: Nriagu (1990).

There are only two possible long-run fates for waste materials: recycling and reuse or dissipative loss.[5] (This is a straightforward implication of the law of conservation of mass.) The more materials are recycled, the less will be dissipated into the environment, and vice versa. Dissipative losses must be made up by replacement from virgin sources. A strong implication of the analysis sketched above is that a long-term (sustainable) steady-state industrial economy would necessarily be characterized by near-total recycling of intrinsically toxic or hazardous materials, as well as a significant degree of recycling of plastics, paper, and other materials whose disposal constitutes an environmental problem. Heavy metals are among the materials that would have to be almost totally recycled to satisfy the sustainability criterion. The fraction of current metal supply needed to replace dissipative losses (i.e., production from virgin ores needed to maintain a stable level of consumption) is thus a useful surrogate measure of "distance" from a steady-state condition, that is, a condition of long-run sustainability.

Most economic analysis in regard to materials, in the past, has focused on availability. Data on several categories of reserves (economically recoverable, potential, etc.) are routinely gathered and published by the U.S. Bureau of Mines, for example. However, as is well known, such figures are a poor proxy for actual reserves. In most cases the actual reserves are much greater than the amounts actually documented. The reason, simply, is that most such data are extrapolated from test borings by mining or drilling firms. There is a well-documented tendency for firms to stop searching for new ore bodies when their existing reserves exceed 20 to 25 years' supply. Even in the case of petroleum (which has been the subject of worldwide searches for many decades) it is not possible to place much reliance on published data of this kind.[6]

However, a sustainable steady state, as discussed above, is less a question of resource availability than of recycling or reuse efficiency. As commented earlier, a good measure of unsustainability is dissipative use. This raises the distinction between *inherently dissipative* uses and uses for which the material could be recycled or reused, in principle, but is not. The latter could be termed *potentially recyclable*. Thus, there are really three important classes of materials use: (1) uses that are economically and technologically compatible with recycling under present prices and regulations; (2) uses that are not economically compatible with recycling but where recycling is technically feasible, for example, if the collection problem were solved; and (3) uses for which recycling is inherently not feasible. Admittedly there is some fuzziness in these classifications, but it should be possible for a group of international experts to arrive at some reconciliation.

Generally speaking, it is arguable that most structural metals and industrial catalysts are in the first category; other structural and packaging materials, as well as most refrigerants and solvents, fall into the second category. This leaves coatings, pigments, pesticides, herbicid s, germicides, preservatives, flocculants, antifreezes, explosives, propellants, fire retardants, reagents, detergents, fertilizers, fuels, lubricants, and the like in the third category. In fact, it is easy to verify that most chemical products belong in the third category, except those physically embodied in plastics, synthetic rubber, or synthetic fibers.

From the standpoint of elements, if one traces the uses of materials from source to final sink, it can be seen that virtually all sulfur mined (or recovered from oil, gas, or metallurgical refineries) is ultimately dissipated in use (e.g., as fertilizers or pigments) or discarded, as waste acid or as ferric or calcium sulfites or sulfates. (Some of these sulfate wastes are classed as hazardous). Sulfur is mostly (75–80 percent) used, in the first place, to produce sulfuric acid, which in turn is used for many purposes. But in every chemical reaction the sulfur must be accounted for—it must go somewhere. The laws of chemistry guarantee that reactions will tend to continue either until the most stable possible compound is formed or until an insoluble solid is formed. If the sulfur is not embodied in a "useful" product, it must end up in a waste stream.

There is only one long-lived structural material embodying sulfur: plaster-of-Paris (hydrated calcium sulfate) which is normally made directly from the natural mineral gypsum. In recent years, sulfur recovered from coal-burning power plants in Germany has been converted into synthetic gypsum and used for construction. However, this potential recycling loop is currently inhibited by the very low price

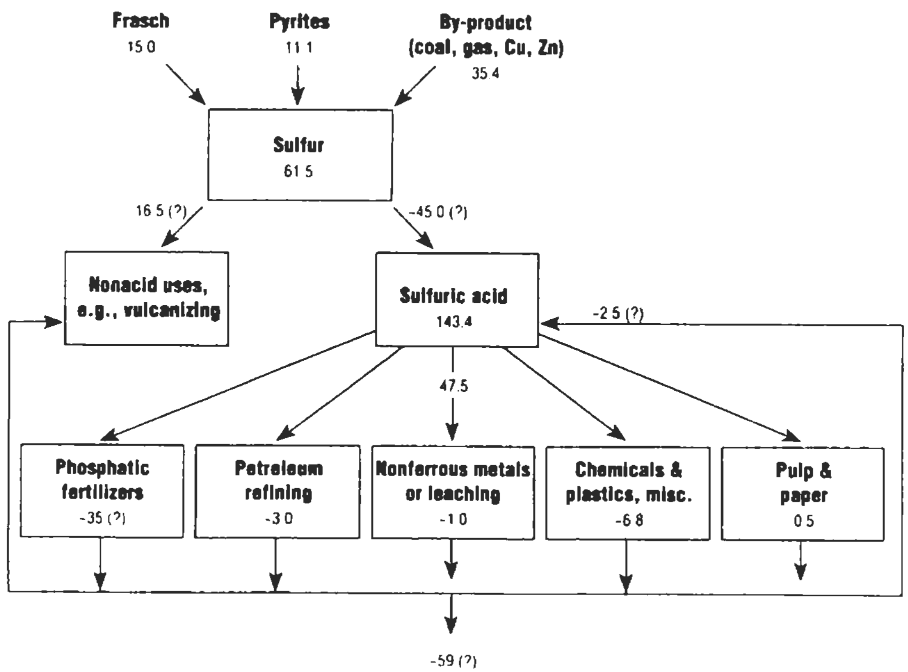

FIGURE 4 Dissipative uses of sulfur, 1988 (millions of metric tons).

TABLE 3 Examples of Dissipative Use

Substance	10^6 T	Dissipative Uses
Other chemicals		
Chlorine	25.9	Acid, bleach, water treatment, PVC solvents, pesticides, refrigerants
Sulfur	61.5	Acid (H_2SO_4), bleach, chemicals, fertilizers, rubber
Ammonia	24.0	Fertilizers, detergents, chemicals
Phosphoric acid	93.6	Fertilizers, nitric acid, chemicals (nylon, acrylics)
NaOH	35.8	Bleach, soap, chemicals
Na_2CO_3	29.9	Chemicals (glass)
Heavy metals		
Copper sulfate ($CuSO_4 \cdot 5H_2O$)	0.10	Fungicide, algicide, wood preservative, catalyst
Sodium bichromate	0.26	Chromic acid (for plating), tanning, algicide
Lead Oxides	0.24	Pigment (glass)
Lithopone (ZuS)	0.46	Pigment
Zinc Oxides	0.42	Pigment (tires)
Titanium Oxide (TiO_2)	1.90	Pigment
Tetraethyl lead	?	Gasoline additive
Arsenic	?	Wood preservative, herbicide
Mercury	?	Fungicide, catalyst

of natural gypsum. Apart from synthetic gypsum, there are no other durable materials in which sulfur is physically embodied. It follows from materials balance considerations that sulfur is entirely dissipated into the environment. Globally, about 61.5 million metric tons of sulfur as sulfur—not including gypsum—were produced in 1988. Of this, less than 2 million tons were recycled (mainly as waste sulfuric acid), as indicated schematically in Figure 4.

Very little is currently used for structural materials. Thus, most sulfur chemicals belong in class 3. Following similar logic, it is easy to see that the same is true of most chemicals derived from ammonia (fertilizers, explosives, acrylic fibers), and phosphorus (fertilizers, pesticides, detergents, fire retardants). In the case of chlorine, there is a division between class 2 (solvents, plastics, etc.) and class 3 (hydrochloric acid, chlorine used in water treatment, etc.).

Chlorofluorocarbon (CFC) refrigerants and solvents are long-lived and nonreactive. In fact, this is the reason they pose an environmental hazard. Given an appropriate system for recovering and reconditioning old refrigerators and air conditioners, the bulk of the refrigerants now in use could be recovered, for either reuse or destruction. Hence, they belong in class 2. However CFCs used for foam-blowing are not recoverable. Table 3 shows world output of a number of materials—mostly chemicals—whose uses are, for the most part, inherently dissipative (class 3). It would be possible, with some research, to devise measures of the inherently dissipative uses of each element, along the lines sketched above.

TABLE Scrap Use in the United States

	Total Consumption (million short tons)			% of Total Consumption in Recycled Scrap		
Material	1977	1982	1987	1977	1982	1987
Aluminum	6.49	5.94	6.90	24.1	33.3	29.6
Copper	2.95	2.64	3.15	39.2	48.0	39.9
Lead	1.58	1.22	1.27	44.4	47.0	54.6
Nickel	0.75	0.89	1.42	55.9	45.4	45.4
Iron/steel	142.40	84.00	99.50	29.4	33.4	46.5
Zinc	1.10	0.78	1.05	20.9	24.1	17.7
Paper	60.00	61.00	76.20	24.3	24.5	25.8

SOURCE: Institute of Scrap Recycling Industries (1988).

Sustainability, in the long run, would imply that such measures decline. Currently, they are almost certainly increasing.

With regard to materials that are potentially recyclable (classes 1 and 2), the fraction actually recycled is a useful measure of the approach toward (or away from) sustainability. A reasonable proxy for this, in the case of metals, is the ratio of secondary supply to total supply of final materials: see, for example, Table 4. This table shows, incidentally, that the recycling ratio in the United States has been rising consistently in recent years only for lead and iron or steel. For lead, the ban on using tetraethyl lead as a gasoline additive (an inherently dissipative use) is entirely responsible.

Another useful measure of industrial metabolic efficiency is the economic output per unit of material input. This measure can be called *materials productivity*. It can be measured, in principle, not only for the economy as a whole, but for each sector. It can also be measured for each major "nutrient" element, such as carbon, oxygen, hydrogen, sulfur, chlorine, iron, and phosphorus. Measures of this kind for the economy as a whole are not reliable indicators of increasing technological efficiency, or progress toward long-term sustainability. The reason is that increasing efficiency—especially in rapidly developing countries—can be masked by structural changes, such as investment in heavy industry, which tend to increase the materials (and energy) intensiveness of economic activity. On the other hand, within a given sector, one would expect the efficiency of materials use—or materials productivity—to increase, in general.[7]

Useful aggregate measures of the state of the environment in relation to sustainability can be constructed from physical data that are already collected and compiled in many countries. To derive these aggregates and publish them regularly would provide policymakers with a valuable set of indicators at little cost.

It is clear that other interesting and useful measures based on physical data are also possible. Moreover, if similar data were collected and published at the sectoral level, it would be possible to undertake more ambiti gineering-economic systems analyses and forecasts—of the kind currently possible only for energy—in the entire domain of industrial metabolism.

POLICY IMPLICATIONS OF THE INDUSTRIAL METABOLISM PERSPECTIVE

It may seem odd to suggest that a mere viewpoint—in contradistinction to empirical analysis—may have policy implications. But it is perfectly possible. In fact, there are two implications that come to mind. First, the industrial metabolism perspective is essentially "holistic" in that the whole range of interactions between energy, materials, and the environment is considered together—at least, in principle. The second major implication, which virtually follows from the first, is that from this holistic perspective it is much easier to see that narrowly conceived or short-run (myopic) "quick fix" policies may be far from globally optimum. In fact, from the larger perspective, such policies can be harmful.

The best way to explain the virtues of a holistic view is by contrasting it with narrower perspectives. Consider the problem of waste disposal. It is a consequence of the law of conservation of mass that the total quantity of materials extracted from the environment will ultimately return thence as some sort of waste residuals or "garbo-junk" (Ayres and Kneese, 1969, 1989). Yet environmental protection policy has systematically ignored this fundamental reality by imposing regulations on emissions *by medium*. Typically, one legislative act mandates a bureaucracy that formulates and enforces a set of regulations dealing with emissions by "point sources" only to the air. Another act creates a bureaucracy that deals only with waterborne emissions, again by "point sources." And so forth.

Not surprisingly, one of the things that happened as a result was that some air pollution (e.g., fly ash and SO_x from fossil fuel combustion) was eliminated by converting it to another form of waste, such as a sludge to be disposed of on land. Similarly, some forms of waterborne wastes are captured and converted to sludges for land disposal (or, even, for incineration). Air and water pollution were reduced, but largely by resorting to land disposal. But landfills also *cause* water pollution (leachate), and air pollution, due to anaerobic decay processes. In short, narrowly conceived environmental policies over the past 20 years and more have largely shifted waste emissions from one form (and medium) to another, without significantly reducing the totals. In some cases, policy has encouraged changes that merely dilute the waste stream without touching its volume at all. The use of high stacks for coal-burning power plants, and the building of longer sewage pipes to carry wastes farther offshore exemplify this approach.

To be sure, these shifts may have been beneficial in the aggregate. But the costs have been quite large, and it is only too obvious that the state of the environment "in the large" is still deteriorating rapidly. One is tempted to think that a more holistic approach, from the beginning, might have achieved considerably more at considerably less cost.

In fact, there is a tendency for suboptimal choices to get "locked in" by widespread adoption. Large investments in so-called clean coal technology would surely extend the use of coal as a fuel—an eventuality highly desired by the energy establishment—but would also guarantee that larger cumulative quantities of sulfur, fly ash (with associated toxic heavy metals), and carbon dioxide would be produced. The adoption of catalytic converters for automotive engine exhaust is another case in point. This technology is surely not the final answer, since it is not effective in older vehicles. Yet it has deferred the day when internal combustion engines will eventually be replaced by some inherently cleaner automotive propulsion technology. By the time that day comes, the world's automotive fleet will be two or three times bigger than it might have been otherwise, and the cost of substitution will be enormously greater.

The implication of all these points for policymakers, of course, is that the traditional governmental division of responsibility into a large number of independent bureaucratic fiefdoms is dangerously faulty.[8] Yet the way out of this organizational impasse is far from clear. Top-down central planning has failed miserably and is unlikely to be tried again soon. On the other hand, pure "market" solutions to environmental problems are limited in cases where there is no convenient mechanism for valuation of environmental resource assets (such as beautiful scenery) or functions (such as the ultraviolet radiation protection afforded by the stratospheric ozone layer). This is primarily a problem of *indivisibility*. Indivisibility means that there is no possibility of subdividing the attribute into "parcels" suitable for physical exchange. In some cases this problem can be finessed by creating exchangeable "rights" or "permits," but the creation of a market for such instruments depends on other factors, including the existence of an effective mechanism for allocating such rights, limiting their number, and preventing poaching or illicit use of the resource.

SUMMARY

Needless to say, the policy problems have economic and sociopolitical ramifications well beyond the scope of this paper. However, as the Chinese proverb has it, the longest journey begins with a single step. Developing industrial metabolism as an analytic tool certainly represents one critical step in understanding industrial ecology systems and effecting change toward sustainability.

NOTES

1. This analogy between firms and organisms can be carried further, resulting in the notion of "industrial ecology." Just as an ecosystem is a balanced, interdependent quasi-stable community of organisms living together, so its industrial analogue may be described as a balanced, quasi-stable collection of interdependent firms belonging to the same economy. The interactions between organisms in an ecosystem range from predation and parasitism to various forms of cooperation and synergy. Much the same can be said of firms in an economy.

2. A moment's thought should convince the reader that if the stock in any compartment changes, the stock in at least one other compartment must also change.
3. Another kind of primitive marine organism apparently used hydrogen sulfide as an energy source. The sulfur, released as a waste, combined with the dissolved iron and precipitated out as iron sulfide (pyrites).
4. However, this statement is not true for greenhouse gases in the atmosphere. Already the concentration of carbon dioxide has increased 20 percent since preindustrial times, while the concentration of methane is up 50 percent. The most potent greenhouse gases of all, chlorofluorocarbons, do not exist in nature at all.
5. The special case of indefinite storage in deep underground mines, wells, or caverns, currently being considered for nuclear wastes, is not really applicable to industrial or consumer wastes except in very special and rare circumstances. Surface landfills, no matter how well designed, are hardly permanent repositories, although little consideration has been given to the long-run disposal of leachates.
6. The reserve-to-production ratio has remained close to 20 years. For example, this figure was widely published in the 1920s by Graf, as cited by Rogner (1987).
7. This need not be true for each individual element, however. A major materials substitution within a sector can result in the use of one material increasing, at the expense of others, of course. The substitution of plastics for many structural materials, or of synthetic rubber for natural rubber, would exemplify this sort of substitution. Currently, glass fibers are in the process of substituting for copper wire as the major carrier of telephonic communications.
8. The analogous problem is beginning to be recognized in the private sector, as the legacy of Frederick Taylor is finally being challenged by new managerial/organizational forms. The large U.S. firms, which adopted Taylorism first and most enthusiastically at the beginning of the twentieth century, have been the slowest to adapt themselves to the new environment of intense international competition and faster technological change.

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Colloquium Paper

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2

Industrial ecology: A philosophical introduction

(industry/manufacturing/environment/waste/pollution)

ROBERT A. FROSCH

ABSTRACT **By analogy with natural ecosystems, an industrial ecology system, in addition to minimizing waste production in processes, would maximize the economical use of waste materials and of products at the ends of their lives as inputs to other processes and industries. This possibility can be made real only if a number of potential problems can be solved. These include the design of wastes along with the design of products and processes, the economics of such a system, the internalizing of the costs of waste disposal to the design and choice of processes and products, the effects of regulations intended for other purposes, and problems of responsibility and liability. The various stakeholders in making the effects of industry on the environment more benign will need to adopt some new behaviors if the possibility is to become real.**

The idea of industrial ecology has been evolving for several decades. For me the idea began in Nairobi with discussions at the United Nations Environment Programme (UNEP), where we were concerned with problems of waste, with the value of materials, and with the control of pollution. At the same time, we were discussing the natural world and the nature of biological and ecological systems. There was a natural ferment of thinking about the human world, its industries, and its waste products and problems and about the coupling of the human world with the rest of the natural world.

In August of 1988, the National Academy of Engineering organized a workshop on technology and the environment (1). A group of us, industrial people, academics, and environmentalists, discussed the industrial production of waste, its coupling to the natural environment, and what could be done about it. I was particularly taken with a paper on "Industrial Metabolism," in which Robert U. Ayres traced the pathways of some materials and their transformations through industry and through society. A number of other papers at the meeting dealt with various aspects of the same problem: dematerialization, the "end of pipe" syndrome, and the necessity for considering ultimate waste and disposal as part of process design.

With this background, when writing an article for *Scientific American*, Nicholas Gallopoulos and I found ourselves falling naturally into use of the term "industrial ecosystem," thinking of industry as heavily analogous to the behavior of the natural world with regard to the use of materials and energy (2). We later found ourselves automatically entitling a talk before the United Kingdom Fellowship of Engineering: "Towards An Industrial Ecology," because the ideas had continued to ferment and the ecological analogy seemed natural (3).

The idea of an industrial ecology is based upon a straightforward analogy with natural ecological systems. In nature an ecological system operates through a web of connections in which organisms live and consume each other and each other's waste. The system has evolved so that the characteristic of communities of living organisms seems to be that nothing that contains available energy or useful material will be lost. There will evolve some organism that will manage to make its living by dealing with any waste product that provides available energy or usable material. Ecologists talk of a food web: an interconnection of uses of both organisms and their wastes. In the industrial context we may think of this as being use of products and waste products. The system structure of a natural ecology and the structure of an industrial system, or an economic system, are extremely similar. This may be a somewhat trivial and banal idea, but when consciously addressed it can help us to discover extremely useful directions in which the industrial system might develop.

The ecological analogy is somewhat beyond the metabolic analogy in the sense of carrying the analogy to another level. I think of the organism as being the industrial process or the set of industrial processes that leads to a particular product or product family and of the ecology as being the network of all industrial processes as they may interact with each other and live off each other, not just in the economic sense but also in the sense of the direct use of each other's material and energy wastes and products. What we have generally neglected to do is to integrate the waste fully into the web of industrial relationships. Waste has not really been totally neglected, but it has not been fully integrated into the interacting industrial system. We must include wastes and products at the end of their lives in the industrial food web both as material and as energy.

We need to think of wastes not only as outputs to be prevented by proper choice but also as part of the industrial process product stream that is to be designed. We can think of the waste and of the products at the end of their useful lives not just as things to be gotten rid of but as part of the useful product stream (provided one can become acquainted with somebody who needs that particular kind of waste product) in order to construct an input to some other industrial process. To some degree this has always happened; there is a lot of use of waste material, but it has mostly happened by accident or in fairly isolated cases. (I remember, though, that one of the meat-packing companies had as one of its mottos: "We use everything from the pig but the squeal!")

Some companies have looked for and found opportunities for particular waste streams, and some wastes are routinely brokered, bought and sold, or handled by waste exchanges, but in general these may be described as islands of exception. For example, it is common that the wastes from the acid "pickling" of steel are used as materials for water treatment, and are sold in the chemicals market. These wastes are the cheapest source of ferrous sulfate and ferrous chloride.

Processes can be, and sometimes already are, designed so that they will accept wastes that are known to be coming from other processes, and new processes can be designed so that

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their wastes are designed to be useful to other processes. This also implies designing products with the same result in mind: to not only design the product for its useful life but also for its potential uses as process input material at the end of its normal useful life.

We need some systematic adoption of these ideas so that it becomes the normal practice to use them in choosing and designing processes not only to minimize waste but also to think of waste and exhausted or discarded products as outputs designed to be used as inputs elsewhere in the industrial system. We need to think of wastes from other processes and producers and of exhausted or discarded products as potential inputs when new processes and industrial systems are being chosen and designed.

The preceding remarks lead to some problems and questions for the industrial world. Those of us who are in the industrial business and deal with such matters are now saying to ourselves: "Well, that's another painful constraint on a very difficult problem. It is already difficult enough to design processes and products; if we now try to design the waste systems both as input and output as well, it will be another painful complication in an already complicated problem." (However, there is something to be said about the potential economic benefits of these possibilities, to which point I will return later.) We now have a new and larger-scale system optimization problem: not just the problems of balancing the cost of product and process choice and of looking for markets and suppliers in the normal sense but also of seeking to incorporate the problems of waste disposal, material recycling, and product end-of-life recycling into the whole process.

This new optimization problem poses a new set of questions about the cost optimization of industrial processes. For example, there is a cost to shifting a process in the direction of preventing a particular waste stream. Separately there might be a different cost if one were to change or adjust processes not to prevent the waste but to change its nature, so that it becomes a more valuable "waste" when seen as an input for some other process somewhere else. These are two potential engineering and cost-optimization possibilities, and presumably they can enter the trade-off thinking in designing the manufacturing system in the same manner as other possibilities. We would expand the concept of the product of the manufacturing system to include the waste and would design the waste for its value along with the design of the product in the normal sense.

(This leads me to a question I have not been able to answer: whether there is a good industrial analogue to the microorganism. Microorganisms do a fantastic amount of the digestion and cleanup work on the planet. I am not sure there is a convenient industrial analogue, but it may be worth thinking about.)

I turn now to some short remarks about several cases of reuse and recycling of particular industrial materials. These cases are illustrative of several points about industrial reuse problems. Somewhat more detail on these cases may be found in ref. 3, along with references to some of the applicable literature.

I will begin with a few remarks concerning plastics. General Motors reuses virtually all of its factory fabrication waste of PVC (polyvinyl chloride). PVC can easily be segregated by color, reground, and put through the process again. However, once PVC has been made into a vehicle in which it is mixed with other plastics and other materials, there is a problem in knowing what to do with it because the various materials may be difficult to separate and identify.

Another possibility for waste materials, and particularly for products at the end of their lives, is that they may cascade down a kind of industrial food chain through a series of more and more degraded uses.

Plastics have begun to be an interesting example of this. They are extremely difficult to recycle into direct uses largely because they turn up in products mixed together and are not identified as to chemical type. The various chemical types require different kinds of treatment for reuse, so they can be very difficult to recycle when mixed, although new methods are continually being found. In a plant, it is frequently possible to reuse the plant waste if it is a reusable material because you know exactly what it is.

Plastics are not easily reusable for anything that is involved with food because they generally do not survive good sterilization temperatures without severe degradation. Plastic food containers tend to be recycled down the industrial food chain and go into pipe and more and more degraded and lower quality uses, eventually being useful presumably only for their embodied energy as fuel.

The iron case is probably the most elaborated of all the material cycles. It exhibits some interesting examples of shifts in recycling as technology changed. When there was a shift from the open-hearth process to the basic oxygen process, which took place because the basic oxygen process is more efficient in a number of ways, the amount of scrap that could be disposed of by remelting decreased drastically because the basic oxygen process can use much less scrap than an open hearth. When there was a further shift to the electric furnace, which uses scrap almost exclusively, there was a shift to more use of scrap, but the balance in industry use between open-hearth, basic oxygen, and electric-furnace processes was such that in the end we ended up with more unused scrap in the basic iron business than was the case in the open-hearth days.

The tale of some of the industrial uses of iron is, of course, the same as in plastics: offal and iron and steel waste can be used directly by the industry that produces it. General Motors buys steel as sheet steel only; all of our iron castings are made from a mixture of the scrap cuttings from making the sheet steel parts plus some reuse of old engine blocks. We buy no steel or iron for the foundries except scrap, and it is mostly our own internally generated scrap.

The platinum group of noble metals is yet another interesting example. They used to be completely recycled because the only use for the platinum group metals was for some scientific and other instruments and jewelry. The value was high, the reprocessing was easy, and the collection of the material in pure form from private hands was so straightforward that it was always possible to obtain easily reusable metal.

Now that we are using a lot of platinum group metals dispersed in automobile catalysts we have a new problem. While there is a valuable mine of platinum metals beginning to build up in the scrapyards, the industry of collecting and recycling that material is only now beginning. The cost of collecting the material is the dominant cost. Once you have the catalyst, it is rather cheap to recycle the material. What the collection and recycling cost leads to is a requirement that the price of platinum has to be more than about $500 an ounce for it to be worthwhile to collect and recycle. Until the past year or so there have not been enough catalysts available in the scrap yards to support a real industry. Recycling of the platinum and rhodium is now beginning to get started, and there are a number of firms in the business.

The examples just given are generally cases of direct recycling and do not generally involve elaborate connections among industries. However, they suggest some problems that are interesting. There may be a disparity in the natural flow of materials between the available wastes and the possible requirement for their use as raw materials. The availability of such waste provides an opportunity for their use as cheap input material if processes or products can be devised to take advantage of them. The problem of collecting dispersed wastes, particularly when they appear in the form of products at the end of their lives, may be challenging because these wastes may be dispersed very widely geographically, and collection, transportation, and separation costs may be nontrivial. There are, of course, the problems of process compatibilities for new types of input materials (metals may be in the wrong valence form, for example). New processes or variations on old processes may have to be devised if waste materials are to be used as process inputs.

Problems also arise from statutes and regulations that may not be appropriate to new waste-utilization opportunities. We have all heard tales of possible uses of hazardous waste materials as inputs to other processes that were impossible to realize because the would-be user and would-be supplier could not solve the problem of getting transportation permits to get the material from the place where it was generated to the place where it could be used. This seems rather foolish, since a transportation permit to *some* place is likely to be required for either destruction or disposal. Refusal to permit transport results in generating a hazardous waste-transportation problem *and* a hazardous waste-disposal problem, instead of generating only a hazardous waste-transport problem, with disposal of the material being an economical input to an industrial process. This is not an argument for no regulation of hazardous or troublesome materials but rather is an argument for regulation appropriate to the problem: regulation that will encourage reuse and recycling in an industrial ecology rather than regulation that turns out to interfere with sensible solutions. An industrial ecology point of view will require that we rethink how we want to regulate waste materials of all kinds.

There are also potential problems arising from liability and responsibility in the transfer of regulated wastes. A generator of a regulated waste may be reluctant to put it in the hands of a broker or waste exchange or even to sell it to a user if the responsibility for ultimate disposal by reuse, destruction in the course of process use, or ultimate disposal cannot also be transferred. It may not be satisfactory to be able only to rent out the use of the material to a sequence of industrial users if the ultimate responsibility cannot be transferred with the material. This problem is already hampering the brokered exchange of some types of waste materials. General Motors is sometimes reluctant or refuses to transfer regulated waste to brokers, waste exchanges, or potential users because it cannot get rid of the legal responsibility for the material and is not sure it can trust the downstream users. We need some new thinking about law and regulation in this area.

The problem that has been outlined is dominated by its intricacy—by its glittering complexity. How can we somehow encourage the growth of the web of interactions of waste production and waste use, as well as waste prevention and some inevitable disposal, to grow into a better integrated and a more elaborated system, with more waste being prevented and with more being cycled through the industrial web and thus with less of it appearing at the end of the industrial system to become a disposal and an environmental problem?

It is known in a number of ecological systems that if a certain system component, an organism, disappears, the entire nature of the system changes, and other organisms may vanish as well, even though their connection with the originally disappearing organism is very indirect and far from obvious. This appears to be the case with predatory fish in lakes and ponds; the absence of a predator can make the whole pond "sick." Sometimes one can correct the problem in such a system by specifically introducing a species that will fill the particular place in the system web. We might consider the problem of "stocking" the industrial pond to make other parts of the web of material cycling operate correctly. Economists will say that this will happen naturally if the values, the costs, and the profits to be made are correct. However, this does not necessarily happen automatically in the natural ecology case, and we might have to stimulate the invention and stocking of some new industrial organisms into the industrial ecology for the purpose of getting a better or preferred balance in the system. Perhaps simply providing public information on the business opportunities available in such cases might do the trick, or perhaps special economic measures might be required for startup.

The problem of cost has been much studied in its system aspects by both ecologists and economists, but the problem of internalizing the costs of handling external wastes, and particularly the problem of internalizing societally diffused costs into the internal cost management systems of industrial enterprises, has not really been solved. In industry, senior managers are conscious that we are paying for waste disposal and transportation and for the more subtle societal costs, even when we have not been directly charged for them. We are paying for these things in direct charges, in taxes, and in loss of public amenities. There is an opportunity for cost minimization within the enterprise if we can figure out a reasonable way to take those costs and reflect them back into the process.

Our product and process design engineers and operating managers are not usually in a position to do a sensible job of incorporating waste questions and environmental questions in their designs or their operations. They have no idea where or what the costs are that they are either avoiding or including by the nature of the design and the manner of operation. The nature of our standard accounting systems is such that those costs appear very far away in the bookkeeping; nowhere in the system do you find out how to attribute such an external cost to a particular design or operating decision. (An engineer who chooses a cadmium-coated fastener may do so in preference to a fastener without the cadmium material coating because the alternative fastener costs more; the price of the cadmium coating as it appears to the engineer does not include the cost of disposal of contaminated plant waste and certainly not the societal cost of final disposal of the bolt when the car is junked.) We sometimes affect such issues artificially by making a manager responsible for solving relevant in-plant problems or by forbidding the use of some materials totally (in effect, by regulation), but the plant operators and design engineers are usually unaware of many external costs as part of their usual management information. A part designer has no way of knowing the effects of design choices and alternatives on such external costs. We need some new internal accounting and bookkeeping methods so that we can understand what it is we are paying for in the total system and to be able automatically to take these costs into account in our design and management trade-off decisions.

This raises the question of how we can get to such an industrial ecology system without using some massive central planning process in which we pretend to design the industrial system from the top down. We have to avoid any temptation to proceed in that direction because it is so clearly not possible and will lead to failure. (I find it curious that after 70 years, when the Eastern Bloc has finally decided that they do not really know how to plan and manage a central economy, most large United States industrial enterprises are beginning to pretend that they do know how to do strategic central planning.) In any case, we do not want to move in the direction of so carefully planned and tightly integrated an industrial system that it becomes fragile because each part is too tightly coupled to and dependent on specific other parts and their specific characteristics. We would like to continue to have a robust, flexible system. We would really like a system that would "self-organize" to accomplish waste minimization by the various methods discussed above.

We need to look for some way in which we can adopt a modest set of policy initiatives, be they economic incentives, taxes, accounting system changes, or other methods that will nudge the components of the industrial system to internalize environmental costs and the results of producing waste materials. We want to move the total system web in the direction of minimizing the production of waste and designing the remaining wastes so as to facilitate the trading, recycling, and reuse of wastes. We need also to find incentives for the design of products so that they are easier to reuse as input materials at the end of their useful lives. It is not clear how to do these things.

There are probably many incentive systems that would be better than direct regulation. For example, we might want to induce a differential cost between virgin materials and waste or recycled materials. It would be useful to try a good deal more brokering of waste. This has been tried in various places in a small way, but it is not always easy to find out what waste products are available and their precise nature. It might be useful for such information to be more easily available than it is now.

I would like to introduce a cautionary note about policy manipulation. The industrial system is strongly nonlinear; it is difficult to predict which way a particular policy change, such as a tax, is likely to move the system as it responds and adjusts to the change. Congress learns this every time it passes a tax law intended for a particular purpose and then discovers that the system does something else with it than the Congress had ever intended or even thought about. They always seem to be shocked and surprised at this, even though the first thing that every accountant and lawyer does is figure out how to make the new tax law work for their clients. It will be necessary to take an experimental attitude and see how things work before we conclude that a particular idea is a panacea. This necessity is unfortunately in conflict with the desire of everyone in business to have a stable policy framework in which to operate. Somehow we need to find a way to combine reasonable stability with the possibility of policy adjustments as we discover the real effects of the policies we try.

I would like to conclude with some advice to particular communities of stakeholders in the outcome of these problems.

Engineers, product and process designers, must take more account of waste generation and waste use and of the problems of product disposal at end of life and must consider waste minimization as part of the cost equation in designs. We need better methods for informing them of these costs at appropriate points in the design cycle.

The business community must think much more about internalizing the waste problem. That has begun to happen; we are beginning to shift from disposal to prevention. We now have to think about the problem of using each other's wastes, of designing wastes to be useful as part of designing product, and of designing product so that when it becomes waste it is easier for the industrial system to use and accept. Business methods will be needed to provide appropriate information during the design and manufacturing cycle.

Legislators, policy makers, and regulators will have to start thinking about the system and stop thinking about the problem of the month. We cannot continue to regulate this system while ignoring its system aspects.

The business and engineering schools are really going to have to start teaching environment and system in a serious way, really producing engineers and managerially and financially trained people who can think about these problems in a much broader way than they now do.

Environmental activists will have to drop their subscriptions to the "horror-of-the-month-club" and start thinking seriously about systems ecology in the natural and industrial worlds, not just talking about ecology and then acting in a nonsystems way with regard to particular items.

It would be useful if the self-appointed helpful would stop running around yelling "FIRE" on the off chance that they might find themselves in a crowded theater and start a panic.

Finally, together we must find a way to end the polarization on environmental and waste issues and find a way to bring various views together to bring a better integrated industrial ecology into being; a system that will really be able to minimize waste by both preventing and using it.

I have tried to outline some ideas about industrial ecology, to raise some issues, to pose some problems, and to suggest some possibly useful directions. We have a great deal to do, but we must remember that the time scale for cultural and system change is likely to be long. We cannot be impatient with this problem. It takes a long time to shift a gigantic social system into a useful direction, and there will be no doubt many failed experiments along the way. Insistence on no failures is also insistence on no experiments. We must begin to try.

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2

Sustainable Development by Design: Review of Life Cycle Design and Related Approaches

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The environmental profile of goods and services that satisfy our individual and societal needs is shaped by design activities. Substantial evidence suggests that current patterns of human activity on a global scale are not following a sustainable path. Necessary changes to achieve a more sustainable system will require that environmental issues be more effectively addressed in design. But at present much confusion surrounds the incorporation of environmental objectives into the design process. Although not yet fully embraced by industry, the product life cycle system is becoming widely recognized as a useful design framework for understanding the links between societal needs, economic systems and their environmental consequences. The product life cycle encompasses all activities from raw material extraction, manufacturing, and use to final disposal of all residuals.

Life cycle design (LCD), Design for Environment (DFE), and related initiatives based on this product life cycle are emerging as systematic approaches for integrating environmental issues into design. This review presents the life cycle design framework developed for the U.S. Environmental Protection Agency as a structure for discussing the environmental design literature. Specifying environmental requirements and evaluation metrics are essential elements of designing for sustainable development. A major challenge for successful design is choosing appropriate strategies that satisfy cost, performance, cultural, and legal criteria while also optimizing environmental objectives. Various methods for specifying requirements, strategies for reducing environmental burden, and environmental evaluation tools are explored and critiqued. Currently, many organizational and operational factors limit the applicability of life cycle design and other design approaches to sustainable development. For example, lack of environmental data and simple, effective evaluation tools are major barriers. Despite these problems, companies are beginning to pursue aspects of life cycle design. The future of life cycle design and sustainable development depends on education, government policy and regulations, and industry leadership but fundamental changes in societal values and behavior will ultimately determine the fate of the planet's life support system.

Sustainable development seeks to meet current needs of society without compromising the ability of future generations to satisfy their own needs. We define sustainable development as a dynamic state that harmonizes economic activities with ecological processes. Our industrial society is not yet on a path towards sustainability.[1-3] The global model developed by Meadows (1992) simulates future outcomes of the world economy by analyzing five primary factors: population, industrial capital, food production, resource consumption, and pollution. This model predicts that major changes in the way humans interact with the natural world will be necessary to achieve a sustainable economy. Although other global economic models envision essentially no limits on growth and rising standards of living,[4] it seems more likely that sustainable development will require a reduction in population along with significant changes in patterns of consumption[5,6] and economic systems. Evidence suggests that conflicts and economic disruptions have already resulted from maldistribution and depletion of otherwise renewable resources.[7]

It may be relatively easy to envision sustainable development but it is much more difficult to change the political, economic, technological, social, and behavioral forces that define our present unsustainable activities. Because the state of the environment is now so influenced by the composite of individual human behaviors and values, preserving the planet's life support system for ourselves and future generations requires the broadest, most fundamental changes. Clearly, no single discipline or set of actions can hope to achieve sustainable development in isolation.

The complexity of issues influencing sustainability can be shown through organizational hierarchies for several critical systems. Table 1 shows organizational hierarchies for three types of systems that provide a boundary for human activities. The web of interactions and links between economic and ecological systems determines the sustainability of human activities. The new field of industrial ecology[9-11] studies how economic and ecological systems shape and influence each other. At present, most design initiatives for achieving sustainable development concentrate on the product system, which is the most basic link between societal needs and the global ecosystem.

Attempts to foster sustainability through design are in an embryonic state. Most current design methods do not explicitly address environmental issues.[12] Not surprisingly, confusion frequently surrounds the design of cleaner products and processes. Products have been labeled clean, earth friendly, green, ozone friendly, recyclable, or biodegradable, even though their impact on the environment may be undocumented or unproven. Some green marketing campaigns have resulted in guidelines and regulatory responses to prevent misleading environmental claims.[13,14] Although public concern for the environment has now been targeted and the level of environmental awareness possibly raised, an effective design response remains the challenge.

Sustainability through design requires integrating environmental issues into a product development process that must also meet many other demands, such as global competitiveness, shortened development cycles, and high quality at least cost. Initiatives now attempting to provide guidance to designers include life cycle design (LCD), design for environment (DFE), and ecodesign. These initiatives are all based on the life cycle framework, which considers the full environmental consequences of a product from raw materials acquisition through manufacturing and use to final disposal of wastes.

This review focuses on integrating environmental issues into product development. It will address durable and nondurable goods rather than architectural or graphic design, although many of the same principles apply to all disciplines. We begin with an overview of the major environmental issues that provide the context for design approaches to sustainable development. This subject is often confused because boundaries of the system under design and goals for product development are not clearly defined. To clarify this issue, we introduce a definition for the product system and present specific goals for life cycle design.

Because life cycle design is a dauntingly large, rapidly expanding subject, we only attempt to highlight major principles and state-of-the-art approaches. We have chosen to use the life cycle design framework recently developed for the EPA[15] as a structure for discussing the design process, design strategies, and evaluation tools.

Table I. Various organizational hierarchies.(after 8)

Geographic and Political	Economic	Ecological
World	Global human material & energy flows	Ecosphere/Biosphere
Continent	Sectors (e.g. transportation, health care)	Biogeographic region
Nation	Corporations and institutions	Biome
Region	Product systems	Landscape
State		Ecosystem
County		Organism
Town		
Human population		
Individual		

Table II. Purchased world energy consumption, 1988.[16]

Resource	Annual Use (quads)[1]	Percent of Total	Reserves[2] (quads)	Years of Supply at 1988 use rates
Oil	121	38%	7000	60
Coal	96	30%	150000	1500
Natural Gas	20	20%	8000	120
Hydroelectric	22	7%		
Nuclear	17	5%		

[1] A quad is 10^{15} BTU.

[2] Economically recoverable; includes known and estimated undiscovered reserves. Undiscovered coal is estimated at 10 times known reserves, oil and gas at less than half known reserves.

Overview of Environmental Problems

Tangible environmental degradation underlies the growing interest in sustainable development and life cycle design. The material demands of our current society inevitably cause environmental stresses that damage our planet's life support system. In attempting to evaluate the state of the environment, it is useful to examine trends in resource use and waste generation.

Resource Consumption and Depletion

Environmental damage caused by human activity begins with consumption of renewable and nonrenewable resources. Renewable resources are capable of being replenished quickly enough to meet near-term demand. At present, renewable resources such as water, forests, and soil are being heavily exploited,[1] resulting in a significant loss of biodiversity. The manner in which these renewable resources are used and managed also determines the level of their sustainability. Overuse can damage ecosystem structure and function, thereby lowering future sustainable yields. Thus, although a resource can appear renewable at current usage, exploitation at the same rate may not be possible for long due to impacts that affect both the resource itself and related ecosystem elements. Increasing consumption of nonsustainable resources seems more obviously self limiting. Energy, now derived primarily from fossil fuels, is one of the most critical needs of our industrialized society and also a prime example of human reliance on nonrenewable resources. The world now depends on fossil fuels for 88 percent of all purchased energy.[16] Table II shows the annual rate at which different energy supplies are consumed.

Increasing world energy use is presented in Figure 1. This figure includes a plot of the expanding world population, showing that as population increased 3.5 times in the last 100 years, energy use increased 13 times.[17] Calculations in the figure are based on total power use, including traditional biomass fuels such as wood, crop wastes, and dung. Fossil fuel use actually rose by a factor of 20 in the last 100 years. Although only about 23% of world population are citizens of the developed world, they account for two-thirds of total energy demand. Thus people in the developed world consume 6.8 times more energy per capita than citizens in less developed countries.[17]

Each year 500 million vehicles consume half of the world's oil or 19 percent of total energy demand.[18] Industrial processes consume another 40 percent of energy demand each year in the developed world.[19] Energy seems relatively abundant in the short term, but our heavy reliance on non-renewable fossil fuel sources and the continued exponential increase in demand as developing countries become more industrialized suggest that future sources and patterns of use must change substantially.

Pollution and Waste Generation

In addition to problems created by depletion, resource and energy use ultimately produce residuals that create significant environmental impacts. Many residuals are temporarily concentrated in landfills, while others are immediately dispersed throughout the ecosphere. A comparison of anthropogenic and natural fluxes of toxic metals on a global scale provides one example of the environmental problems created by human activity. Human actions dramatically increase the dispersion of these toxic metals.[20,21] Widespread accumulation of toxic metals in the biosphere is generally harmful, and thus not compatible with sustainable human practices.[22] The implication for toxic metal production - substantial reduction in mining virgin ores, and virtual elimination of their releases as residuals, applies to other hazardous and toxic materials if humans are to achieve a sustainable society.

Dispersing pollutants into the environment may cause irreparable damage. For example, fossil fuel combustion releases greenhouse gases that can lead to global warming. Fossil fuel combustion accounts for approximately 70% of greenhouse gas emissions from human activity. Using one index of greenhouse gas loading, the United States, former Soviet Union, Brazil, China, India, and Japan account for 50% of global increases in greenhouse gases each year. Although the severity and distribution of potential climate change is as yet unknown, it already appears that average global temperature will rise from 1.5 to 2.5 degrees Celsius in the next 60 to 100 years. This could cause major human and ecological dislocations. Given current practices, it will be difficult to avoid the consequences of climate change. Just to stabilize atmospheric concentrations of greenhouse gases at current levels, emissions of many species will have to be reduced by about 80 percent.

Other environmental consequences of human activity, such as ozone depletion, can also affect the entire planet. A global perspective is necessary to understand these broad environmental issues, but local and regional problems should also be considered when evaluating sustainability. Local issues often dominate the environmental agenda because they seemingly affect individual lives more directly, even though greater benefits might be achieved by addressing problems that exist on regional and global scales.

In the United States and other countries, municipal solid waste (MSW) generation reflects increasing resource consumption. In 1960 the United States generated 2.65 pounds of MSW per person per day. This compares to the nearly 4 pounds per person generated daily in 1988. By 2010, per capita daily generation is expected to reach 4.9 pounds. As Figure 2 shows, both gross and net discards have been trending upwards recently. Even after material recovery, net discards nearly doubled between 1960 and 1988. Consumer products account for a significant fraction of MSW, but industrial production generates the vast majority of this nation's solid and hazardous waste. Each year, U.S. industries produce 10.9 billion tons of nonhazardous waste reported under the solid waste management provisions of the Resource Conservation and Recovery Act (although classified as solid, wastewater accounts for 70 percent of this total). US industries also generate 700 million tons of hazardous waste annually.

Once designers recognize that environmental problems need to be addressed in their work, establishing priorities can help concentrate efforts on the most critical areas. The following priorities for environmental impacts set by the Ecology and Welfare Subcommittee of the Science Advisory Board of the U.S. EPA provide one example of such a global ranking:

Relatively High-Risk Problems
- Global climate change
- Habitat alteration and destruction
- Species extinction and overall loss of biodiversity
- Stratospheric ozone depletion

Relatively Medium-Risk Problems
- Acid deposition
- Airborne toxics
- Herbicides/pesticides
- Toxics, nutrients, biochemical oxygen demand, and turbidity in surface waters

Relatively Low-Risk Problems
- Acid runoff to surface waters
- Groundwater pollution
- Oil spills
- Radionuclides
- Thermal pollution

Items within the three groups are ranked alphabetically, not by priority. The EPA undertook this study to target environmental protection efforts on the basis of opportunities for the greatest risk reduction. In developing the hierarchy, EPA considered reducing ecological risk as important as reducing human health risk. Of course, many human actions are interrelated and produce multiple consequences, so assigning environmental priority to specific actions will be complex. Furthermore, it is difficult to apply such global rankings to design of a discrete product. For example, companies are much more likely to focus on reducing toxic releases, especially those that are regulated, rather than reduce releases of greenhouse gases such as carbon dioxide.

System Definition

Defining the system is fundamental to any design activity. The definition of the product system begins with a clear statement of the basic societal needs being met by the design. In the project initiation stage, design teams determine the scope of their activity but frequently do not explicitly state the spatial and temporal boundaries of the proposed design. In life cycle design, boundaries should usually be determined by the full environmental consequences arising from a product system. The physical dimen-

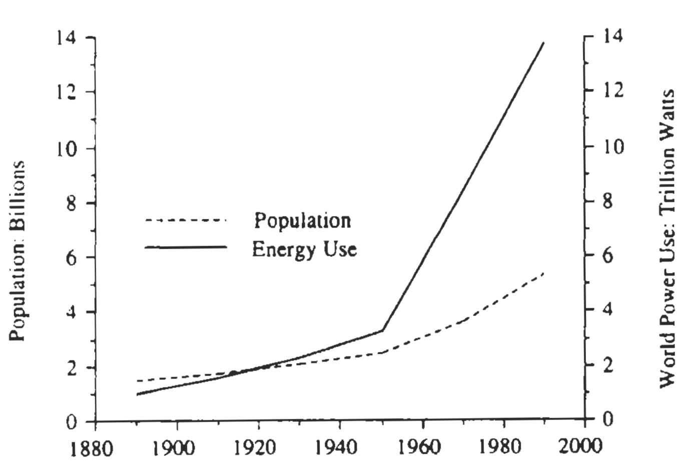

Figure 1. World population and power use.

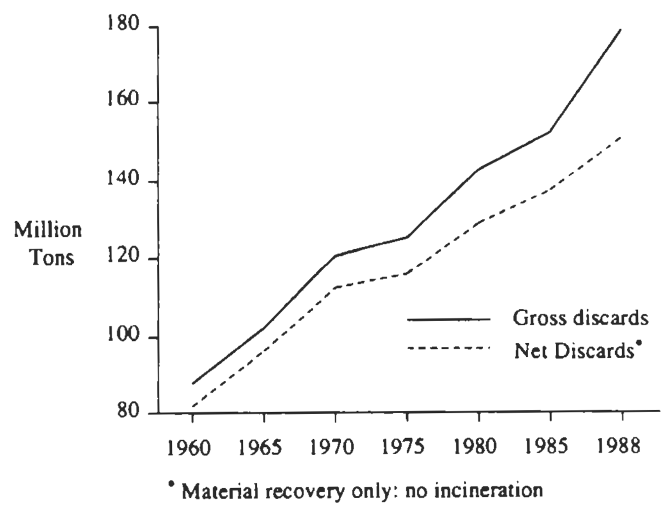

Figure 2. Trends in gross and net discards of U.S. municipal solid waste.

sions of the system encompass the material and energy flows and transformations associated with an entire product life cycle. In the process of defining boundaries for a design project, the various groups potentially impacted by the design should also be identified.

The product life cycle provides a logical framework for sustainable design because it considers the full range of environmental consequences and other stakeholder interests associated with a product. By addressing a life cycle system, designers can help prevent shifting impacts between media (air, water, land) and between other life cycle stages. This framework also includes stakeholders (e.g., suppliers, manufacturers, consumers/users, resource recovery and waste managers), whose involvement is critical to successful design improvement. The life cycle system is complex due to its dynamic nature and its geographic scope. Life cycle activities may be widely distributed over the planet, and they may also create environmental consequences on global, regional, and local levels.

Life Cycle Stages

Several diagrams have been proposed to represent the product life cycle.[15,12,16] Figure 3 is a general diagram which shows the circular nature of material and energy flows through a product life cycle. On an elementary level, every product requires that resources be consumed and wastes generated which accumulate in the earth and biosphere. A product life cycle can be organized into the following stages:

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

Raw materials acquisition includes mining nonrenewable material and harvesting biomass. These bulk materials are processed into base materials by separation and purification. Examples include flour milling and converting bauxite to aluminum. Some base materials are combined through physical and chemical means into engineered and specialty materials. Examples include

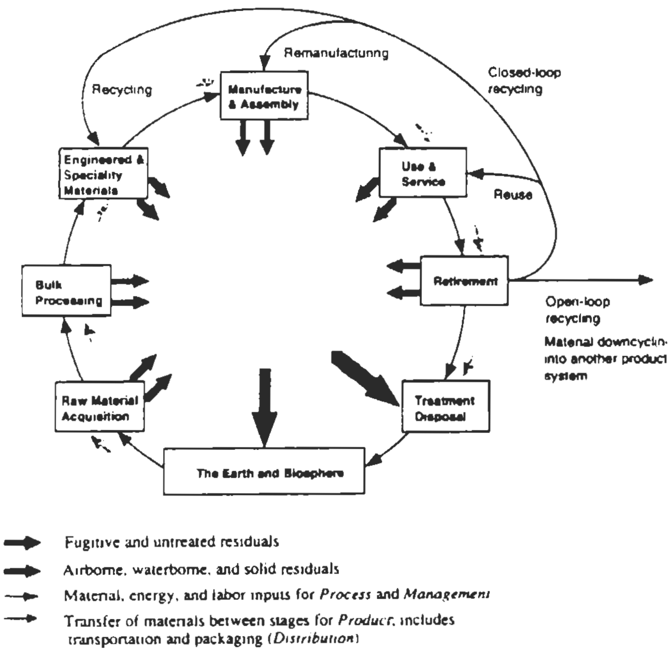

Figure 3. The life cycle system.

polymerization of ethylene into polyethylene pellets and the production of high-strength steel. Base and engineered materials are then manufactured through various fabrication steps, and parts are assembled into a final product.

Products sold to customers are consumed or used for one or more functions. Throughout their use, products and processing equipment may be serviced to repair defects or maintain performance. Users eventually decide to retire a product. After retirement, a product can be reused or re-manufactured. Material and energy can also be recovered through recycling, composting, incineration, or pyrolysis.

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

Product System Components

A product system is characterized by both a physical flux of material and energy as well as a flux of information across each stage of the life cycle.[15,16,17] The entire system can be organized into four basic components: product, process, distribution and management. As much as possible, life cycle design seeks to integrate these components.

Figure 4 gives a limited example of elements in the product system of a plastic cup over its life cycle. Although far from complete, this simplified example illustrates how components are defined across the life cycle.

Product. The product component consists of all materials constituting the final product and includes all forms of those materials in each stage of the life cycle. For example, the product component for the plastic cup shown in figure 4 consists of petroleum or natural gas from raw material acquisition; the high density polyethylene (HDPE) pellets, stabilizers, and pigments that are molded into cups; and the discarded cup or residuals from recycling in a municipal solid waste landfill. Gases, water vapor, ash, and other substances related to pigments and stabilizers are produced if the retired cup is incinerated.

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

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

- Facility or plant
- Unit operations or process steps
- Equipment and tools

	Raw Material Extraction	*Bulk Processing/ Engineered Mat.*	*Manufacturing*	*Use*	*Retirement/ Disposal*
Product	Petroleum Natural gas	HDPE pellets Stabilizers, pigments	Cup	Cup	Cup or residuals from recycle, incineration
Process	Drilling equipment, labor, energy	Ethylene production, polymerization	Injection molding	Handling, filling, cleaning	Collect, process Recycle, burn, or landfill
Distribution	Pipeline and tankers	Rail, barge, truck, containers	Transport, wholesale, retail, pckg	Trucks, containers	
Information/ Management	Valdez principles TRI data	Corporate environmental goals	Product labeling Office management		SPI markings for recycling

Figure 4. Partial example of product system elements for a reusable plastic cup over its life cycle.

- Labor
- Direct and indirect material inputs
- Energy

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

Distribution. Distribution consists of packaging systems and transportation networks used to contain, protect, and transport products and process materials. Both packaging and transportation result in significant environmental impacts. Packaging accounted for 31.6 percent of municipal solid waste generated in the US in 1988.[26] Material transfer devices such as pumps and valves, carts and wagons, and material handling equipment (forklifts, crib towers, etc.) are also part of the distribution component.

Distribution is sometimes considered a life cycle stage (between manufacturing and use) but in the product system, distribution links all stages. For example, materials and energy require transportation and containment to move between the extraction and bulk processing life cycle stages, just as products require the same to move between manufacturing and use, and then between the use and disposal stages. Thus the distribution component exists throughout the life cycle of a product.

Storage facilities such as vessels and warehouses are necessary for distribution and thus included in this component. In addition, both wholesale and retail merchandising is considered part of distribution.

Management. The management component includes the entire information network that supports decision making throughout the life cycle. Within a corporation, management responsibilities include administrative services, financial management, personnel, purchasing, marketing, customer services, legal services, and training and education programs.

Interconnected Product Systems

Each product system contains many product life cycles within it. The interconnected state of these systems complicates analysis but also offers opportunities for reducing environmental impact. On the product system level, products are interconnected through material exchange or common processes activities. Figure 5 shows how product systems can be linked through recycling. This demonstrates the need for designers to address how product systems fit into a larger industrial web of highly integrated activities.

Goals for Sustainable Development

The fundamental goal of life cycle design is to promote sustainable development at the global, regional, and local levels. Principles for achieving sustainable development should include: sustainable resource use (conserve resources, minimize depletion of non-renewable resources, use sustainable practices for managing renewable resources), maintenance of ecosystem structure and function, and environmental equity. These principles are interrelated and highly complementary.

Sustainable Resource Use

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

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

Ecological Health

Maintaining healthy ecosystem structure and function is a principle element of sustainability. Because it is difficult to imagine how human health can be maintained in a degraded, unhealthy natural world, the issue of ecosystem health should be a more fundamental concern. Sustainability requires that the health of all diverse species as well as their interrelated ecological functions be maintained. As only one species in a complex web of ecological interactions, humans cannot separate their success from that of the overriding system.

Environmental Equity

The issue of environmental equity is as complex as the subject of sustainable development. A major challenge in sustainable development is achieving both intergenerational and intersocietal environmental equity. Over-consuming resources and polluting the planet in such a way that it enjoins future generations from access to reasonable comforts irresponsibly transfers problems to the future in exchange for short-term gain. Beyond this intergenerational conflict, enormous inequities in the distribution of resources continue to exist between developed and less-developed countries. Inequities also occur within national boundaries. Pollution and other impacts from production are also unevenly distributed.[18] Studies show that low-income communities in the United States are often exposed to higher health risks from industrial activities than are higher-income communities.[19] Inconsistent

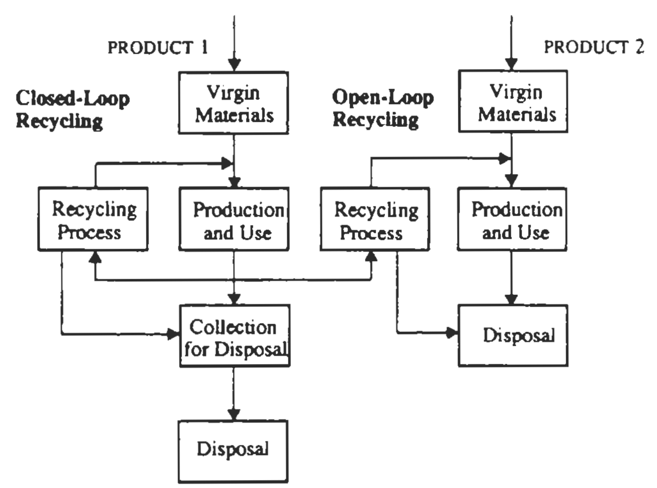

Figure 5. Links between product systems in closed- and open-loop recycling.

regulations in the US have also led to different definitions of acceptable risk levels for workers and consumers.[40]

Specific Objectives of Life Cycle Design

Life cycle design applies sustainable development principles at the product system level. The environmental goal for life cycle design is to minimize the aggregate life cycle environmental burden associated with meeting societal demands for goods and services. One method for characterizing the aggregate impacts for each stage and the cumulative impacts for the entire life cycle is an environmental profile, such as that illustrated in Figure 6. This figure shows a hypothetical impact profile because at present there is no universal method for characterizing environmental burden so precisely. As illustrated, impacts are generally not uniformly distributed across the life cycle. It is also important to recognize that human communities and ecosystems are also impacted by many other product life cycle systems.

Evolution of Life Cycle Design and Related Approaches

This section highlights the evolution of life cycle design and related design-based approaches for sustainable development. Major concepts introduced here will be elaborated later. Until recently, the life cycle framework has been much more widely associated with environmental assessment than design. Life cycle assessment (LCA),[14,15,41] resource and environmental profile analysis (REPA),[42] and ecobalance[43,44] are all methods for evaluating the life cycle environmental consequences of a product from "cradle to grave." LCA and related approaches are evaluation tools, not design methods. There are thus quite distinct from life cycle design (LCD). Although LCA may be employed as an analysis tool in LCD, its application for this purpose is currently very limited.[45]

As early as 1962, Asimow developed a life cycle framework for engineering design in *Introduction to Design*.[36] He organized a design project into seven phases consisting of primary design (I-III) and planning for the "production-consumption cycle" (IV-VII), which included production, distribution, consumption, and recovery or disposal. In planning for retirement (phase VII), he introduced the following guidelines which have been adopted by most current environmental design programs:

- Designing physical life to match anticipated service life.
- Designing for several levels of use so that when service life at a higher level of use is terminated, the product will be adaptable to further use at a less demanding level.
- Design the product so that reusable materials and long-lived components can be recovered.

Asimow explicitly stated the importance of "socio-ecological" systems on design and their interrelationship with the production-consumption cycle. More recently, the importance of the product life cycle in design has gained broader recognition.[15,32,33,37,46-52]

Pollution prevention, with its emphasis on proactive environmental protection rather than end-of-pipe control and treatment,[53] provides a fundamental philosophy for life cycle design. Life cycle design adopts a similar multimedia approach and extends it

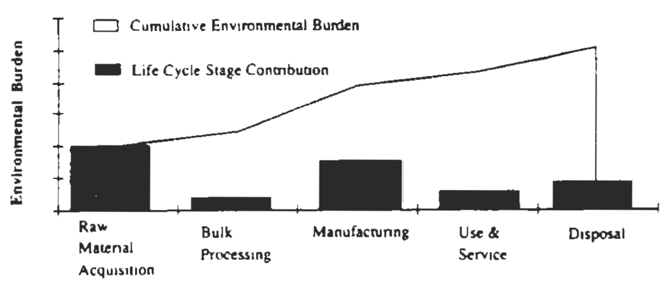

Figure 6. Aggregate environmental burden over life cycle of hypothetical product system.

over the entire life cycle to prevent shifting pollutants between media or life cycle stages.

In the past, product and process design have been treated as two separate functions in a linear design sequence: product design followed by process design. While environmental progress has been made in the last two decades through process design, product-oriented approaches to sustainable design are now receiving more attention.[54] LCD seeks to integrate product and process design in a single function to more effectively reduce aggregate environmental impacts associated with product systems. This principle of LCD originates from concurrent design programs.

Design for Environment (DFE) is another widely used term for incorporating environmental issues into a concurrent design process. DFE has been defined as "a practice by which environmental considerations are integrated into product and process engineering design procedures."[55] LCD and DFE are difficult to distinguish from each other; they are usually considered different names for the same approach. Yet, despite their similar goals, the genesis of DFE is quite different from that of LCD. DFE evolved from the design for X (DFX) approach, where X can represent manufacturability, testability, reliability, or other downstream design considerations.[56] Allenby developed a DFE framework to address the entire product life cycle.[55] AT&T has begun to implement DFE and LCD by developing guidelines, checklists, and requirements matrices,[57,58] as discussed in detail later in this review.

Many other initiatives for reducing environmental impacts and conserving resources through design pursue a specific strategy. One widely explored approach focuses on product life extension, which includes appropriate durability, adaptability, reuse, and remanufacture.[48,59-62] Product life extension is on top of the hierarchy of LCD strategies. Another single-strategy effort, design for recyclability, aims at closing the material life cycle loop.[63-65] Although recycling can be an effective strategy, designers and the public may have overemphasized this approach rather than giving careful consideration to other means of designing more benign products.

Extended producer responsibility is a more general approach that promotes cleaner products by explicitly expanding the role of the producer beyond the manufacturing stage.[66] The recent adoption of total quality management (TQM) principles focused on customer satisfaction has also contributed to the development of LCD.[67,68] This emphasis on the customer and multistakeholder participation has now evolved to include the environment. Rather than being driven by regulations, innovative companies are beginning to recognize the value of applying the life cycle framework to their operations as they adopt total quality environmental management programs.[69] Such initiatives promote a sustainable economy and provide the necessary support for LCD.

A life cycle framework for design was investigated by the authors in a three-year project with the US EPA Risk Reduction Engineering Laboratory. This effort resulted in the publication of the EPA *Life Cycle Design Guidance Manual*, which defined LCD as ."systems-oriented approach for designing more ecologically and economically sustainable product systems which integrates environmental requirements into the earliest stages of design. In life cycle design, environmental, performance, cost, cultural, and legal requirements are balanced." In addition to this manual, other guidance documents are now available[70,71] or are under development.[72] A comprehensive survey of life cycle design issues in the international literature has also been prepared by van Weenen.[11] In addition to these works, more general, philosophical publications that promote environmental design without offering specific frameworks or suggestions for implementation have also been written.[73-75]

Preparing design guidelines is only the first step in encouraging widespread adoption of sustainable design practices. Such guidelines must be applied to actual design projects so their practicality can be assessed, and the suggested procedures improved through learning. Several industry, government, and university projects are now testing the feasibility of elements of LCD and other systems approaches for environmental design.[76-80]

Life Cycle Design Framework

The life cycle design framework introduced in *Life Cycle Design Guidance Manual* provides the template used in this paper for reviewing major concepts and approaches to LCD. Figure 7 demonstrates the complexity of integrating environmental issues into design. The goal of sustainable development is located at the top to indicate its fundamental importance. As the figure shows, both internal and external forces shape the creation, synthesis, and evaluation of a design.

External factors include government regulations and policy, market demand, infrastructure, state of the economy, state of the environment, scientific understanding of environmental risks, and public perception of these risks. Within a company, both organizational and operational changes must take place to effectively implement life cycle design.

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

Research and technology development uncover new approaches for reducing environmental impacts, while increased understanding of the state of the environment by the scientific community and the general public provides global, regional, and local priorities for environmental problems that can be addressed by design. In this way, current and future environmental needs are translated into appropriate designs.

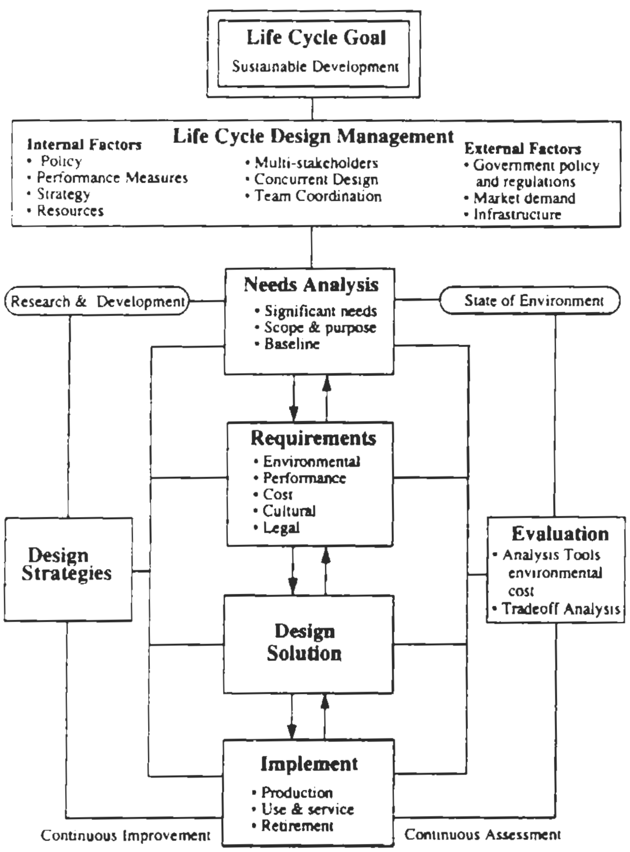

Figure 7. Life cycle design process.

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 or initiation phase, the purpose and scope of the project are defined, and customer needs are clearly identified.

Needs are then expanded into a full set of design criteria that includes environmental requirements. Various strategies are explored to meet these requirements, which act as a lens for focusing knowledge and new ideas into a feasible solution. The development team continuously evaluates alternatives throughout the design process. Environmental analysis tools ranging from single environmental metrics to comprehensive life cycle assessments (LCA) may be used in addition to other analysis tools. Successful designs must ultimately balance environmental, performance, cost, cultural, and legal requirements.

Although this model is overly simple, it demonstrates essential elements and relationships in life cycle design. Many different connections and feedback mechanisms exist among the activities shown in Figure 7. Design itself is an iterative process which includes multiple sequences of analysis, synthesis, and evaluation.

Environmental Management System and Design Management

Product development occurs within the broader corporate management structure. Increasingly, environmental stewardship issues are being addressed within corporations by formal environmental management systems.[81,82] A corporation's environmental management system supports environmental improvement through a number of key components including environmental policy and goals, performance measures, and a strategic plan. Ideally, the environmental management system is interwoven within the corporate structure and not treated as a separate function.[82] Successful life cycle design projects require commitment from all employees and all levels of management.

Mission Statement and Policy. Mission statements and policies containing environmental principles help to communicate the importance of environmental issues to internal and external stakeholders. A well-known example of this is the corporate environmental policy developed by 3M in 1975.[83] This policy stated that 3M would prevent pollution at the source, develop products with minimal environmental effect, conserve resources, and assure that facilities and products meet all regulations while also assisting government agencies and others in their environmental activities. The Valdez principles, and the Responsible Care Program developed by the Chemical Manufacturers Association provide examples of how groups of companies or sectors may cooperate to develop environmental policies. Major elements of the Valdez principles pledge companies to: protect the biosphere through safeguarding habitats and preventing pollution, conserve nonrenewable resources and make sustainable use of renewable resources, reduce waste and follow responsible disposal methods, reduce health risks to workers and the community, disclose incidents that cause environmental harm, and make public the annual evaluations of progress toward implementing these principles.

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

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

- Business cycle (recovery, inflation, recession)
- Product life cycle (R&D, production, termination, service)

- Useful life of the product
- Facility life
- Equipment life
- Process
- Cultural trends (fashion obsolescence)
- Regulatory change
- Technology cycles
- Environmental impacts

Understanding, coordinating, and responding to issues occurring within these time scales can be a key element in improved design. If a life cycle design strategy is to succeed, the underlying technological capability[84] of a corporation must be reconfigured to support that strategy. Businesses cannot successfully launch new programs that are not consistent with their abilities,[85] no matter how well intentioned.

Corporate strategies for implementing LCD include:

- Discontinuing/phasing out product lines with unacceptable impacts
- Investing in research and development of low-impact technology
- Investing in improved facilities/equipment
- Recommending regulatory policies that assist life cycle design
- Educating and training employees in life cycle design

Many companies are under pressure to shorten development times. This is due in part to competition to continuously bring new products to market. Strategic planning must balance these factors with the need to meet and even exceed life cycle goals.

Management should develop short and long term goals that are sufficiently detailed to guide design. Examples of well-defined environmental goals include reducing or phasing out the use of toxic chemicals within a specific time period, enhancing the energy efficiency of a product in use, and reducing packaging waste from suppliers to a specific level.

Environmental Performance Measures. The progress of design projects should be clearly assessed with appropriate measures to help members of the design team pursue environmental goals. Consistent prioritized measures of impact reduction in all phases of design provide valuable information for design analysis and decision making. It is important to establish measures that cover efficient resource use (materials and energy utilization), and waste reduction (multi-media), as well as measures to assess human health and ecosystem sustainability. These last two measures are much more difficult to assess.

Companies may measure progress toward stated goals in several ways. Regardless of how progress is measured, life cycle design is likely to be more successful when environmental aspects are part of a firm's incentive and reward system. Even when life cycle design may cut short-term costs, enhance immediate performance, or increase annual profitability, a discrete measure of environmental responsibility should still be included when assessing an employee's performance. If companies claim to follow sound environmental policies, but never reward and promote people for reducing impacts, managers and workers will naturally focus on other areas of the business.

Management Information Systems and Communications. Access to reliable environmental data and information throughout the product development process is essential for achieving environmental improvements. Collecting, analyzing, and reporting/disseminating information are critical functions of management information systems. A management information system should be capable of meeting all internal needs of the development team and external reporting/ permit requirements by the shareholders, the public, and regulators.

Concurrent Design and Team Participation. Life cycle design is a logical extension of concurrent design, 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.[86] By having all those responsible for separate stages or components of a product's life cycle participate in a project from the outset, problems that often develop between different disciplines can be reduced. Product quality can also be improved through such cooperation, while development time and costs can be reduced. Figure 8 depicts the various members of the design team that can participate in a development project.

Needs Analysis and Project Initiation

Ideas that lead to design projects come from many sources, including customer focus groups and research and development. In addition, environmental assessment of existing product systems may uncover opportunities for design improvement. In any case, the need which a design intends to fulfill must be clearly defined and the current options for meeting this need must be assessed. The basic needs of society have not changed; but the means for satisfying them have evolved, frequently in an unsustainable manner. Life cycle design projects should contribute to sustainable economies by pursuing the most sustainable pathways for addressing needs.

Identifying Significant Needs and Responding to Market Demand

Surveys reveal a high degree of public awareness and concern for the environment.[87,88] The willingness to change behavior to reflect this concern, however, is less clear. When the Roper Organization conducted a poll in 1990 to determine how public environmental attitudes correlate with behavior, the actively concerned segment of the U.S. population was 11 percent rather than the 80 percent reported in the previously cited polls.[89] The segment of the population deemed actively concerned was nearly twice as high in Canada, demonstrating that cultural differences may play a major role in public response to environmentally responsible products.

Although there seems to be a positive correlation between informing the public of a discrete environmental problem and encouraging some form of appropriate behavior, there may be less correlation between general environmental concern and specific actions.[90,91] Human behavioral response to potentially large-scale environmental changes, such as global warming or ozone depletion, still remains largely unknown, due in part to the uncertainty of scientific predictions concerning the magnitude and impact of such changes.[92] In light of this, companies must make difficult choices about the types of needs they will address and how willing their customers are to purchase environmentally responsible products. Product development managers should first recognize that environmental burdens can be substantially reduced by ending production of environmentally harmful product lines for which more benign alternatives are available.

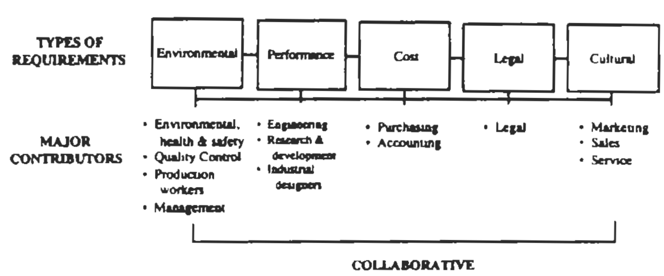

Figure 8. The development team for LCD.

Scope of Design Project

In addition to defining the project timeline and budget, the development team should define system boundaries. The ideal framework for design considers the full life cycle from raw material acquisition to the ultimate fate of residuals, but more restricted system boundaries may be justified by the development team in order to meet the demands of a particular product development cycle.

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

Evaluate Baseline and Benchmark Best in Class

Baseline analysis of existing products and benchmarking competitors may indicate opportunities for improving a product system's environmental performance.[91,94] While companies have programs to compare their products' performance and cost against those of their competitors, environmental criteria are generally more difficult to benchmark. LCA can be used for comparative analysis internally and externally, but this tool has several limitations, not the least of which is that benchmarking activities are influenced by available company resources. Regardless of methods chosen, the following basic guidelines apply:[93]

- plan and determine goals and scope of benchmarking study
- collect preliminary data
- select "best-in-class"
- ascertain data on best-in-class
- review and assess data in teams
- develop implementation plan
- assess program performance continuously

Baseline analysis and benchmarking can be used to identify opportunities and vulnerabilities that will be addressed in the current design or used for strategic planning.

Design Requirements

Formulating requirements may well be the most critical phase of design.[95] Design initiatives such as quality function deployment (QFD)[96,97] and total quality management (TQM)[98,99] recognize the primacy of customer needs, and thus increasingly focus on ensuring quality and value at the earliest stages of development. Through their emphasis on designing quality into products, rather than achieving it through later remediation, these programs prepared the way for LCD's focus on environmental requirements. Requirements define the expected outcome and are crucial for translating needs and environmental goals into an effective design solution. Design usually proceeds more efficiently when the solution is clearly bounded by well-considered requirements. In later phases of design, alternatives are evaluated on how well they meet requirements.

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

Regardless of the project's nature, the expected design outcome should not be overly restricted or too broad. Requirements defined too narrowly eliminate attractive designs from the solution space. On the other hand, vague requirements (such as those arising from corporate environmental policies that are too broad to provide specific guidance), lead to misunderstandings between potential customers and designers while making the search process inefficient.[95]

An estimated 70 percent of product system costs are fixed in the design stage. Activities through the requirements phase typically account for 10 to 15 percent of total product development costs,[100] yet decisions made at this point can determine 50 to 70 percent of costs for the entire project.[101,102]

Different methods are available to assist the design team in establishing requirements,[12] including requirements matrices and design checklists. Requirements can also be established by formal procedures such as the "house of quality" approach.[103]

Design Checklists

Checklists are usually a series of questions formulated to help designers be systematic and thorough when addressing design topics such as environmental issues. Proprietary checklists for DFE have been developed by AT&T which are similar to the Design for Manufacturability (DFM) checklists widely used by designers.[58] For example, a Toxic Substance Inventory checklist is used to identify whether a product contains a select group of toxic metals. The Canadian Standards Association is currently developing a Design for the Environment (DFE) standard which includes checklists of critical environmental core principles.[104] A series of yes/no questions are being proposed for each major life cycle stage: raw materials acquisition, manufacturing, use, and waste management.

Environmental design checklists that accommodate quantitative, qualitative, and inferential information through different design stages have also been offered for consideration.[12] In addition, Quakernaat and Weenk[105] propose management or design checklists based on "environmental merit," which is an assessment of the potential to reduce environmental burdens. Although their concept has not yet been well demonstrated, their checklist of environmental issues and parameters may be useful.

Checklists are not difficult to use but they must be compiled carefully without demanding excessive time from the designers to read.[12] Checklists can also interfere with creativity because designers may rely on them exclusively to address environmental issues without considering which prompts in the lists are most appropriate for their specific project.

Requirements Matrix

Matrices allow product development teams to study the interactions between life cycle requirements. Figure 9 shows a multilayer matrix for developing requirements. The matrix for each type of requirement contains columns that represent life cycle stages. Rows of each matrix are formed by the product system components: product, process, distribution, and management. Each row is subdivided into inputs and outputs. Elements within the rows and columns can be described and tracked in as much detail as necessary.

There are no absolute rules for organizing matrices. Development teams should choose a format that is appropriate for their project. The requirements matrices shown in Figure 9 are strictly conceptual: in practice such matrices can be simplified to address requirements more broadly during the earliest stages of design, or each cell can be further subdivided to focus requirements in more depth. For example, the manufacturing stage could be subdivided into parts suppliers and the original equipment manufacturer, while the distribution component of this stage could be organized in further detail that includes receiving, shipping, and wholesale activities. Dividing the product system components into inputs and outputs helps designers recognize physical flows through the system. In this way, it might be easier to track material and energy inputs as well as various outputs in a more comprehensive manner.

Environmental Requirements

Environmental requirements should be developed to minimize:

- The use of natural resources (particularly nonrenewables)
- Energy consumption
- Waste generation
- Threats to ecological health
- Human health and safety risks

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

Table III lists issues that can help development teams define environmental requirements. Although these lists are not complete, they introduce many important topics. Depending on the project, teams may express these requirements quantitatively or qualitatively. For example, it might be useful to state a requirement that limits solid waste generation for the entire product life cycle to a specific weight.

In addition to criteria discovered in the needs analysis or benchmarking, government policies can also be used to set requirements. For example, the Integrated Solid Waste Management Plan developed by the EPA in 1989 targets municipal solid waste disposal for a 25 percent reduction by 1995.[106] Other initiatives, such as the EPA's 33/50 program are aimed at reducing toxic releases to the environment. It may benefit companies to develop requirements that match the goals of these programs.

It can also be wise to set environmental requirements that exceed existing government statutes. Designs based on such proactive requirements offer many benefits. Major modifications dictated by regulation can be costly and time consuming. In addition, such changes may not be consistent with a firm's own development cycles, creating even more problems that could have been avoided.

Performance

Performance requirements define functions of the product system. Functional requirements range from size tolerances of parts to time and motion specifications for equipment. Typical performance requirements for an automobile include fuel economy, maximum driving range, acceleration and braking capabilities, handling characteristics, passenger and storage capacity, and

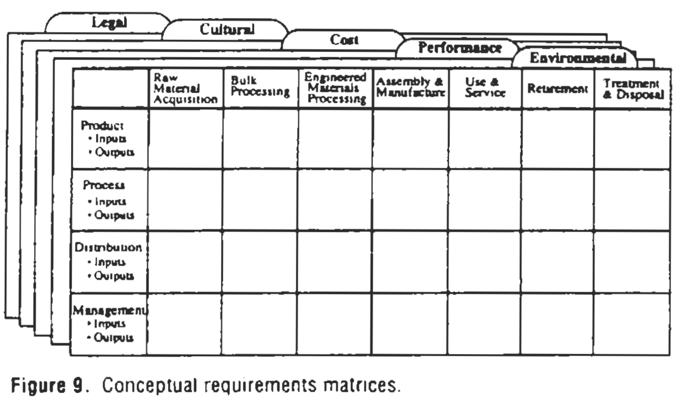

Figure 9. Conceptual requirements matrices.

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

Product system performance is limited by technical factors. Practical performance limits are usually defined by best available technology, while absolute limits that products may strive to achieve are determined by thermodynamics or the laws of nature. In many cases, process design is constrained by existing facilities and equipment which can also limit product performance by restricting possible materials and features. When such limitations occur, the success of a major new design project may depend on upgrading or investing in new technology.

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

Cost

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

Modified accounting systems that fully reflect environmental costs and benefits[107,108] are important to life cycle design. With more complete accounting, low-impact designs may show financial advantages. However, in many other cases it may be difficult to properly internalize environmental costs that competitors pass on to society.

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

Cost requirements need to reflect market possibilities. Value can be conveyed to customers through estimates of a product's total cost over its expected useful life, such as DOE labels for energy use on appliances. Total customer costs include purchase price, consumables, service, and retirement costs. In this way, quality products are not always judged on least first cost, which addresses only the initial purchase price or financing charges.

Cultural

Cultural and aesthetic requirements define the shape, form, color, texture, and image that a product projects. Material selection, product finish, colors, and size are driven by consumer preferences. Demand for paint or pigment colors that rely on toxic heavy metals has direct environmental consequences. Chrome plating is another example of a process that is done almost solely for appearance, even though it results in significant environmental harm. In either case, changes in preference can lead to substantial environmental improvements. However, because customers usually do not know about the full environmental consequences of their cultural choices, creating pleasing, environmentally superior products is a major design challenge.

Cultural requirements may overlap with others. Convenience is usually considered part of performance, but it is strongly influenced by culture. In many cultures, convenience is deemed so important that it may directly conflict with environmental requirements for waste minimization or energy conservation.

Anticipated environmental gains from design innovations are often offset by changes in patterns of consumption. For example, automobile manufacturers doubled average fleet fuel economy over the last twenty years, but gasoline consumption in the United States remains nearly the same because more vehicles are being driven more miles. Unexpectedly, widespread computer use apparently increases paper consumption. Printouts of drafts of this manuscript are a case in point.

Legal

Local, state, and federal environmental, health, and safety regulations are mandatory requirements. Violation of these requirements leads to fines, revoked permits, criminal and civil prosecution, and other penalties. Long-term liabilities also result from the production, use, and ultimate disposal of certain toxic and hazardous materials.

A plethora of regulations apply to most product systems. Environmental professionals, health and safety staff, legal advisors, and government regulators can identify legal issues for life cycle design. Principal local, state, federal, and international regulations that apply to the product system provide a framework for legal requirements. Regulations can vary dramatically both in type and detail between these jurisdictions, adding to the complexity of formulating legal requirements for products that will be sold on a global basis.

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

Ranking and Weighing

Ranking and weighting distinguishes between critical and merely desirable requirements. An example of one useful classification scheme follows:

- Must requirements are conditions that designs have to meet. No design is acceptable unless it satisfies all must requirements. Government regulations are examples of must requirements.
- Want requirements are desirable traits that are not mandatory. Want requirements help designers seek the best solution, not just the first alternative that satisfies mandatory conditions. These criteria play a critical role in customer acceptance and perceptions of quality.
- Ancillary functions are low-ranked in terms of relative importance. They are relegated to a wish list. Designers should be aware that such desires exist, but ancillary functions should only be expressed in design when they do not compromise more critical functions. Customers or clients should not expect designs to reflect many ancillary requirements.

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

Requirements can also be strategically organized in a time dimension. Future or anticipated requirements which may not be presently met can be distinguished from other requirements that apply to current designs.

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

Development teams can expect various requirements to conflict with each other. If conflicts cannot be resolved between must requirements, there is no solution space for design. When a solution space exists but it is so restricted that little choice is possible, must requirements may have been defined too narrowly. The absence of conflicts usually indicates that requirements are too loosely defined, producing a cavernous solution space in which virtually any alternative seems desirable. Under such conditions, there is no practical method of choosing the best design. In all of these cases, design teams need to redefine or assign new priorities to requirements.

Table III. Some issues to consider when developing environmental requirements.

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

Design Strategies

Presented by themselves, strategies may seem to define the goals of a design project. But effective design relies on a synthesis of multiple strategies for translating requirements into solutions. Although it may be tempting to pursue an intriguing strategy for reducing environmental impacts at the outset of a project, deciding on a course of action before the destination is known can be an invitation to disaster. Strategies flow from requirements, not the reverse.

Appropriate strategies need to satisfy the entire set of design requirements, thus promoting integration of environmental requirements into design. For example, essential product performance must be preserved when design teams choose a strategy for reducing environmental impacts. If performance is so degraded that the product fails in the marketplace, the benefits of environmentally responsible design are only illusory.

General strategies for fulfilling environmental requirements are shown in Table IV. Most of these strategies reach across product system boundaries; life extension, for example, can be applied to various elements in all four components. In most cases, a single strategy will not be best for meeting all environmental requirements. One strategy is even less likely to satisfy the full set of all requirements, so development teams will usually need to adopt a range of strategies. As an example, design responses to initiatives such as extended producer responsibility[110, 111] can usually best be expressed through a variety of strategies. Waste reduction, reuse, recycling, and aspects of product life extension may variously be employed to meet such challenges.

Several key strategies will now be outlined to illustrate how they may be used in LCD.

Product System Life Extension

In many cases, longer-lived products save resources and generate less waste, because fewer units are needed to satisfy the same needs.[58] Such product life extension is one of the most direct ways to reduce environmental impacts associated with human activities.[45] Before pursuing this strategy, designers should understand useful life. Useful life measures how long a system will operate safely and meet performance standards when maintained properly and not subject to stresses beyond stated limits.[112] Measures of useful life vary with function. Some common measures are: number of uses or duty cycles (washers, switches), length of operation (automobiles, light bulbs), and shelf life (food, unstable chemicals). Retirement is the defining event of useful life. Reasons why products are no longer in use include: technical obsolescence, fashion obsolescence, degraded performance or structural fatigue caused by normal wear over repeated uses, environmental or chemical degradation, and damage caused by accident or inappropriate use. Clearly, product systems intended for a long service life must successfully address issues beyond simple wear and tear. As Table IV shows, there are a variety of ways to extend the life of a product.

Table IV. Strategies for meeting requirements in LCD.

Product Life Extension	• Extend useful life • Make appropriately durable • Ensure adaptability • Facilitate serviceability by simplifying maintenance and allowing repair • Enable remanufacture • Accommodate reuse
Material Life Extension	• Specify recycled materials • Use recyclable materials
Material Selection	• Substitute materials • Reformulate products
Reduced Material Intensity	• Conserve resources
Process Management	• Process substitution • Process energy efficiency • Process materials efficiency • Process control • Improved process layout • Inventory control and material handling • Facilities planning • Treatment and disposal
Efficient Distribution	• Choose efficient transportation • Reduce packaging • Use lower impact/reusable packaging
Improved Management Practices	• Use office materials and equipment efficiently • Phase out high-impact products • Choose environmentally responsible suppliers or contractors • Label properly and advertise demonstrable environmental improvements

Appropriate Durability. A durable product continues to satisfy customer needs over a long useful life by withstanding wear, stress, and environmental degradation, but durability should be enhanced only when appropriate. Designs that allow a product or component to last well beyond its expected useful life can be wasteful.

When market price is the major determinant of purchasing decisions, higher-quality durable products may encounter market resistance. In such cases, enhanced durability can be part of a broader strategy focused on leasing rather than direct sale to customers. Original equipment manufacturers who maintain ownership of their leased equipment benefit from enhancing the durability of key components, thereby reducing the need for replacement or repair.[113]

Products based on rapidly changing technology may not always be proper candidates for enhanced durability. If a simple product will soon be obsolete, making it more durable could be wasteful. In complicated products subject to rapid change, adaptability is usually a better strategy.

Adaptability. Adaptable designs either allow continual updating or they perform several different functions. Modular construction is usually the key to ensuring adaptability in products with many parts, because it allows fast-changing components to be easily upgraded without replacing the entire unit. In this manner, single-function products can evolve and improve as needed.

Adaptable designs rely on interchangeable components. Interchangeability controls dimensions and tolerances of manufactured parts so that components can be replaced with minimal adjustments or on-site modifications.[112] Thus, fittings, connectors, or information formats on upgrades are consistent with the original product. For example, an adaptable strategy followed by a European computer mainframe manufacturer featured a portable operating system that allowed previously incompatible software to be used by the same hardware. The system also featured a future performance guarantee made possible in part by the use of modular components which permit continual upgrading of peripheral equipment and user programs.[113] Flexible manufacturing is another example of adaptable design.

Reliability. A reliable system accomplishes its design mission in the intended environment for a certain period of time. Unreliable products or processes, even if they are durable, may be retired prematurely because customers will not tolerate untrustworthy performance, inconvenience, and expense for long.

The number of components, the individual reliability of components, and configuration are important aspects of reliability. Parts reduction and simplified design can increase both reliability and manufacturability, which in turn help reduce resource use and waste. In life cycle design, reliability is designed into products rather than achieved through later inspection. Screening out potentially unreliable products after they are made is wasteful because such products must either be repaired or discarded. In both cases, environmental impacts and costs increase.

Serviceability. A serviceable system can be adjusted for optimum performance under controlled conditions. Many complex products designed to have a long useful life require service and support. When designing serviceable products, development teams should consider whether original equipment manufacturers, dealers, private business, customers, or various combinations of these groups will be servicing the product. Types of tools and the level of expertise needed to perform tasks strongly influences who is capable of providing service. In any case, simple procedures are an advantage. Design teams should also recognize that equipment and an inventory of parts are a necessary investment for any service network.

Service activities may be broken into two major categories: maintainability and repairability. Maintenance includes periodic, preventative, and minor corrective actions. The relative difficulty or time required to support a certain level of system performance determines whether that system can be practically maintained. Issues that need to be addressed when designing easily maintained product systems include: downtime, tool availability, personnel skills, complexity of required procedures, potential for error, accessibility, and frequency of design-dictated maintenance. This is not an exhaustive list, but it identifies some key factors affecting maintenance, most of which are interrelated.

Durable products may also need repair to stay in extended service. Repairability is determined by the feasibility of replacing dysfunctional parts and returning a system to operating condition. Factors relating to downtime, complexity, and accessibility are as important in repair as they are in maintenance. Easily repaired products also rely on interchangeable and standard parts. Interchangeability usually applies to parts produced by one manufacturer, while standardization refers to compatible parts that conform to accepted design standards made by different manufacturers.[112] Designs that feature unique dimensions for common parts can confound normal repair efforts; specialty parts usually require expanded inventories and extra training for repair people. In the burgeoning global marketplace, following proper standards enables practical repair.

Cost also determines repairability. If normal repair is too expensive, practical repairability does not exist. Labor, which is directly related to complexity and accessibility, is a key factor in repair; when labor is costly, only relatively high-value items will be repaired.

As in maintenance, infrequent need, ease of intervention, and a high probability of success enhance repairability and translate directly into perceptions of higher quality. Finally, repairable designs need proper after-sale support. Manufacturers of repairable products should offer information about trouble-shooting, procedures for repair, tools required, and the expected useful life of components and parts. User decisions about when to retire rather than repair a product are complex and have significant environmental consequences.

Remanufacturing. Worn products can be restored to like-new condition through remanufacturing. In a factory, a retired product is first completely disassembled. Its usable parts are then cleaned, refurbished, and put into inventory. Finally, a new product is reassembled from both old and new parts, creating a unit equal in performance and expected life to the original or a currently available alternative. In contrast, a repaired or rebuilt product usually retains its identity, and only those parts that have failed or are badly worn are replaced.[61]

Industrial equipment or other expensive products not subject to rapid change are the best candidates for remanufacture. Typical remanufactured products include jet engines, buses, railcars, manufacturing equipment, and office furniture. Viable remanufacturing systems rely on the following factors: a sufficient population of old units (cores), an available trade-in network, low collection costs, and storage and inventory infrastructure.[62]

In addition to these factors, no remanufacturing program can succeed without design actions that address ease of disassembly, allowing sufficient wear tolerances on critical parts, avoiding irreparable damage to parts during use, and ensuring interchangeability of parts and components in a product line.[62]

When properly pursued, remanufacturable designs can provide clear benefits. For example, one original equipment manufacturer of jet engines also remanufactures engines for customers at a cost of $900,000 plus trade-in, compared to $1.6 million for a new engine. Fuel efficiency in the remanufactured engine is 4% better than original specifications for that model of engine.[62]

Reuse. An item can still be used after it is retired from a clearly defined duty. Reusable products are returned to the same or less demanding service without major alterations, although they may undergo some minor processing, such as cleaning, between services.

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

Material Life Extension

Recycling is the reformation or reprocessing of a recovered material. The EPA defines recycling as the series of activities, including collection, separation, and processing, by which products or other materials are recovered or otherwise diverted from the solid waste stream for use in the form of raw materials in the manufacture of new products other than fuel.[113]

Many designers, policy makers, and consumers believe recycling is the best solution to a wide range of environmental problems. Even though recycling does divert discarded material from landfills it also causes other impacts and so may not be the best way to minimize waste and conserve resources. Before designers focus on making products easier to recycle, they should understand several recycling basics such as types of recovered material, pathways, and the necessary infrastructure.

Types of Recycled Material. Material available for recycling falls into the following three classes: home scrap, preconsumer, and postconsumer. Home scrap consists of materials and byproducts generated and commonly recycled within an original manufacturing process.[114] Many materials and products contain home scrap that should not be advertised as recycled content. For example, mill broke (wet pulp and fibers) has historically been used as a pulp substitute in paper making rather than discarded, so it is misleading to consider it recycled content. Preconsumer material consists of overruns, rejects, or scrap generated during any stage of production outside the original manufacturing process.[114] It is generally clean, well-identified, and suitable for high-quality recovery, and thus frequently recycled in many areas. In contrast, postconsumer material has served its intended use and been discarded before recovery. Unfortunately, in many cases postconsumer material has been a relatively low-quality source of input for future products.

Recycling Pathways. Development teams choosing recycling as an attractive way to meet requirements should be aware of the two major pathways recycled material can follow, as shown in Figure 5. In closed-loop systems, recovered materials and products are suitable substitutes for virgin material. They are thus used to produce the same part or product again. Some waste is generated during each reprocessing, but in theory a closed-loop model can operate for an extended period of time without virgin material. Of course, energy, and in some cases process materials, are required for each recycling. Solvents and other industrial process ingredients are the most common materials recycled in a closed loop. Postconsumer material is much more difficult to recycle in a closed loop, because it is often degraded or contaminated. Designs that anticipate closed-loop recycling of such waste may thus overstate the likely benefits. However, there can be successful programs that rely on 100 percent postconsumer material for new products. In one such program, ABS (acrylonitrile-butadiene-styrene) regrind, derived from scrapped telephone housings, was used to produce mounting panels for another product.[95]

Open-loop recycling occurs when recovered material is recycled into product applications. Most postconsumer material is recycled in an open loop. The slight variation or unknown composition of such material usually causes it to be downgraded to less demanding uses. Some materials also enter a cascade open-loop model in which they are degraded several times before final discard.

Infrastructure. Suitable programs must be in place or planned to ensure the success of any recycling system. Key considerations include: recycling programs and participation rates, collection and reprocessing capacity, quality of recovered material, and economics and markets.

Economic and market factors ultimately determine whether a material will be recycled. Markets for some secondary materials may be easily saturated. Recycling programs and high rates of participation address only collection; unless recovered material is actually used, no recycling has occurred. Take-back legislation in Germany for packaging illustrates the importance of anticipating the full range of recycling issues. Although the legislation includes reuse and other possible strategies,[116] the main method of dealing with packaging items that manufacturers must take back is recycling. To date the privately financed "Green Dot" program for identifying packaging suitable for recycling has exceeded initial expectations. The quantity of material recovered has overwhelmed recyclers, forcing the German government to heavily subsidize use of the material.[65] This difference between simple collection and intended use for recovered material may delay similar take-back ordinances aimed at automobiles and electronic equipment.

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

Design Considerations. Under ideal circumstances, most materials would be recovered many times until they became too degraded for further use. Designing with recycling in mind is crucial if this goal is to be reached.[63] Even so, design for recyclability is not the ultimate strategy for meeting all environmental requirements. As an example, refillable glass bottles use much less life cycle energy than single-use recycled glass to deliver the same amount of beverage.[117]

When suitable infrastructure appears to be in place, or the development team is capable of planning it, recycling can be greatly abetted by design practices which consider recycling needs.[64] Features that enhance recycling include:

- ease of disassembly
- material identification
- simplification and parts consolidation
- material selection and compatibility

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

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

Simplification and parts consolidation can also make products easier to recycle. As previously mentioned, this is an attractive strategy for many other reasons. In many design projects, material selection has not been coordinated with environmental strategies. As a result, many designs contain a bewildering number of materials chosen for combined cost and performance attributes. There may be little chance of recovering material from such complex products unless they contain large components made of a single, practically recyclable material.

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

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

Material Selection

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

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

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

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

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

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

Efficient Distribution

Both transportation and packaging are required to transfer most goods between life cycle stages.

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

- Choose an energy-efficient mode
- Reduce air pollutant emissions from transportation
- Maximize vehicle capacity where appropriate
- Backhaul materials
- Ensure proper containment of hazardous materials
- Choose routes carefully to reduce potential exposure from spills and explosions

Trade-offs between various modes of transportation are necessary. Time and cost considerations, as well as convenience and access, play a major role in choosing the best transportation. When selecting a transportation system, designers should also consider infrastructure requirements and their potential impacts.

Packaging. Only packaging generally used between the manufacturing, use, and retirement stages will be discussed here. Packaging must contain and protect goods during transport and handling to prevent damage. Regardless of how well-designed an item might be, damage during distribution and handling may cause it to be discarded before use. To avoid such waste, products and packaging should be designed to complement each other.

Table V. Environmental requirements matrix for AT&T LCD demonstration project for a business telephone.

Product		
Manufacture Materials should be recyclable (preferably on-site) • plastic regrind – Maximize use of recyclable materials when environmentally preferable – Choose ozone-depleting-substance (ODS) free components – Eliminate the use of toxic materials (e.g., Pb)	**Use/Service** – Extend useful life through modular design with sufficient forward and backward capability – Make product upgradable • ROM parts • sockets for additional memory and/or processor chips	**End-of Life-Management** – Reuse parts (e.g. handsets, cords) – Standardize parts to facilitate remanufacture – Product components recyclable after consumer use – Open-loop recycling into fiber cables, spools, reels – Easy to disassemble: no rivets, glues, ultrasonic welding - minimal use of composites – Components easy to sort by marking and minimal use of materials – Housing should be shredable
Process		
Manufacture – Minimize process wastes including air emissions, liquid effluents and hazardous and nonhazardous solid wastes – Minimize resource and power consumption – Meet five corporate environmental goals – Do not commingle waste streams	**Use/Service** – Energy efficient operation (operate on line power only)	**End-of-Life Management** – Maximize material recycling of components not reused – Service or reconditioning operations should minimize use of paints and solvents – Minimize wastes including air emissions, liquid effluents and hazardous and non-hazardous solid wastes from refurbishing operations
Distribution		
Manufacture – Minimize supplier packaging • non hazardous – Packaging containing recycled material (post-consumer content specified) – Reusable trays for parts in factory	**Use/Service** – Minimize product packaging • use Electronic Packaging Guidelines • non hazardous inks, etc. – Optimize number of phones per package – Specify packaging containing recycled material (post-consumer content specified) – Use recycled paper for manual – Minimize material variety for packaging	**End-of-Life Management** – Use recyclable packaging – Use packaging containing recycled materials – Use reusable shipping containers
Information Management		
Manufacture – Use DFE guidelines, checklists, other DFE tools – Encourage suppliers to discontinue use of ODS in parts manufacturing	**Use/Service** – Print manual on recycled paper (list environmental features) – Print recycling instructions on product packaging	**End-of-Life Management** – Supply toxic material content – Provide product recycling instructions – Provide product disposal instructions

The concurrent practices of life cycle design are particularly effective in reducing impacts from packaging. As a first step, products should be designed to withstand both shock and vibration. When cushioned packaging is required, members of the development team need to collaborate to ensure that cushioning does not amplify vibrations and thus damage critical parts.[illegible] One of the most effective ways to meet life cycle design goals for packaging is packaging reduction. Adverse impacts associated with packaging can be lessened by distributing appropriate products unpackaged, reusing packaging, modifying products so they require less packaging, and using less material for packaging.

Shipping items without packaging is the simplest approach to impact reduction. In the past, many consumer products such as screwdrivers, fasteners, and other items were offered unpackaged. They can still be hung on hooks or placed in bins that provide proper containment while allowing customer access. This method of merchandising avoids unnecessary plastic wrapping, paperboard, and composite materials. Wholesale packaging can also be eliminated in many cases, such as when uncartoned furniture is shipped with protective blankets that are returned after delivery.

Reusable packaging systems are also an attractive design option. Wholesale items that require packaging are commonly shipped in reusable containers such as tanks, wire baskets, wooden shooks, and plastic boxes.

Necessary design elements for most reusable packaging systems include: collection or return infrastructure; procedures for inspecting items for defects or contamination; repair, cleaning, and refurbishing capabilities, and storage and handling systems. Unless such measures are in place or planned, packaging may be discarded rather than reused. Manufacturers and distributors cannot reuse packaging unless infrastructure is in place to collect, return, inspect, and restore packaging for another service.

One way producers can reduce these infrastructure needs is by offering their product in bulk. Some system will still be required for reusable wholesale packaging, but it should be much less complex than that needed to handle consumer packaging. When products are sold in bulk, customers control all phases of reuse for their own packaging. Even so, waste generation and other environmental impacts are only reduced when customers reuse their container several times. Customers who use new packaging for each bulk purchase generally consume more packaging than customers who buy prepackaged products. This is particularly true of items distributed in single-use bulk packaging.[119]

Product modification is another approach to packaging reduction. Sturdy products may require less packaging while also proving more robust in service. Depending on the delivery system, some products can safely be shipped without packaging of any kind. Even when products require primary and secondary packaging to ensure their integrity during delivery, product modi-

Table VI. Legal requirements matrix for AT&T LCD demonstration project for a business telephone.

Product

Manufacture	Use/Service	End-of Life-Management
1. US Regulations/Product Safety Standards – Clean Air Act Amendments: CFC labeling requirement (April 15, 1993) – Underwriter Laboratories • UL 746D fabricated parts: use of regrind and recycled materials 2. Foreign Regulations/Product Safety Standards – Blue Angel and other relevant standards	– Underwriter Laboratories • UL 1459-product safety • UL 94-flammability test (must meet UL 94-HB at minimum) – PFC/telephones – Proposed ban on polybrominated fire retardants (European Community) – Canadian Safety Specs • CSA C22.2 – European Safety Specs • EN 60 950 (IEC 950; safety, network capability, EMC, susceptibility) • EN 41003 • EN 71 (lead pigments and stabilizers in plastic parts)	– Product should meet applicable statutory requirements • product should not contain hazardous materials under RCRA • pigments and other plastic additives should not contain heavy metals – Electronic Waste Ordinance (Germany, Jan. 1, 1994) – UL flammability test: approval of recycled resins difficult – Previous flame retardant banned in Europe which prohibits recycling of old terminals – Proposed ban on polybrominated fire retardants (EC)

Process

Manufacture	Use/Service	End-of-Life Management
– Clean Air Act – Clean Water Act – CERCLA (SARA-313) – RCRA – EPCRA – OSHA		– Recycling and refurbishing operations must not violate anti-trust provisions of Sherman Act

Distribution

Manufacture	Use/Service	End-of-Life Management
– DOT (transportation of hazardous materials)	– Packaging complies with German packaging ordinance	

Information Management

Manufacture	Use/Service	End-of-Life Management
– ISO Marking Codes for plastics	– FTC Guidelines	– Recycled content – FTC Guidelines: definitions for labeling – ISO Marking Codes for plastics – Provide information on returning product (German electronic waste ordinance) – Specific claims on packaging • Green Dot Program

fications may decrease packaging needs. Designers can further reduce the amount of packaging used by avoiding unusual product features or shapes that are difficult to protect.

Reformulation is another type of product modification that may reduce packaging needs for certain items, such as those containing ingredients in diluted form that can be distributed as concentrates. In some cases, customers can simply use concentrates in reduced quantities, while in others, a reusable container can also be sold in conjunction with concentrates that allows customers to dilute the product as appropriate.

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

A Life Cycle Design Demonstration

Requirements

The matrix method of formulating requirements was recently applied to designing a business telephone in a demonstration project conducted between the authors and AT&T.[57] Radical departures from previous designs were not deemed feasible for this next generation product. Given this and other constraints, the project concentrated on a partial, consolidated life cycle consisting of manufacturing, use, and end-of-life management stages. Examples of some environmental and legal must and want design requirements formulated by the project team are listed in Tables V and VI. These matrices resulted from seven "green product realization" team meetings attended by representatives from product line management, marketing, research design, product engineering, and environmental health and safety engineering. Tables V and VI contain some examples of the critical requirements relevant to this particular design and also certain considerations for the future.

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

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

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

Strategies Used in the Demonstration Project

This demonstration project also provides a practical example of applying several environmental strategies to satisfy requirements. Only a few strategies pertaining to a single product component, the housing, will be discussed here. Environmental requirements for the manufacturing stage state that material for the housing be recycled and recyclable, toxics eliminated, and waste reduced. End-of-life requirements state that the housing be reusable or at least recyclable.

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

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

In addition, AT&T has a network of reclamation and service centers which

Table VII. Definitions of accounting and capital budgeting terms relevant to LCD.(fr: 108)

Accounting	
Full Cost Accounting	A method of managerial cost accounting that allocates both direct and indirect environmental costs to a product, product line, process, service, or activity. Not everyone uses this term the same way. Some include only costs that affect the firm's bottom line, while others include the full range of costs throughout the life cycle, some of which do not have any indirect or direct effect on a firm's bottom line.
Life Cycle Costing	In the environmental field, this has come to mean all costs associated with a product system throughout its life cycle, from materials acquisition to disposal. Where possible, social costs are quantified; if this is not possible, they are addressed qualitatively. Traditionally applied in military and engineering to mean estimating costs from acquisition of a system to disposal. This does not usually incorporate costs further upstream than purchase.
Capital Budgeting	
Total Cost Assessment	Long-term, comprehensive financial analysis of the full range of internal (i.e. private) costs and savings of an investment. This tool evaluates potential investments in terms of private costs, excluding social considerations. It does include contingent liability costs.

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

Design Evaluation

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

LCA and Its Application to Design

Methodology. LCA consists of several techniques for identifying and evaluating the adverse environmental effects associated with a product system.[34,35,38,120-122] The most widely recognized framework for LCA consists of inventory analysis, impact assessment, and improvement assessment components. At present, inventory analysis is the most established methodology of LCA. For an inventory analysis, material and energy inputs and outputs for the product system are identified and quantified.[35] Impact assessment, which is still under development, applies quantitative and qualitative techniques to characterize and assess the environmental effects associated with inventory items. Impacts are usually classified as resource depletion, human health and safety effects, ecological degradation, and other social welfare effects relating to environmental disturbances. Improvement analysis uses life cycle inventory and/or impact assessment methods to identify opportunities for reducing environmental burdens. Other efforts have also focused on developing streamlined tools that are not as rigorous as LCA (e.g., Canadian Standards Association).

In principle LCA represents the most accurate tool for design evaluation in LCD and DFE. Many methodological problems, however, currently plague LCA, thus limiting its applicability to design.[45] Costs to conduct an LCA can be prohibitive, especially to small firms, and time requirements may not be compatible with short development cycles.[69,124] Although significant progress has been made towards standardizing life cycle inventory analysis,[34,35,41,120,123] results can still vary significantly.[124,125] Such discrepancies can be attributed to differences in system boundaries, rules for allocation of inputs and outputs between product systems, and

Table VIII. Policy options that could affect material flows in LCD.[140]

Life Cycle Stage	Regulatory Instruments	Economic Instruments
Raw material extraction and processing	Regulate mining, oil, and gas nonhazardous solid wastes under the Resource Conservation and Recovery Act (RCRA). Establish depletion quotas on extraction and import of virgin material.	Eliminate special tax treatment for extraction of virgin materials, and subsidies for agriculture. Tax the production of virgin material.
Manufacturing	Tighten regulations under Clean Air Act, Clean Water Act, and RCRA. Regulate nonhazardous industrial waste under RCRA. Mandate disclosure of toxic materials use. Raise Corporate Average Fuel Economy Standards for automobiles. Mandate recycled content in products. Mandate manufacturer take-back and recycling of products. Regulate product composition, e.g., volatile organic compounds or heavy metals. Establish requirements for product reuse, recyclability, or biodegradability. Ban or phase out hazardous chemicals	Tax industrial emissions, effluents, and hazardous wastes. Establish tradable emissions permits. Tax the carbon content of fuels. Establish tradable recycling credits. Tax the use of virgin toxic materials. Create tax credits for use of recycled materials. Establish a grant fund for clean technology research.
Purchase, use, and disposal	Mandate consumer separation of materials for recycling.	Establish weight/volume-based waste disposal fees. Tax hazardous or hard-to-dispose products. Establish a deposit-refund system for packaging or hazardous products. Establish a fee/rebate system based on a product's energy efficiency. Tax gasoline.
Waste management	Tighten regulation of waste management facilities under RCRA. Ban disposal of hazardous products in landfills and Mandate recycling diversion rates for various materials. Exempt recyclers of hazardous wastes from RCRA Subtitle C. Establish a moratorium on construction of new landfills and incinerators. Establish surcharges on wastes delivered to landfills or incinerators.	Tax emissions or effluents from waste management facilities. Establish surcharges on wastes delivered to landfills or incinerators.

data availability and quality issues. LCA also generally lacks uncertainty analysis of results.

Incommensurable data presents another major challenge to LCA and other environmental analysis tools. The problem of evaluating environmental data remains inherently complicated when data is in such different measuring units as kilojoules, cancer risks, or kilograms of solid waste. Furthermore, different conversion models for translating inventory items into impacts are required for each impact, and these models vary widely in complexity and uncertainty. For example, risk assessment and fate and transport models are required to evaluate human and ecosystem health effects associated with toxic emissions. Model sophistication dictates whether additional data beyond inventory results will be needed for proper evaluation. Simplifying approaches for impact assessment, such as the "critical volume or mass" method have fundamental limitations.[122] These general models are usually much less accurate than more elaborate site-specific assessment models, but full assessment based on site-specific models is not presently feasible. Other simple conversion models, such as those translating emissions of various gases into a single number estimating global warming potential or ozone depleting potential,[123-126] are available for assessing global impacts.

Integration of LCA and Design. LCA and more streamlined approaches can potentially be applied in needs analysis, requirements specification, and evaluation of conceptual through detailed design phases. Although numerous life cycle inventories have been conducted for a variety of products,[125] only a small fraction have been used for product development. Proctor and Gamble is one company that has used life cycle inventory studies to guide environmental improvement for several products.[127] One of their case studies on hard surface cleaners revealed that heating water resulted in a significant percentage of total energy use and air emissions related to cleaning.[128] Based on this information, opportunities for reducing impacts were identified which include designing cold water and no-rinse formulas or educating consumers to use cold water.

The Product Ecology Project represents another example where life cycle inventory and a valuation procedure are used to support product development.[129] For this project, the Environmental Priority Strategies in product design (the EPS system) evaluates the environmental impact of design alternatives with a single metric based on environmental load units. An inventory is conducted using the LCA Inventory Tool developed by Chalmers Industriteknik and valuation is based on a willingness-to-pay model, which accounts for biodiversity, human health, production, resources, and aesthetic values. This system enables the designer to easily compare alternatives, but the reliability of the outcome will be heavily dependent on the valuation procedure.

Several LCA software tools and computerized databases may make it easier to apply LCA in design. Examples of early attempts in this area include: SimPro, developed by the Centre of Environmental Science (CML), Leiden University, Netherlands; LCA inventory tool, developed by Chalmers Industriteknik in Göteborg, Sweden; and PIA, developed by the Institute for Applied Environmental Economics (TME) in The Hague, Netherlands [available from the Dutch Ministry for Environment and Informatics (BMI)]. These tools can shorten analysis time when exploring design alternatives, particularly in simulation studies, but data availability and quality are still limiting. In addition to these tools, a general guide to LCA for European businesses has been compiled which provides background and a list of sources for further information.[130]

Other Design Evaluation Approaches

Environmental Indicators. In contrast to a comprehensive life cycle assessment, environmental performance parameters or indicators can be used to evaluate design alternatives. Navin-Chandra[131] introduced the following set of environmental indicators: percent recycled, degradability, life, junk value, separability, life cycle cost, potential recyclability, possible recyclability, useful life and utilization, total and net emissions, and total hazardous fugitives. Many of these indicators can be calculated relatively easily; the last two, however, require life cycle inventory data to compute.

Watanabe[132] proposes a Resource Productivity measure for evaluating "industrial performance compatible with environmental preservation." The resource productivity is defined as:

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

where the individual terms in the denominator are expressed in monetary units. Longer product life, higher material recycle, and less material and energy consumption all contribute to a higher resource productivity. Watanabe has applied this metric in evaluating three rechargeable battery alternatives. While resource productivity incorporates many environmental concerns, it is not comprehensive because costs associated with toxic emissions and human and ecosystem health are ignored. In addition, the value added component of the numerator includes other factors besides environmental considerations. Despite these limitations, this metric is relatively simple to evaluate and accounts for resource depletion, which correlates with many other environmental impacts.

Matrix Approaches. DFE methods developed by Allenby[49,53] use a semi-quantitative matrix approach for evaluating life cycle environmental impacts. A graphic scoring system weighs environmental effects based on available quantitative information for each life cycle stage. In addition to an environmental matrix and toxicology/exposure matrix, manufacturing and social/political matrices are used to address both technical and non-technical aspects of design alternatives.

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

Computer Tools. ReStar is a design analysis tool for evaluating recovery operations such as recycling and disassembly.[133] A computer algorithm determines an optimal recovery plan based on tradeoffs between recovery costs and the value of secondary materials or parts.

Cost Analysis

Cost analysis for product development is often the most influential tool guiding decision-making. Life cycle costs can be analyzed from the perspective of three stakeholder groups: manufacturers or producers, consumers, and society at large. Table VII shows definitions for some accounting and capital budgeting terms relevant to LCD.

For life cycle design to be effective, environmental costs need to be allocated accurately to product centers. Environmental costs are commonly treated as overhead. Methods such as activity based costing (ABC) may be useful in properly assigning product costs in many situations, resulting in improved decision making.[134,135] Properly allocating environmental costs can be one of the most powerful motivators for addressing environmental issues in design.

Unfortunately, because the current market system does not fully reflect environmental costs, prices for goods and services do not reflect total costs or benefits. For this reason, a design that minimizes environmental burden may appear less attractive than an environmentally inferior alternative. The most important element of unrealized costs in design are externalities, such as those resulting from pollution, which are borne by outside parties (society) not involved in the original transaction (between manufacturers and customers). For example, pollution costs to society are difficult to properly address within a company if the pollution is emitted within permissible limits. Corporations choosing to reduce these emissions and internalize the associated costs can find themselves at a competitive disadvantage unless their competitors do so as well.[136] Methods for evaluating and internalizing externalities are also limited. Despite these problems, manufacturers can benefit from pursuing design initiatives which produce tangible costs reductions through material conservation, reduction in waste management costs, and reduced liability costs.

A number of resources are available to identify full environmental costs.[107,137] In the EPA Pollution Prevention Benefits Manual, costs are divided into four categories: usual costs, hidden regulatory costs, liability costs, and less tangible costs. Usual costs are the standard capital and operating expenses and revenues for the product system, while hidden costs represent environmental costs related to regulation (e.g., permitting, reporting, monitoring). Costs due to noncompliance and future liabilities for forced cleanup, personal injury, and property damage as well as intangible costs/benefits such as effects on corporate image are difficult to estimate.

From a consumer's perspective, life cycle costing is a useful tool aiding in product selection decisions. In traditional use, life cycle costs consist of the initial purchase price plus operating costs for consumables, such as fuel or electricity, and servicing not covered under warranty as well as possible disposal costs.[138] Providing estimates of life cycle cost can be a useful marketing strategy for environmentally sound products. The most comprehensive definition of life cycle costs is the sum of all internal and external costs associated with a product system throughout its entire life cycle.[108,139] At present, government regulation and related economic policy instruments appear to be the only effective methods of addressing environmental costs to society.

Future Directions

Government Policy

Government plays an important role in promoting life cycle design through both regulatory and voluntary programs. The US Congress Office of Technology Assessment (OTA) recently conducted a thorough study of policy options for promoting green product design.[140] Although existing market incentives and environmental regulations have been somewhat effective in promoting sustainable practices, OTA concluded that Congress can foster further progress in this area by supporting: research, information for consumers, policies that internalize environmental costs, and coordinating and harmonizing various programs. Table VIII outlines regulatory and market-based incentives to internalize environmental costs associated with a product system.

Clearly the greatest role government plays is in establishing regulations for environmental protection. The media-specific regulatory framework formerly practiced by the US EPA was effective in driving environmental impact reduction, but the agency's recent pollution prevention strategy[141] improves on past practice by adopting a multimedia approach to environmental protection which acknowledges the life cycle framework. The proactive and systems-oriented characteristics of pollution prevention are particularly relevant to life cycle design. Design itself can be viewed as the most proactive, direct action one can take to achieve pollution prevention.

It remains to be seen whether regulations can be rewritten to promote the LCD approach for reducing environmental burdens. One effort in this direction by EPA is the Source Reduction Review Project (SSRP). This program evaluates how the formulation and implementation of new regulations can be made consistent with preserving source reduction opportunities. At present, 17 industrial categories including pulp and paper production, metal products and machinery, degreasing operations, and polystyrene production are targeted by SSRP.

The government also has a major responsibility in supporting research to develop and coordinate the environmental databases necessary for LCD. The lack of environmental data is currently a major limitation for decision makers in product development. In addition, corporations which must already meet a variety of government reporting requirements could modify and expand their information gathering to serve both internal decision-making needs, and the needs of outside stakeholders. With such an expanded system, perhaps encouraged by government support, an environmental profile (energy use, resource inputs, and wastes produced) of product systems at each life cycle stage would be publicly available. However, proprietary information would have to be protected. In the US Congress, Representative Brown of California recently proposed the Environmental Technologies Act (H.R. 3603) for funding to support further research in LCA.

Other countries are pursuing a variety of strategies to promote LCD. In Germany, the Packaging Ordinance, several ecolabeling programs, and various proposed waste ordinances promote extended producer responsibility and thus encourage impact reductions. In the Netherlands, the UNEP-Cleaner Production Programme recently established a new working group on Sustainable Product Development. The Secretariat of the group is based at the Interfaculty Department of Environmental Science at the University of Amsterdam.

Education

Education can be one of the most effective means of promoting sustainable development and life cycle design. However, industry programs for environmental design are frequently far ahead of their academic counterparts. In general, engineering and industrial design curricula at the university level are not yet emphasizing pollution prevention or focusing on integrating environmental issues into design. Many faculty are still in the command and control mode of teaching environmental protection. For this reason, new curriculum topics must compete with established subjects which are less effective in conveying the type of background essential to LCD. Faculty in engineering, business, and industrial design need to treat environmental issues as an important element of their design and management courses. Until a greater number of faculty and administrators recognize the value of such innovative topics, teaching in this area will only occur sporadically.

Despite this lack of attention, efforts to introduce environmental aspects into design education do exist. Programs at the Rhode Island School of Design, UCLA, Carnegie Mellon, the University of Michigan, Grand Valley State University (Michigan), and the University of the Arts in Philadelphia have begun to develop some educational resources. UCLA produced an engineering problem set that incorporates LCA and pollution prevention into calculations illustrating a variety of engineering principles.[142] Class exercises illustrating a design for recyclability strategy were produced at Grand Valley State[143] while the National Pollution Prevention Center (NPPC) at the University of Michigan developed a refrigeration design case for chemical and mechanical engineering students which explores the use of non-CFC refrigerants and strategies to meet DOE energy efficiency requirements.[144]

Professional education courses are also being developed to train engineers, designers, and other product development participants about LCD/DFE at the NPPC, the University of Wisconsin, and the IEEE (Institute of Electrical and Electronics Engineers) annual International Symposium on Electronics and the Environment.

Industry

Industry is responsible for implementing the designs which will lead to a sustainable economy. Beyond responding to customer demands, industry can also play an important role in fostering sustainable development by creating innovative, environmentally responsible designs. Many corporations recognize the product life cycle as a useful framework for addressing environmental issues in product development. Although this framework is recognized, corporations are just now attempting to translate corporate goals and policies into life cycle design programs. In order to implement life cycle design, corporations need to provide proper training to their employees in life cycle principles, use internal and external resources that support LCD more effectively, and establish better environmental performance metrics for evaluating their products. In addition, companies should work to make environmental data as readily available to development teams as cost and performance data, which can be a primary role of environmental health and safety professionals.

Many new products represent significant reductions in environmental impacts. Whirlpool's recent non-CFC, energy efficient refrigerator design demonstrates how market incentives and regulations can promote environmental design improvements. This design won the $30 million award offered by a consortium of utility companies, while also using 25% less energy than mandated by the Federal Energy Standard and eliminating use of ozone-destroying CFCs.

In general, however, environmental improvements have been incrementally focused on one or two elements of the product system or limited life cycle stages, rather than the full product life cycle system. Designers are thus not yet pursuing innovative life cycle strategies that represent a more direct pathway towards sustainable development. The challenge for industry is to take a leadership role by adopting a broader systems approach. This will require full collaboration with partners from government, environmental groups, and academia.

Conclusion

Our present rates and patterns of resource consumption and the corresponding waste generation and dispersion of pollutants are unsustainable. Achieving a sustainable economy for a rapidly expanding world population of over 5 billion demands fundamental and dramatic changes for both the industrialized world and developing countries. Although the public, industry, and government generally recognize this need, the response has not always been well focused. Green design and related concepts have been proposed as one possible means of achieving a sustainable economy, even though they often lack clear definitions of system boundaries, goals and objectives, principles, and environmental metrics.

Life cycle design and related approaches are being developed to establish a more coherent means of integrating environmental issues into product development. Life cycle design and Design for Environment are generally indistinguishable; although they originated from different points, they are converging to the same set of goals and principles. For both, the product life cycle serves as the unifying system that links economic activities and societal needs with their full ecological consequences. This life cycle design framework is the most logical way to prevent shifting adverse impacts between media (air, water, land) and life cycle stages. Concurrent design of product system components (product, process, distribution, and information/management) is also an important principle of both LCD and DFE.

At present, implementing the life cycle design framework requires significant organizational and operational changes in business. Each product system is highly interconnected to other product systems, forming a complex web which is often difficult to disentangle for a product development team.

In order to effectively promote the goals of sustainable development, life cycle designs must successfully address cost, performance, cultural and legal factors. Environmental objectives clearly cannot be pursued in isolation from these other factors. Strategies for reducing a product system's environmental burden, presented in Table IV, are generally well known to designers. The ultimate challenge in life cycle design is to choose the best strategies and synthesize them into designs that satisfy the full spectrum of requirements. Technology and thermodynamics constrain design capabilities, but societal values strongly influence product acceptance. Design changes for fostering sustainable development may thus have to be accompanied by changes in behavior.

Individually and collectively, designers and other participants in product development shape the environmental profile for a product system. Access to reliable environmental data may be considered the greatest internal need for those implementing life cycle design. Participants must have access to the same quality of information regarding environmental impacts that they have for cost and performance evaluations.

Once this information is available, the development team then requires metrics for evaluating environmental impacts associated with the product system. At present, simple tools for determining environmental profiles give an incomplete picture, while more elaborate tools such as LCA are still under development and have many practical limitations in design. In addition, because incommensurable data is a fundamental problem in environmental evaluation, it will always be necessary to make value judgments regarding dissimilar environmental impacts. Design analysis is further complicated when environmental criteria are compared with cost, performance and other factors. Although designers routinely make difficult choices, environmental analysis of life cycle issues adds another layer of complexity to a process that is already under significant time and cost pressures. Despite these limitations, designs that enhance resource efficiency, reduce liabilities associated with residuals and other environmental burdens, and achieve competitiveness are obviously beneficial.

In addition to these internal factors, external forces play a critical role in determining whether life cycle design goals for achieving sustainable development can be met. The complexity of interrelationships between internal and external factors in life cycle design was shown in Figure 7. A corporation's environmental management system must be responsive to external factors influencing design such as government regulations, market forces, infrastructure, and state of the environment, as well as scientific understanding and public perception of risks. Current regulations and economic instruments are not optimal for supporting life cycle design. The federal government is just beginning to recognize the need for regulations and policies that promote sustainable development, but changing to a more sustainable system will be difficult. New policies and practices may have to be phased in to minimize economic dislocations. If a more sustainable economic system can be realized, interdisciplinary participation will then be the key to developing product systems that reflect multistakeholder (suppliers, manufacturers, consumers, resource recovery and waste managers, public, regulators) needs.

Life cycle design can be treated as an optimization problem to maximize value-added activities (i.e., satisfying basic societal needs) while minimizing resource consumption and waste dispersion activities. Designers play a major role in defining and solving design problems, but designers alone cannot meet the life cycle design goal of harmonizing economic and ecological processes. Such a fundamental change in direction requires the full participation of all members of society.

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