Pollution Prevention and Industrial Ecology
NATIONAL POLLUTION PREVENTION CENTER FOR HIGHER EDUCATION

Industrial Ecology: An Introduction

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This portion of the industrial ecology compendium provides an overview of the subject and offers guidance on how one may teach it. Other educational resources are also emerging. *Industrial Ecology* (Thomas Graedel and Braden Allenby; New York: Prentice Hall, 1994), the first university textbook on the topic, provides a well-organized introduction and overview to industrial ecology as a field of study. Another good textbook is *Pollution Prevention: Homework and Design Problems for Engineering Curricula* (David T. Allen, N. Bakshani, and Kirsten Sinclair Rosselot; Los Angeles: American Institute of Chemical Engineers, American Insttute for Pollution Prevention, and the Center for Waste Reduction Technologies, 1993). Both serve as excellent sources of both qualitative and quantitative problems that could be used to enhance the teaching of industrial ecology concepts. Other sources of information are noted elsewhere in this introduction and in the accompanying "Industrial Ecology Resource List."

Background

The development of industrial ecology is an attempt to provide a new conceptual framework for *understanding* the impacts of industrial systems on the environment (see the "Overview of Environmental Problems" section of this compendium). This new framework serves to identify and then implement strategies to reduce the environmental impacts of products and processes associated with industrial systems, with an ultimate goal of sustainable development.

Industrial ecology is the study of the physical, chemical, and biological interactions and interrelationships both within and between industrial and ecological systems. Additionally, some researchers feel that industrial ecology involves identifying and implementing strategies for industrial systems to more closely emulate harmonious, sustainable, ecological ecosystems.[1]

Environmental problems are systemic and thus require a systems approach so that the connections between industrial practices / human activities and environmental / ecological processes can be more readily recognized. A systems approach provides a holistic view of environmental problems, making them easier to identify and solve; it can highlight the need for and advantages of achieving sustainability. **Table 1** depicts hierarchies of political, social, industrial, and ecological systems. Industrial ecology studies the interaction between different industrial systems as well as between industrial systems and ecological systems. The focus of study can be at different system levels.

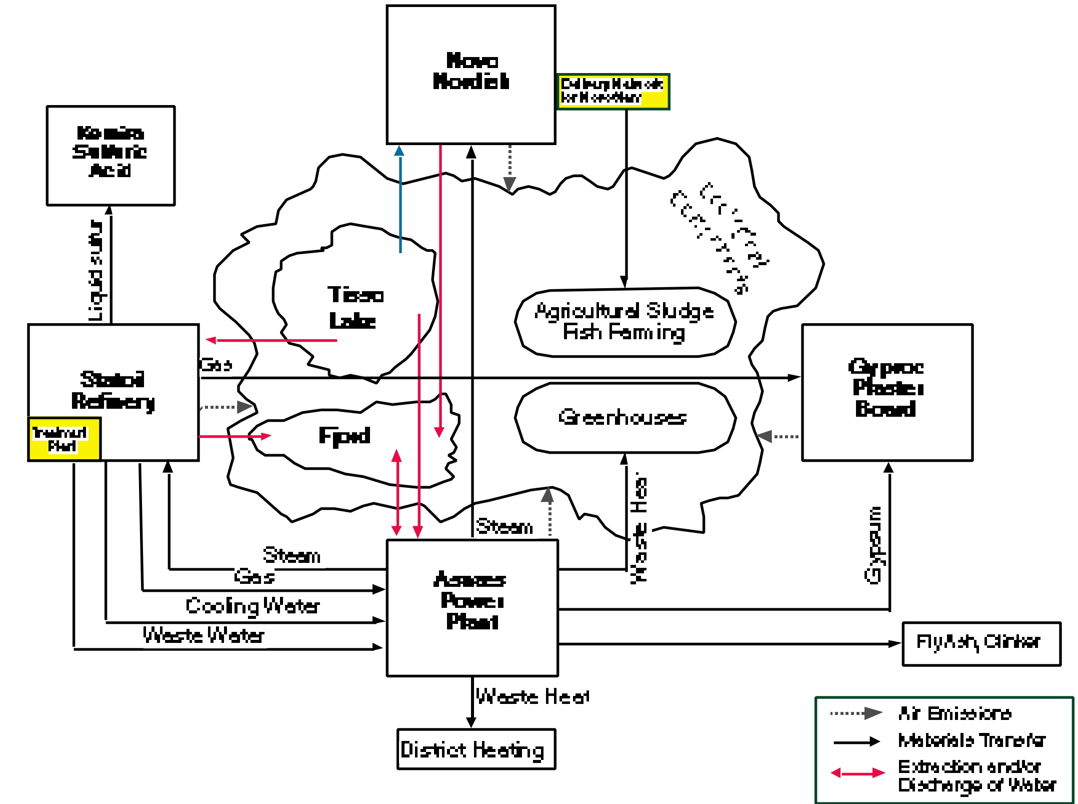
One goal of industrial ecology is to change the linear nature of our industrial system, where raw materials are used and products, by-products, and wastes are produced, to a cyclical system where the wastes are reused as energy or raw materials for another product or process. The Kalundborg, Denmark, eco-industrial park represents an attempt to create a highly integrated industrial system that optimizes the use of byproducts and minimizes the waste that that leaves the system. **Figure 1** shows the symbiotic nature of the Kalundborg park (see **Appendix A** for a more complete description).

Fundamental to industrial ecology is identifying and tracing flows of energy and materials through various systems. This concept, sometimes referred to as *industrial metabolism*, can be utilized to follow material and energy flows, transformations, and dissipation in the industrial system as well as into natural systems.[2] The mass balancing of these flows and transformations can help to identify their negative impacts on natural ecosystems. By quantifying resource inputs and the generation of residuals and their fate, industry and other stakeholders can attempt to minimize the environmental burdens and optimize the resource efficiency of material and energy use within the industrial system.

TABLE 1: ORGANIZATIONAL HIERARCHIES

Political Entities	Social Organizations	Industrial Organizations	Industrial Systems	Ecological Systems
UNEP	World population	ISO	Global human material and energy flows	Ecosphere
U.S. (EPA, DOE)	Cultures	Trade associations	Sectors (e.g., transportation or health care)	Biosphere
State of Michigan (Michigan DEQ)	Communities	Corporations	Corporations/institutions	Biogeographical region
Washtenaw County	Product systems	Divisions	Product systems	Biome landscape
City of Ann Arbor	Households	Product development teams	Life cycle stages/unit steps	Ecosystem
Individual Voter	Individuals/ Consumbers	Individuals		Organism

Source: Keoleian et al., *Life Cycle Design Framework and Demonstration Projects* (Cincinnati: U.S. EPA Risk Reduction Engineering Lab, 1995), 17.



Notes:
(1) This figure is not drawn to scale, nor is it an accurate geographic depiction.
(2) Unused residuals resulting from all activities in the industrial ecopark are eventually released into the biosphere.

FIGURE 1: THE KALUNDBORG PARK

Industrial ecology is an emerging field. There is much discussion and debate over its definition as well as its practicality. Questions remain concerning how it overlaps with and differs from other more established fields of study. It is still uncertain whether industrial ecology warrants being considered its own field or should be incorporated into other disciplines. This mirrors the challenge in teaching it. Industrial ecology can be taught as a separate, semester-long course or incorporated into existing courses. It is foreseeable that more colleges and universities will begin to initiate educational and research programs in industrial ecology.

Industrial Ecology: Toward a Definition

Historical Development

Industrial ecology is rooted in systems analysis and is a higher level systems approach to framing the interaction between industrial systems and natural systems. This systems approach methodology can be traced to the work of Jay Forrester at MIT in the early 1960s and 70s; he was one of the first to look at the world as a series of interwoven systems (*Principles of Systems*, 1968, and *World Dynamics,* 1971; Cambridge, Wright-Allen Press). Donella and Dennis Meadows and others furthered this work in their seminal book *Limits to Growth* (New York: Signet, 1972). Using systems analysis, they simulated the trends of environmental degradation in the world, highlighting the unsustainable course of the then-current industrial system.

In 1989, Robert Ayres developed the concept of *industrial metabolism*: the use of materials and energy by industry and the way these materials flow through industrial systems and are transformed and then dissipated as wastes.[3] By tracing material and energy flows and performing mass balances, one could identify inefficient products and processes that result in industrial waste and pollution, as well as determine steps to reduce them. Robert Frosch and Nicholas Gallopoulos, in their important article “Strategies for Manufacturing” (*Scientific American* 261; September 1989, 144–152), developed the concept of industrial ecosystems, which led to the term *industrial ecology*. Their ideal industrial ecosystem would function as “an analogue” of its biological counterparts. This metaphor between industrial and natural ecosystems is fundamental to industrial ecology. In an industrial ecosystem, the waste produced by one company would be used as resources by another. No waste would leave the industrial system or negatively impact natural systems.

In 1991, the National Academy of Science's Colloqium on Industrial Ecology constituted a watershed in the development of industrial ecology as a field of study. Since the Colloqium, members of industry, academia and government have sought to further characterize and apply it. In early 1994, The National Academy of Engineering published *The Greening of Industrial Eco-systems* (Braden Allenby and Deanna Richards, eds.). The book brings together many earlier initiatives and efforts to use systems analysis to solve environmental problems. It identifies tools of industrial ecology, such as design for the environment, life cycle design, and environmental accounting. It also discusses the interactions between industrial ecology and other disciplines such as law, economics, and public policy.

Industrial ecology is being researched in the U.S. EPA's Futures Division and has been embraced by the AT&T Corporation. The National Pollution Prevention Center for Higher Education (NPPC) promotes the systems approach in developing pollution prevention (P2) educational materials. The NPPC's research on industrial ecology is a natural outgrowth of our work in P2.

Defining Industrial Ecology

There is still no single definition of industrial ecology that is generally accepted. However, most definitions comprise similar attributes with different emphases. These attributes include the following:

- a systems view of the interactions between industrial and ecological systems
- the study of material and energy flows and transformations
- a multidisciplinary approach
- an orientation toward the future
- a change from linear (open) processes to cyclical (closed) processes, so the waste from one industry is used as an input for another
- an effort to reduce the industrial systems' environmental impacts on ecological systems
- an emphasis on harmoniously integrating industrial activity into ecological systems
- the idea of making industrial systems emulate more efficient and sustainable natural systems
- the identification and comparison of industrial and natural systems hierarchies, which indicate areas of potential study and action (see **Table 1**).

There is substantial activity directed at the product level using such tools as *life cycle assessment* and *life cycle design* and utilizing strategies such as pollution prevention. Activities at other levels include tracing the flow of heavy metals through the ecosphere.

A cross-section of definitions of industrial ecology is provided in **Appendix B**. Further work needs to be done in developing a unified definition. Issues to address include the following.

- Is an industrial system a natural system? Some argue that everything is ultimately natural.
- Is industrial ecology focusing on integrating industrial systems into natural systems, or is it primarily attempting to emulate ecological systems? Or both?
- Current definitions rely heavily on technical, engineered solutions to environmental problems. Some authors believe that changing industrial systems will also require changes in human behavior and social patterns. What balance between behavioral changes and technological changes is appropriate?
- Is systems analysis and material and energy accounting the core of industrial ecology?

Teaching Industrial Ecology

Industrial ecology can be taught as a separate course or incorporated into existing courses in schools of engineering, business, public health and natural resources. Due to the multidisciplinary nature of environmental problems, the course can also be a multidisciplinary offering; the sample syllabi offered in this compendium illustrate this idea. Degrees in industrial ecology might be awarded by universities in the future.[4]

Chauncey Starr has written of the need for schools of engineering to lead the way in integrating an interdisciplinary approach to environmental problems in the future. This would entail educating engineers so that they could incorporate social, political, environmental and economic factors into their decisions about the uses of technology.[5] Current research in environmental education attempts to integrate pollution prevention, sustainable development, and other concepts and strategies into the curriculum. Examples include environmental accounting, strategic environmental management, and environmental law.

Industrial Ecology as a Field of Ecology

The term "Industrial Ecology" implies a relationship to the field(s) of ecology. A basic understanding of ecology is useful in understanding and promoting industrial ecology, which draws on many ecological concepts.

Ecology has been defined by the Ecological Society of America (1993) as:

> The scientific discipline that is concerned with the relationships between organisms and their past, present, and future environments. These relationships include physiological responses of individuals, structure and dynamics of populations, interactions among species, organization of biological communities, and processing of energy and matter in ecosystems.

Further, Eugene Odum has written that:

> ... the word ecology is derived from the Greek *oikos*, meaning "household," combined with the root *logy*, meaning "the study of." Thus, ecology is, literally the study of households including the plants, animals, microbes, and people that live together as interdependent beings on Spaceship Earth. As already, the environmental house within which we place our human-made structures and operate our machines provides most of our vital biological necessities; hence we can think of ecology as the study of the earth's life-support systems.[6]

In industrial ecology, one focus (or object) of study is the interrelationships among firms, as well as among their products and processes, at the local, regional, national, and global system levels (see **Table 1**). These layers of overlapping connections resemble the food web that characterizes the interrelatedness of organisms in natural ecological systems.

Industrial ecology perhaps has the closest relationship with applied ecology and social ecology. According to the *Journal of Applied Ecology*, applied ecology is:

> . . . application of ecological ideas, theories and methods to the use of biological resources in the widest sense. It is concerned with the ecological principles underlying the management, control, and development of biological resources for agriculture, forestry, aquaculture, nature conservation, wildlife and game management, leisure activities, and the ecological effects of biotechnology.

The Institute of Social Ecology's definition of social ecology states that:

> Social ecology integrates the study of human and natural ecosystems through understanding the interrelationships of culture and nature. It advances a critical, holistic world view and suggests that creative human enterprise can construct an alternative future, reharmonizing people's relationship to the natural world by reharmonizing their relationship with each other.[7]

Ecology can be broadly defined as the study of the interactions between the abiotic and the biotic components of a system. *Industrial ecology* is the study of the interactions between industrial and ecological systems; consequently, it addresses the environmental effects on both the abiotic and biotic components of the ecosphere. Additional work needs to be done to designate industrial ecology's place in the field of ecology. This will occur concurrently with efforts to better define the discipline and its terminology.

There are many textbooks that introduce ecological concepts and principles. Examples include Robert Ricklefs' *Fundamentals of Ecology* (3rd edition; New York: W. H. Freeman and Company, 1990), Eugene Odum's *Ecology and Our Endangered Life-Support Systems*, and *Ecology: Individuals, Populations and Communities* by Michael Begens, John Harper, and Colin Townsend (London: Blackwell Press, 1991).

Goals of Industrial Ecology

The primary goal of industrial ecology is to promote sustainable development at the global, regional, and local levels.[8] Sustainable development has been defined by the United Nations World Commission on Environment and Development as "meeting the needs of the present generation without sacrificing the needs of future generations."[9] Key principles inherent to sustainable development include: the sustainable use of resources, preserving ecological and human health (e.g. the maintenance of the structure and function of ecosystems), and the promotion of environmental equity (both intergenerational and intersocietal).[10]

Sustainable Use of Resources

Industrial ecology should promote the sustainable use of renewable resources and minimal use of non-renewable ones. Industrial activity is dependent on a steady supply of resources and thus should operate as efficiently as possible. Although in the past mankind has found alternatives to diminished raw materials, it can not be assumed that substitutes will continue to be found as supplies of certain raw materials decrease or are degraded.[11] Besides solar energy, the supply of resources is finite. Thus, depletion of nonrenewables and degradation of renewables must be minimized in order for industrial activity to be sustainable in the long term.

Ecological and Human Health

Human beings are only one component in a complex web of ecological interactions: their activities cannot be separated from the functioning of the entire system. Because human health is dependent on the health of the other components of the ecosystem, ecosystem structure and function should be a focus of industrial ecology. It is important that industrial activities do not cause catastrophic disruptions to ecosystems or slowly degrade their structure and function, jeopardizing the planet's life support system.

Environmental Equity

A primary challenge of sustainable development is achieving intergenerational as well as intersocietal equity. Depleting natural resources and degrading ecological health in order to meet short-term objectives can endanger the ability of future generations to meet their needs. Intersocietal inequities also exist, as evidenced by the large imbalance of resource use between developing and developed countries. Developed countries currently use a disproportionate amount of resources in comparison with developing countries. Inequities also exist between social and economic groups within the U.S.A. Several studies have shown that low income and ethnic communities in the U.S., for instance, are often subject to much higher levels of human health risk associated with certain toxic pollutants.[12]

Key Concepts of Industrial Ecology

Systems Analysis

Critical to industrial ecology is the systems view of the relationship between human activities and environmental problems. As stated earlier, industrial ecology is a higher order systems approach to framing the interaction between industrial and ecological systems. There are various system levels that may be chosen as the focus of study (see **Table 1**). For example, when focusing at the product system level, it is important to examine relationships to higher-level corporate or institutional systems as well as at lower levels, such as the individual product life cycle stages. One could also look at how the product system affects various ecological systems ranging from entire ecosystems to individual organisms. A systems view enables manufacturers to develop products in a sustainable fashion. Central to the systems approach is an inherent recognition of the interrelationships between industrial and natural systems.

In using systems analysis, one must be careful to avoid the pitfall that Kenneth Boulding has described:

> seeking to establish a single, self-contained 'general theory of practically everything' which will replace all the special theories of particular disciplines. Such a theory would be almost without content, for we always pay for generality by sacrificing content, and all we can say about practically everything is almost nothing.[13]

The same is true for industrial ecology. If the scope of a study is too broad the results become less meaningful; when too narrow they may be less useful. Refer to Boulding's *World as a Complete System* (London: Sage, 1985) for more about systems theory; see Meadows et al.'s *Limits to Growth* (New York: Signet, 1972) and *Beyond the Limits* (Post Mills, VT: Chelsea Green, 1992) for good examples of how systems theory can be used to analyze environmental problems on a global scale.

Material and Energy Flows and Transformations

A primary concept of industrial ecology is the study of material and energy flows and their transformation into products, byproducts, and wastes throughout industrial systems. The consumption of resources is inventoried along with environmental releases to air, water, land, and biota. **Figures 2, 3,** and **4** are examples of such material flow diagrams.

One strategy of industrial ecology is to lessen the amount of waste material and waste energy that is produced and that leaves the industrial system, subsequently impacting ecological systems adversely. For instance, in **Figure 3**, which shows the flow of platinum through various products, 88% of the material in automotive catalytic converters leaves this product system as scrap. Recycling efforts could be intensified or other uses found for the scrap to decrease this waste. Efforts to utilize waste as a material input or energy source for some other entity within the industrial system can potentially improve the overall efficiency of the industrial system and reduce negative environmental impacts. The challenge of industrial ecology is to reduce the overall environmental burden of an industrial system that provides some service to society.

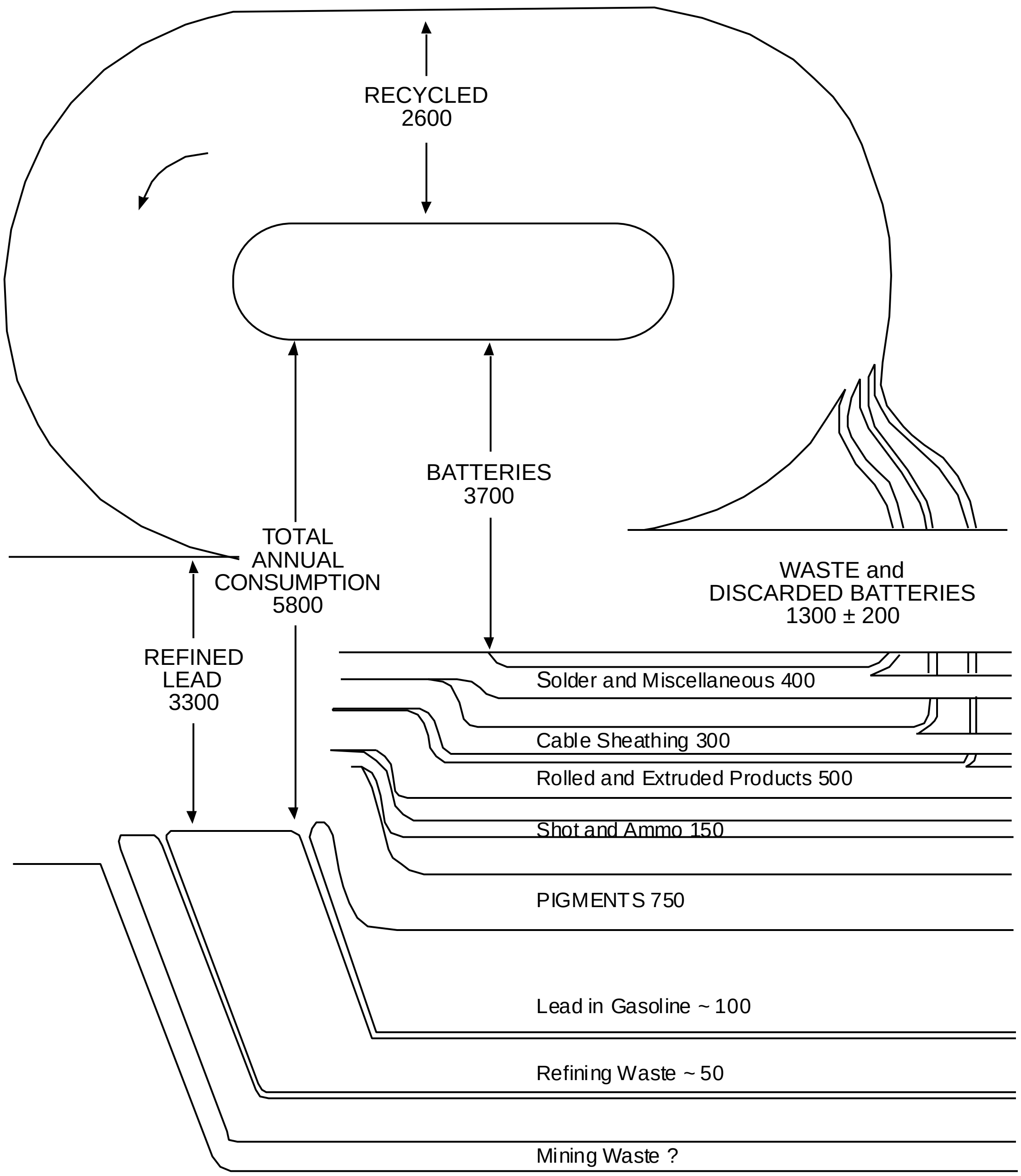


FIGURE 2: WORLD EXTRACTION, USE, AND DISPOSAL OF LEAD, 1990 (THOUSAND TONS)

R. Socolow, C. Andews, F. Berkhout, and V. Thomas, eds., *Industrial Ecology and Global Change* (New York: Cambridge University Press, 1994). Reprinted with permission from the publisher. Data from International Lead and Zinc Study Group, 1992.

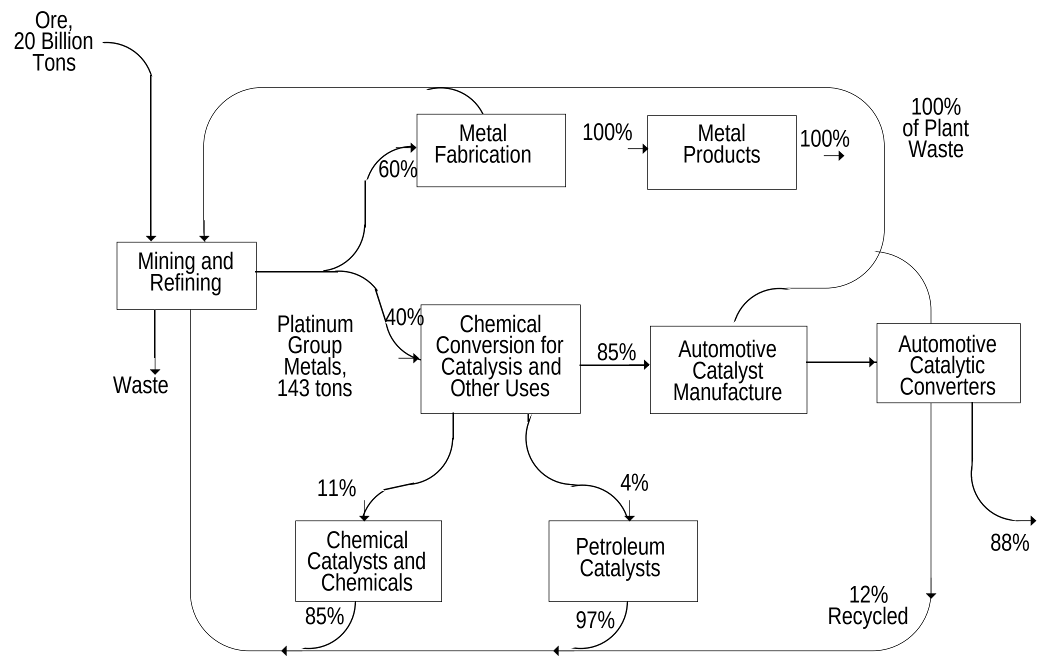


FIGURE 3: FLOW OF PLATINUM THROUGH VARIOUS PRODUCT SYSTEMS

Source: R. A. Frosch and N. E. Gallopoulos, "Strategies for Manufacturing" *Scientific American* 261 (September 1989), p. 150.

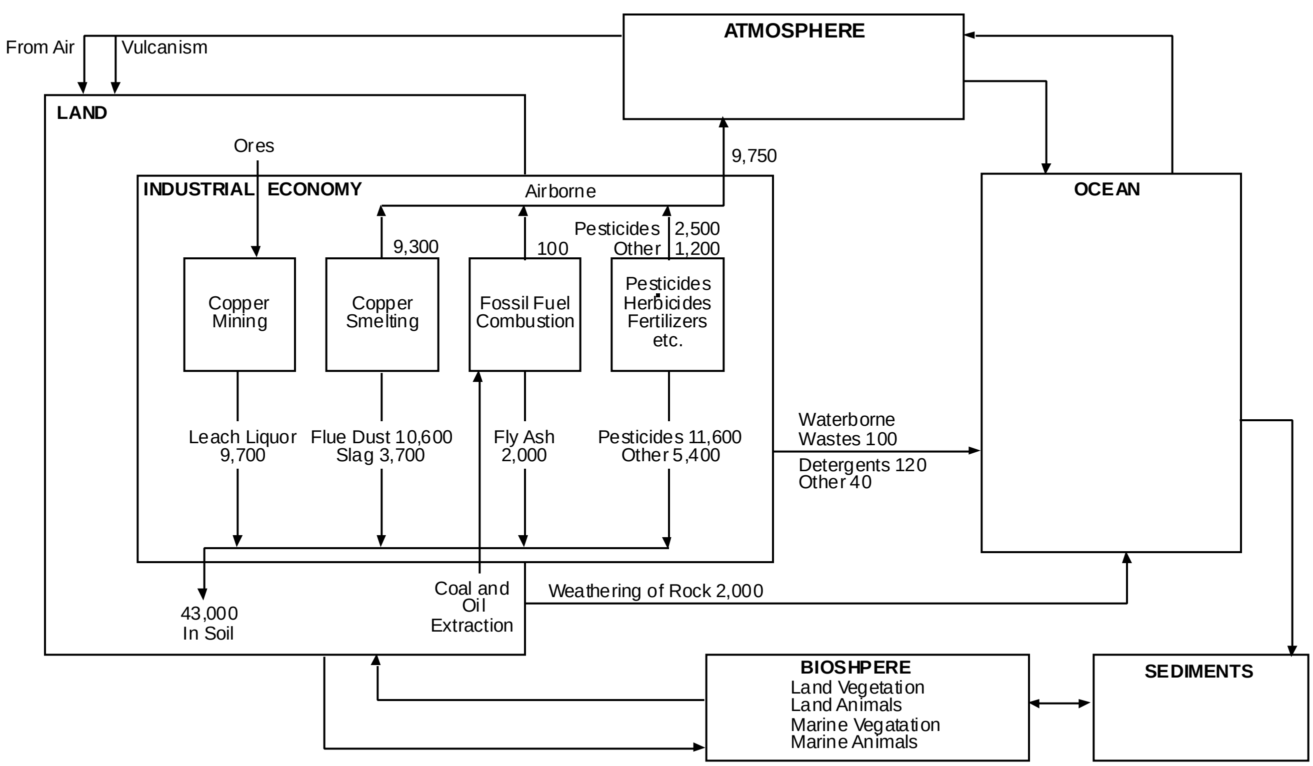


FIGURE 4: SIMPLIFIED REPRESENTATION OF ARSENIC PATHWAYS IN THE U.S. (METRIC TONS), 1975.

Source: Ayres et al. (1988).

TABLE 2: WORLDWIDE ATMOSPHERIC EMISSIONS OF TRACE METALS (THOUSAND TONNES/YEAR)

Element	Energy production	Smelting, refining, and mining	Manufacturing processes	Commercial uses, incineration, and transit	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

Source: J.O. Nriagu, "Global Metal Pollution: Poisoning the Biosphere?" *Nature* 338 (1989): 47–49. Reproduced with permission of Haldref Publications.

TABLE 3: GLOBAL FLOWS OF SELECTED MATERIALS*

Material	Flow (Million metric tons/yr)	Per-capita flow**
Minerals		1.2 ***
Phosphate	120	
Salt	190	
Mica	280	
Cement	890	
Metals		0.3
Al	097.0	
Cu	8.5	
Pb	3.4	
Ni	0.8	
Sn	0.2	
Zn	7.0	
Steel	780	
Fossil Fuels	1.6	
Coal	3,200	
Lignite	1,200	
Oil	2,800	
Gas	920	
Water	41,000,000	8,200.0

* Data sources include *UN Statistical Yearbooks* (various years), *Minerals Yearbooks* (U.S. Department of the Interior, 1985), and *World Resources 1990–1991* (World Resources Institute, 1990).

** Per-capita figures are based on a population of five billion people and include materials in addition to those highlighted in this table.

*** Does not include the amount of overburden and mine waste involved in mineral production; neglects sand, gravel, and similar material but includes cement.

Source: Thomas E. Graedel and Braden Allenby, *Industrial Ecology.* Chapter III: Table III.2.1 (New York: Prentice Hall, 1993; pre-publication copy).

TABLE 4: RESOURCES USED IN AUTOMOBILE MANUFACTURING

Plastics Used in Cars, Vans, and Small Trucks— Millions of Pounds (1989)

Material	U.S. Auto	All U.S.	Percent of Total
Nylon	141	595	23.7
Polyacetal	25	141	17.7
ABS	197	1,243	15.8
Polyurethane	509	3,245	15.7
Unsat PE	192	1,325	14.5
Polycarbonate	50	622	8.0
Acrylic	31	739	4.2
Polypropylene	298	7,246	4.1
PVC	187	8,307	2.3
TP PE	46	2,101	2.2
Polyethylene	130	18,751	0.7
Phenolic	19	3,162	0.6

Other Resources—as percentage of total U.S. consumption (1988)

Material	Percent of Total
Lead	67.3
Alloy Steel	10.7
Stainless Steel	12.3
Total Steel	12.2
Aluminum	18.3
Copper and Copper Alloys	10.2
Malleable Iron	63.8
Platinum	39.1
Natural Rubber	76.6
Synthetic Rubber	50.1
Zinc	23.0

Source: Draft Report, *Design and the Environment—The U.S. Automobile.*
The authors obtained this information from the Motor Vehicle Manufacturers Association *1990 Annual Data Book*.

To identify areas to target for reduction, one must understand the dissipation of materials and energy (in the form of pollutants) — how these flows intersect, interact, and affect natural systems. Distinguishing between natural material and energy flows and anthropogenic flows can be useful in identifying the scope of human-induced impacts and changes. As is apparent in **Table 2**, the anthropogenic sources of some materials in natural ecosystems are much greater than natural sources. **Tables 3** and **4** provide a good example of how various materials flow through one product system, that of the automobile.

Industrial ecology seeks to transform industrial activities into a more closed system by decreasing the dissipation or dispersal of materials from anthropogenic sources, in the form of pollutants or wastes, into natural systems. In the automobile example, it is useful to further trace what happens to these materials at the end of the products' lives in order to mitigate possible adverse environmental impacts.

Some educational courses may wish to concentrate on developing skills to do mass balances and to trace the flows of certain energy or material forms in processes and products. Refer to Chapters 3 and 4 in Graedel and Allenby's *Industrial Ecology* for exercises in this subject area.

Multidisciplinary Approach

Since industrial ecology is based on a holistic, systems view, it needs input and participation from many different disciplines. Furthermore, the complexity of most environmental problems requires expertise from a variety of fields — law, economics, business, public health, natural resources, ecology, engineering — to contribute to the development of industrial ecology and the resolution of environmental problems caused by industry. Along with the design and implementation of appropriate technologies, changes in public policy and law, as well as in individual behavior, will be necessary in order to rectify environmental impacts.

Current definitions of industrial ecology rely heavily on engineered, technological solutions to environmental problems. How industrial ecology should balance the need for technological change with changes in consumer behavior is still subject to debate. Some see it as having a narrow focused on industrial activity; to others, it is a way to view the entire global economic system.

Analogies to Natural Systems

There are several useful analogies between industrial and natural ecosystems.[14] The natural system has evolved over many millions of years from a linear (open) system to a cyclical (closed) system in which there is a dynamic equilibrium between organisms, plants, and the various biological, physical, and chemical processes in nature. Virtually nothing leaves the system, because wastes are used as substrates for other organisms. This natural system is characterized by high degrees of integration and interconnectedness. There is a food web by which all organisms feed and pass on waste or are eaten as a food source by other members of the web. In nature, there is a complex system of feedback mechanisms that induce reactions should certain limits be reached. (See Odum or Ricklefs for a more complete description of ecological principles.)

Industrial ecology draws the analogy between industrial and natural systems and suggests that a goal is to stimulate the evolution of the industrial system so that it shares the same characteristics as described above concerning natural systems. A goal of industrial ecology would be to reach this dynamic equilibrium and high degree of interconnectedness and integration that exists in nature.

Both natural and industrial system have cycles of energy and nutrients or materials. The carbon, hydrogen, and nitrogen cycles are integral to the functioning and equilibrium of the entire natural system; material and energy flows through various products and processes are integral to the functioning of the industrial system. These flows can affect the global environment. For example, the accumulation of greenhouse gases could induce global climate change.

There is a well-known eco-industrial park in Kalundborg, Denmark. It represents an attempt to model an industrial park after an ecological system. The companies in the park are highly integrated and utilize the waste products from one firm as an energy or raw material source for another. (This park is illustrated in **Figure 1** and described in **Appendix A**.)

Linear (Open) Versus Cyclical (Closed) Loop Systems

The evolution of the industrial system from a linear system, where resources are consumed and damaging wastes are dissipated into the environment, to a more closed system, like that of ecological systems, is a central concept to industrial ecology. Braden Allenby has described this change as the evolution from a Type I to a Type III system, as shown in **Figure 5.**

A Type I system is depicted as a linear process in which materials and energy enter one part of the system and then leave either as products or by-products / wastes. Because wastes and by-products are not recycled or reused, this system relies on a large, constant supply of raw materials. Unless the supply of materials and

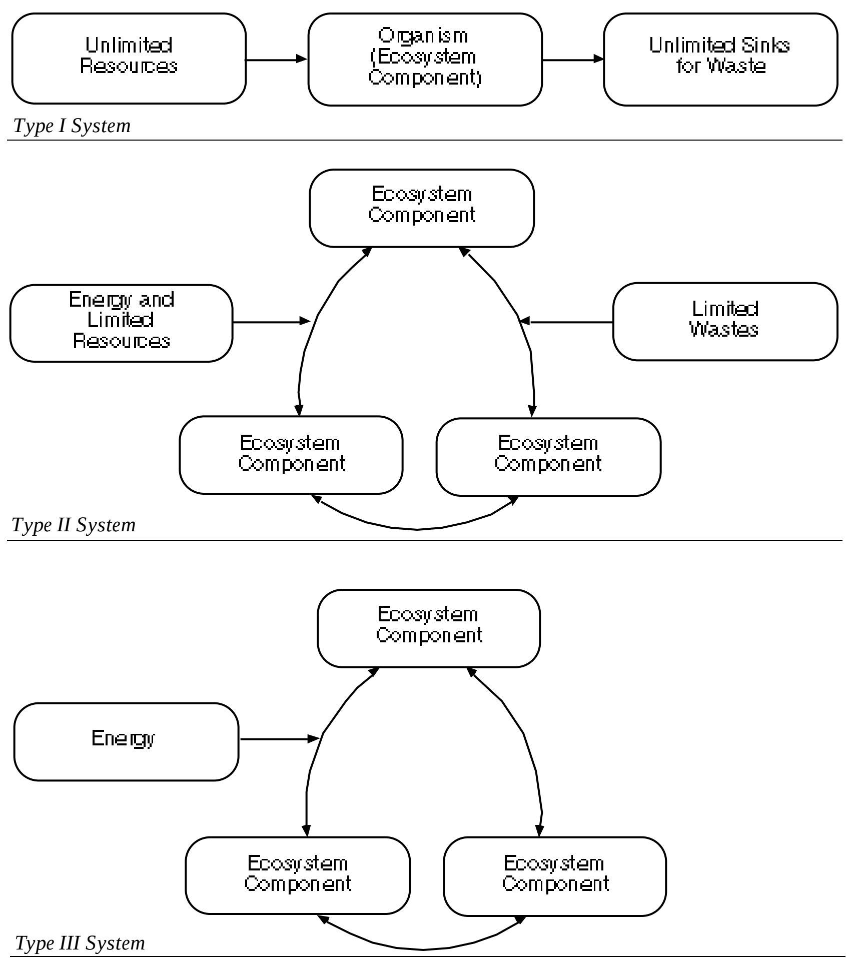


FIGURE 5: SYSTEM TYPES

Source: Braden R. Allenby, "Industrial Ecology: The Materials Scientist in an Environmentally Constrained World," *MRS Bulletin* 17, no. 3 (March 1992): 46–51. Reprinted with the permission of the Materials Research Society.

energy is infinite, this system is unsustainable; further, the ability for natural systems to assimilate wastes (known as "sinks") is also finite. In a Type II system, which characterizes much of our present-day industrial system, some wastes are recycled or reused within the system while others still leave it.

A Type III system represents the dynamic equilibrium of ecological systems, where energy and wastes are constantly recycled and reused by other organisms and processes within the system. This is a highly integrated, closed system. In a totally closed industrial system, only solar energy would come from outside, while all byproducts would be constantly reused and recycled within. A Type III system represents a sustainable state and is an ideal goal of industrial ecology.

Strategies for Environmental Impact Reduction: Industrial Ecology as a Potential Umbrella for Sustainable Development Strategies

Various strategies are used by individuals, firms, and governments to reduce the environmental impacts of industry. Each activity takes place at a specific systems level. Some feel that industrial ecology could serve as an umbrella for such strategies, while others are wary of placing well-established strategies under the rubris of a new idea like industrial ecology. Strategies related to industrial ecology are briefly noted below.

Pollution prevention is defined by the U.S. EPA as "the use of materials, processes, or practices that reduce or eliminate the creation of pollutants at the source." Pollution prevention refers to specific actions by individual firms, rather than the collective activities of the industrial system (or the collective reduction of environmental impacts) as a whole.[15] The document in this compendium entitled "Pollution Prevention Concepts and Principles" provides a detailed examination of this topic with definitions and examples.

Waste minimization is defined by the U.S. EPA as "the reduction, to the extent feasible, of hazardous waste that is generated or subsequently treated, sorted, or disposed of."[16] *Source reduction* is any practice that reduces the amount of any hazardous substance, pollutant or contaminant entering any waste stream or otherwise released into the environmental prior to recycling, treatment or disposal.[17]

Total quality environmental management (TQEM) is used to monitor, control, and improve a firm's environmental performance within individual firms. Based on well-established principles from Total Quality Management, TQEM integrates environmental considerations into all aspects of a firm's decision-making, processes, operations, and products. All employees are responsible for implementing TQEM principles. It is a holistic approach, albeit at level of the individual firm.

Many additional terms address strategies for sustainable development. *Cleaner production,* a term coined by UNEP in 1989, is widely used in Europe. Its meaning is similar to pollution prevention. In *Clean Production Strategies*, Tim Jackson writes that clean production is

> . . . an operational approach to the development of the system of production and consumption, which incorporates a preventive approach to environmental protection. It is characterized by three principles: precaution, prevention, and integration.[18]

These strategies represent approaches that individual firms can take to reduce the environmental impacts of their activities. Along with environmental impact reduction, motivations can include cost savings, regulatory or consumer pressure, and health and safety concerns. What industrial ecology potentially offers is an organizing umbrella that can relate these individual activities to the industrial system as a whole. Whereas strategies such as pollution prevention, TQEM, and cleaner production concentrate on firms' individual actions to reduce individual environmental impacts, industrial ecology is concerned about the activities of *all* entities within the industrial system.

The goal of industrial ecology is to reduce the overall, collective environmental impacts caused by the totality of elements within the industrial system.

System Tools to Support Industrial Ecology

Life Cycle Assessment (LCA)

Life cycle assessment (LCA), along with "ecobalances" and resource environmental profile analysis, is a method of evaluating the environmental consequences of a product or process "from cradle to grave."[19] [20] [21] The Society for Environmental Toxicology & Chemistry (SETAC) defines LCA as "a process used to evaluate the environmental burdens associated with a product, process, or activity."[22] The U.S. EPA has stated that an LCA "is a tool to evaluate the environmental consequences of a product or activity holistically, across its entire life."[23] In the United States, SETAC, the U.S. EPA and consulting firms are active in developing LCAs.

COMPONENTS OF AN LCA

LCA methodology is still evolving. However, the three distinct components defined by SETAC and the U.S. EPA (see **Figure 6)** are the most widely recognized:

1. *inventory analysis* — identification and quantification of energy and resource use and environmental releases to air, water, and land

2. *impact analysis* — technical qualitative and quantitative characterization and assessment of the consequences on the environment

3. *improvement analysis* — evaluation and implementation of opportunities to reduce environmental burden

Some life cycle assessment practitioners have defined a fourth component, the scoping and goal definition or initiation step, which serves to tailor the analysis to its intended use.[24] Other efforts have also focused on developing streamlined tools that are not as rigorous as LCA (e.g., Canadian Standards Association.)

METHODOLOGY

A Life Cycle Assessment focuses on the product life cycle system as shown in **Figure 7**. Most research efforts have been focused on the inventory stage. For an inventory analysis, a process flow diagram is constructed and material and energy inputs and outputs for the product system are identified and quantified as depicted in **Figure 8**. A template for constructing a detailed flow diagram for each subsystem is shown in **Figure 9**.

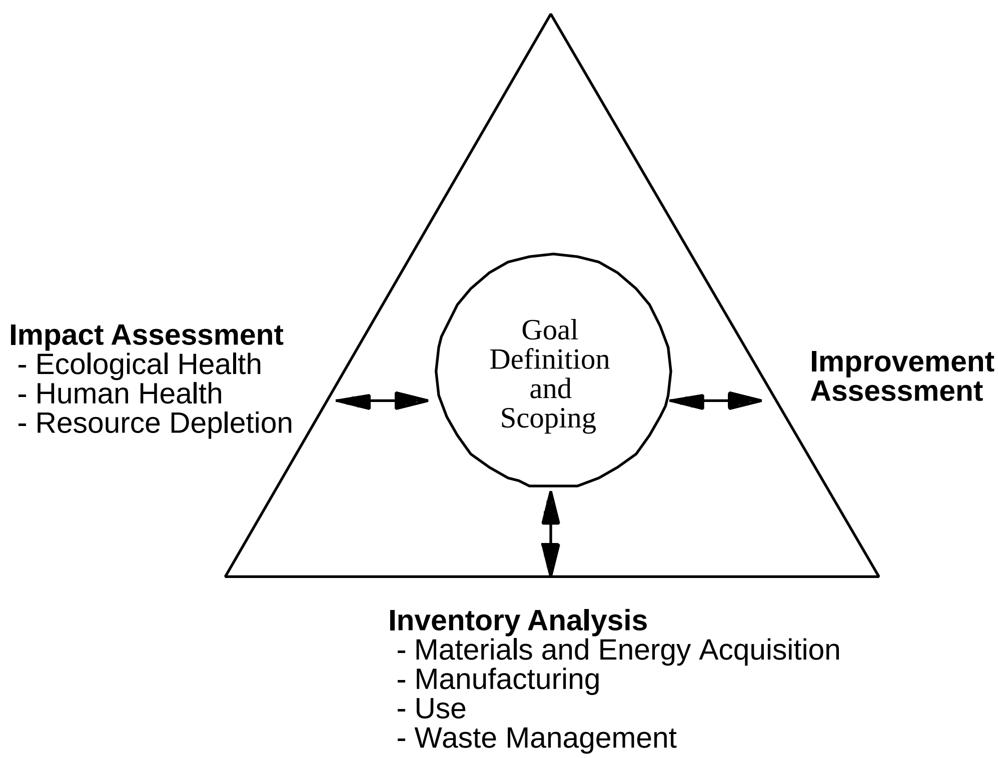
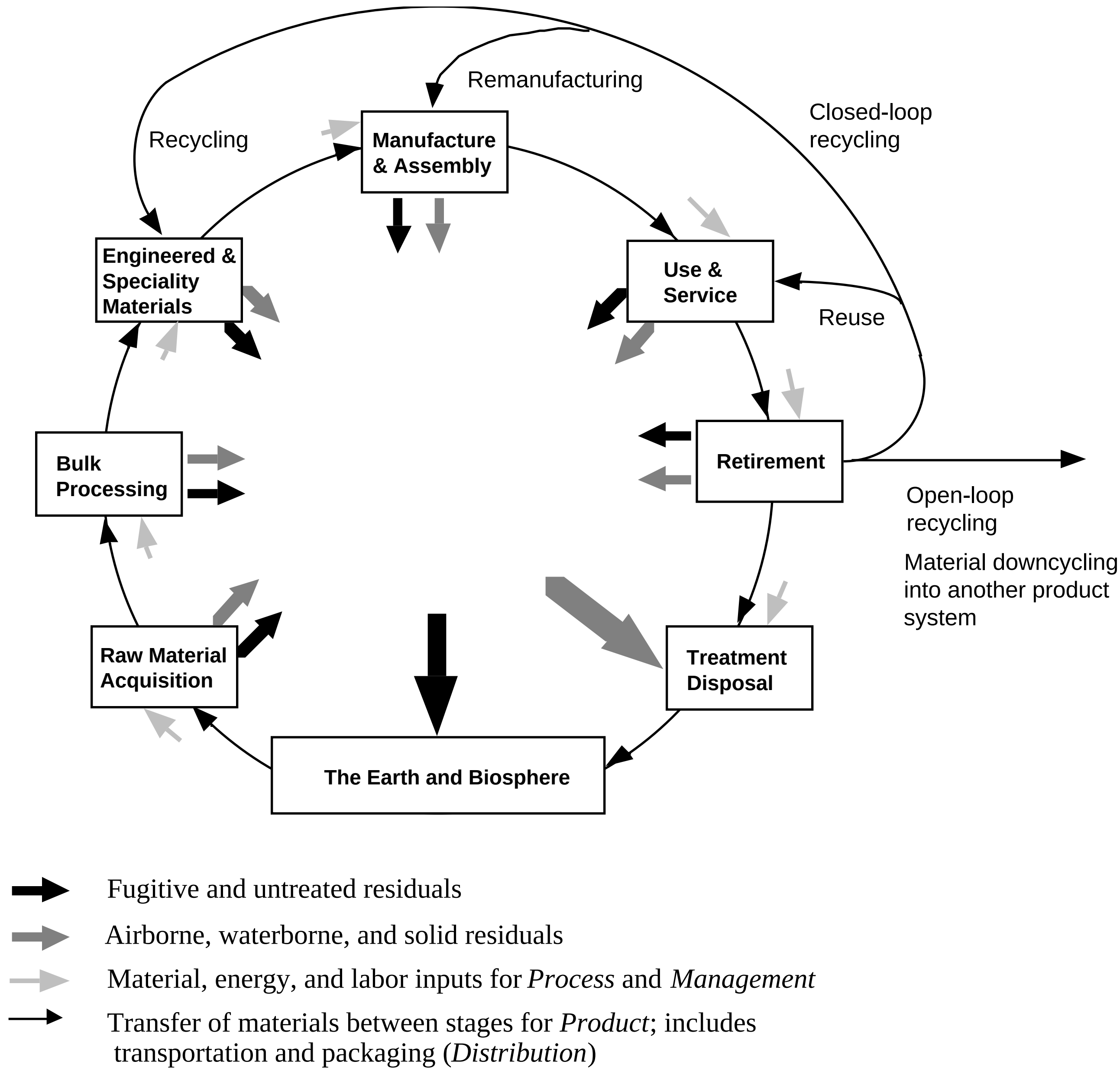


FIGURE 6: TECHNICAL FRAMEWORK FOR LIFE-CYCLE ASSESSMENT

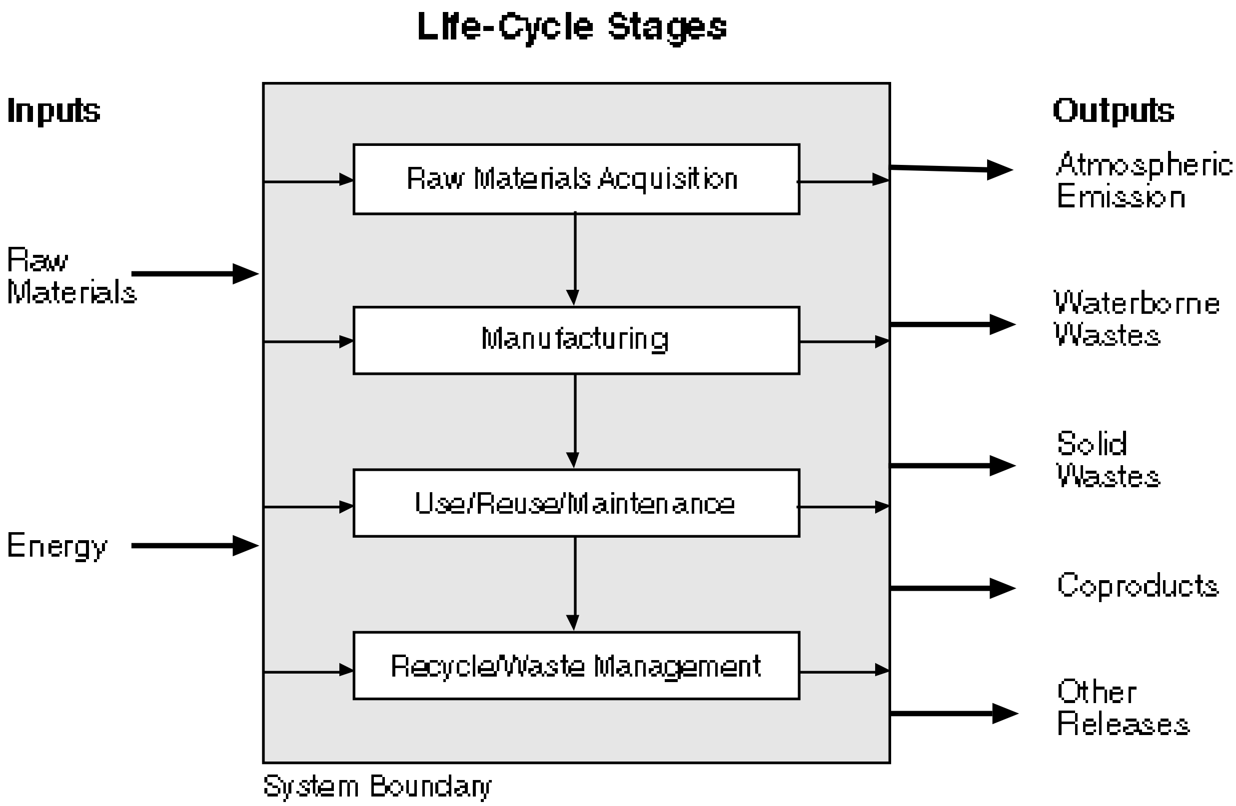
Reprinted with permission from *Guidelines for Life-Cycle Assessment: A "Code of Practice,"* F. Consoli et al., eds. Proceedings from the SETAC Workshop held in Sesimbra, Portugal, 31 March–3 April 1993. Copyright 1993 Society of Environmental Toxicology and Chemistry, Pensacola, Florida, and Brussels, Belgium.

Checklists such as those in **Figure 10** may then be used in order to further define the study, set the system boundaries, and gather the appropriate information concerning inputs and outputs. **Figure 11** shows the many stages involved in the life cycle of a bar of soap, illustrating how, even for a relatively simple product, the inventory stage can quickly become complicated, especially as products increase in number of components and in complexity.



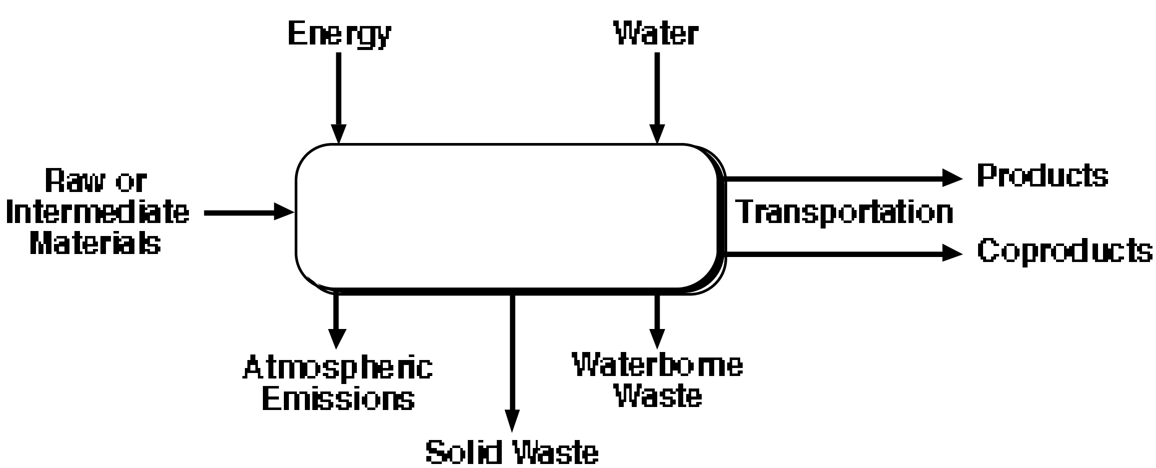
Source: Gregory A. Keoleian and Dan Menerey, *Life Cycle Design Guidance Manual* (Cincinnati: U.S. EPA Risk Reduction Engineering Lab, 1993), 14.

FIGURE 7: THE PRODUCT LIFE CYCLE SYSTEM



Source: B. W. Vigon et al., "Life Cycle Assessment: Inventory Guidelines and Principles" (Cincinnati: U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, 1993), 17.

FIGURE 8: PROCESS FLOW DIAGRAM



Source: Franklin Associates, cited in B. W. Vigon et al., "Life Cycle Assessment: Inventory Guidelines and Principles" (Cincinnati: U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, 1993), 41.

FIGURE 9: FLOW DIAGRAM TEMPLATE

LIFE-CYCLE INVENTORY CHECKLIST PART I—SCOPE AND PROCEDURES
INVENTORY OF: ____

Purpose of Inventory: (check all that apply)

Private Sector Use

Internal Evaluation and Decision-Making
- ☐ Comparison of Materials, Products or Activities
- ☐ Resource Use and Release Comparison With Other Manufacturer's Data
- ☐ Personnel Training for Product and Process Design
- ☐ Baseline Information for Full LCA

External Evaluation and Decision-Making
- ☐ Provide Information on Resource Use and Releases
- ☐ Substantiate Statements of Reductions in Resource Use and Releases

Public Sector Use

Evaluation and Policy-Making
- ☐ Support information for Policy and Regulatory Evalution
- ☐ Information Gap Identification
- ☐ Help Evaluate Statements of Reductions in Resource Use and Releases

Public Education
- ☐ Develop Support Materials for Public Education
- ☐ Assist in Curriculum Design

Systems Analyzed

List the prodoct/process systems analyzed in this inventory: ____

____

Key Assumptions: (list and describe)

____

____

____

Define the Boundaries

For each system analyzed, define the boundaries by life-cycle stage, geographic scope, primary processes, and ancillary inputs included in the system boundaries.

Postconsumer Solid Waste Management Options: Mark and describe the options analyzed for each system.
- ☐ Landfill ______________________________
- ☐ Combustion ______________________________
- ☐ Composting ______________________________
- ☐ Open-loop Recycling ______________________________
- ☐ Closed-loop Recycling ______________________________
- ☐ Other ______________________________

Basis for Comparison

☐ This is not a comparative study. ☐ This is a comparative study.

State basis for comparison between systems: (*Example: 1,000 units, 1,000 uses)*____________________________________

____

If products or processes are not normally used on a one-to-one basis, state how equivalent function was established.

____

Computational Model Construction
- ☐ System calculations are made using computer spreadsheets that relate each system component to the total system.
- ☐ System calculations are made using another technique. Describe: ____

____

Describe how inputs to and outputs from postconsumer solid waste management are handled. ____________________________

____

____

Quality Assurance: (state specific activities and initials of reviewer)

Review performed on:
- ☐ Data-Gathering Techniques ______________
- ☐ Coproduct Allocation ____________________
- ☐ Input Data ______________________________
- ☐ Model Calculations and Formulas ______________
- ☐ Results and Reporting _______________________

Peer Review: (state specific activities and initials of reviewer)

Review performed on:
- ☐ Scope and Boundary ____________________
- ☐ Data-Gathering Techniques ______________
- ☐ Coproduct Allocation ____________________
- ☐ Input Data ______________________________
- ☐ Model Calculations and Formulas ______________
- ☐ Results and Reporting _______________________

Results Presentation
- ☐ Methodology is fully described
- ☐ Individual pollutants are reported
- ☐ Emissions are reported as aggregated totals only. Explain why. ____________________________________

  ____
- ☐ Report is sufficiently detailed for its defined purpose.

Report may need more detail for additional use beyond defined purpose.

Sensitivity analyses are included in the report.
List: ____

Sensitivity analyses have been performed but are not included in the report. List: ______________________

____

FIGURE 10: TYPICAL CRITERIA CHECKLIST WITH WORKSHEET FOR PERFORMING LIFE-CYCLE INVENTORY

LIFE-CYCLE INVENTORY CHECKLIST PART II—MODULE WORKSHEET

Inventory of: ________________________________ Preparer: ____________________________

Life-Cycle Stage Description: ____

Date: ________________________ Quality Assurance Approval: ____________________________

MODULE DESCRIPTION: ____

	Data Value[(a)]	**Type**[(b)]	**Data**[(c)] **Age/Scope**	**Quality Measures**[(d)]
		MODULE INPUTS		
Materials				
Process				
Other[(e)]				
Energy				
Process				
Precombustion				
Water Usage				
Process				
Fuel-Related				
		MODULE OUTPUTS		
Product				
Coproducts[(f)]				
Air Emissions				
Process				
Fuel-Related				
Water Effluents				
Process				
Fuel-Related				
Solid Waste				
Process				
Fuel-Related				
Capital Repl.				
Transportation				
Personnel				

(a) Include units.

(b) Indicate whether data are actual measurements, engineering estimates, or theoretical or published values and whether the numbers are from a specific manufacturer or facility, or whether they represent industry-average values. List a specific source if pertinent, e.g., “obtained from Atlanta facility wastewater permit monitoring data.”

(c) Indicate whether emissions are all available, regulated only, or selected. Designate data as to geographic specificity, e.g., North America, and indicate the period covered, e.g., average of monthly for 1991.

(d) List measures of data quality available for the data item, e.g., accuracy, precision, representativeness, consistency-checked, other, or none.

(e) Include nontraditional inputs, e.g., land use, when appropriate and necessary.

(f) If coproduct allocation method was applied, indicate basis in quality measures column, e.g. weight

Source: Vigon et al., “Life Cycle Assessment: Inventory Guidelines and Principles” (Cincinnati: U.S. EPA, Risk Reduction Engineering Lab, 1993), 24–25.

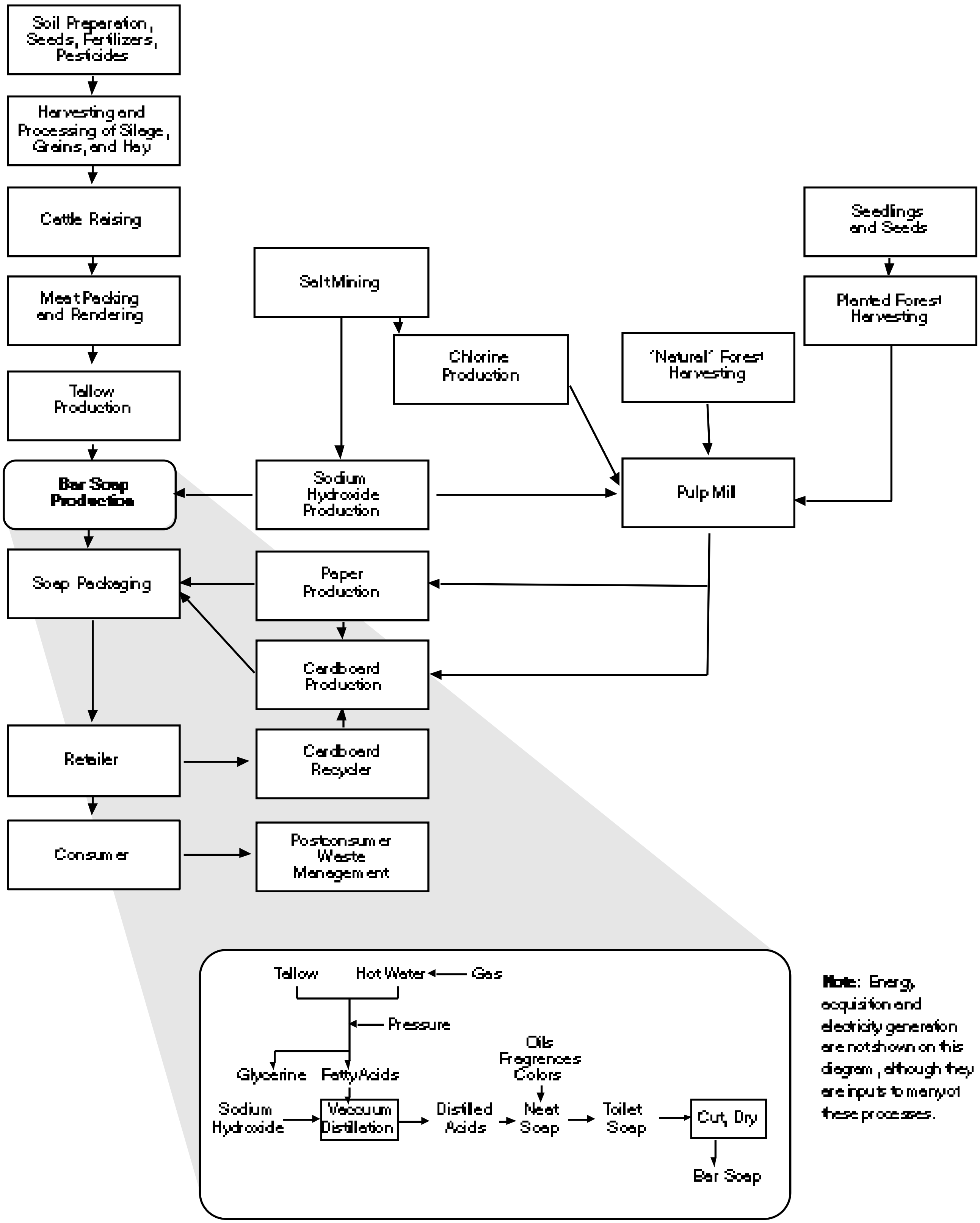


FIGURE 11: DETAILED SYSTEM DIAGRAM FOR BAR SOAP

Source: Vigon et al., "Life Cycle Assessment: Inventory Guidelines and Principles" (Cincinnati: U.S. EPA Risk Reduction Engineering Laboratory), 42.

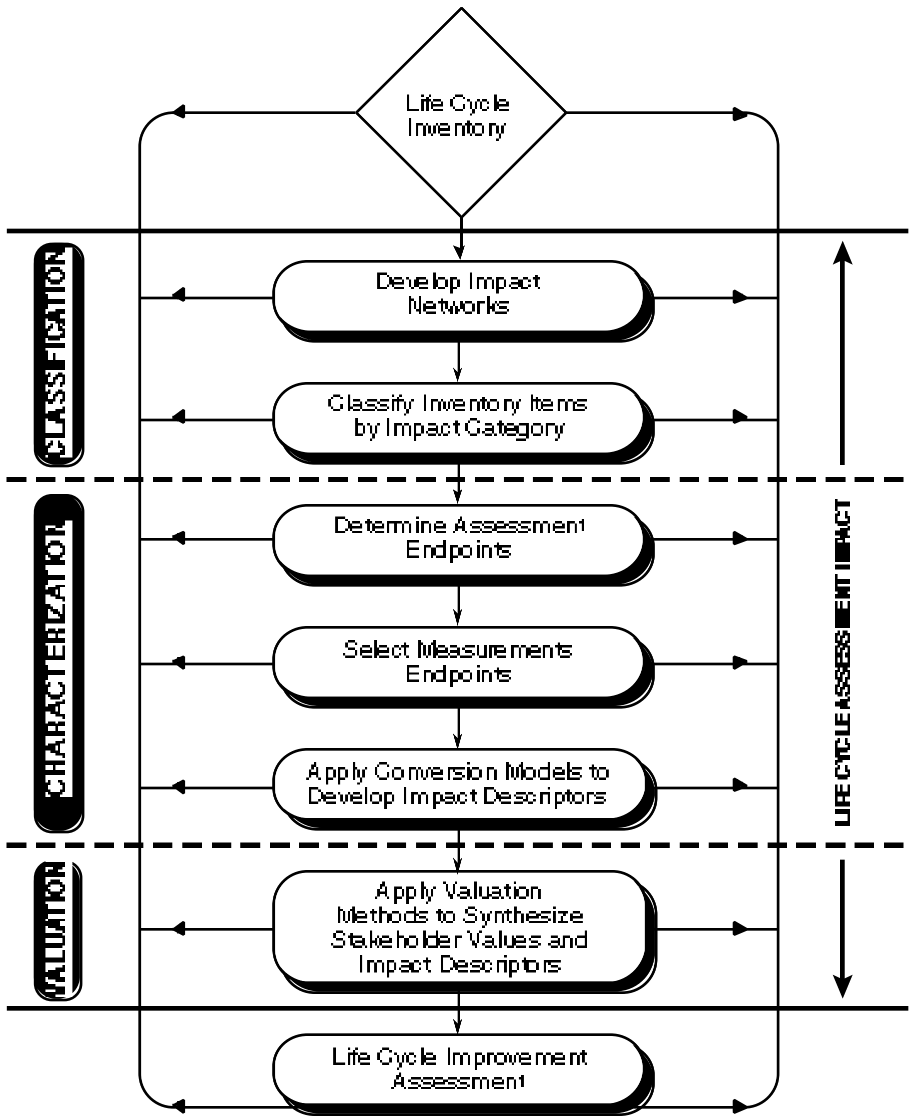


FIGURE 12: IMPACT ASSESSMENT CONCEPTUAL FRAMEWORK

Source: Keoleian et al., *Life Cycle Design Framework and Demonstration Projects* (Cincinnati: U.S. EPA Risk Reduction Engineering Lab, 1995), 55.

Once the environmental burdens have been identified in the *inventory analysis*, the impacts must be characterized and assessed. The *impact assessment* stage seeks to determine the severity of the impacts and rank them as indicated by **Figure 12**. As the figure shows, the impact assessment involves three stages: classification, characterization, and valuation. In the classification stage, impacts are placed in one of four categories: resource depletion, ecological health, human health, and social welfare. Assessment endpoints must then be determined. Next, conversion models are used to quantify the environmental burden. Finally, the impacts are assigned a value and / or are ranked.

Efforts to develop methodologies for impact assessment are relatively new and remain incomplete. It is difficult to determine an endpoint. There are a range of conversion models, but many of them remain incomplete. Furthermore, different conversion models for translating inventory items into impacts are required for each impact, and these models vary widely in complexity, uncertainty, and sophistication. This stage also suffers from a lack of sufficient data, model parameters and conversion models.

The final stage of a LCA, the *improvement analysis*, should respond to the results of the inventory and / or impact assessment by designing strategies to reduce the identified environmental impacts. Proctor and Gamble is one company that has used life cycle inventory studies to guide environmental improvement for several products.[25] One of its case studies on hard surface cleaners revealed that heating water for use with the product resulted in a significant percentage of total energy use and air emissions related to cleaning.[26] Based on this information, opportunities for reducing impacts were identified, such as designing cold-water and no-rinse formulas and educating consumers to use cold water.

APPLICATIONS OF LCA

Life cycle assessments can be used both internally (within an organization) and externally (by the public and private sectors).[27] Internally, LCAs can be used to establish a comprehensive baseline (i.e., requirements) that product design teams should meet, identify the major impacts of a product's life cycle, and guide the improvement of new product systems toward a net reduction of resource requirements and emissions in the industrial system as a whole. Externally, LCAs can be used to compare the environmental profiles of alternative products, processes, materials, or activities and to support marketing claims. LCA can also support public policy and eco-labeling programs.

DIFFICULTIES WITH LCA

As shown in **Table 5**, many methodological problems and difficulties inhibit use of LCAs, particularly for smaller companies. For example, the amount of data and the staff time required by LCAs can make them very expensive, and it isn't always easy to obtain all of the necessary data. Further, it is hard to properly define system boundaries and appropriately allocate inputs and outputs between product systems and stages. It is often very difficult to assess the data collected because of the complexity of certain environmental impacts. Conversion models for transforming inventory results into environmental impacts remain inadequate. In many cases there is a lack of fundamental understanding and knowledge about the actual cause of certain environmental problems and the degree of threat that they pose to ecological and human health.

TABLE 5: GENERAL DIFFICULTIES AND LIMITATIONS OF THE LCA METHODOLOGY

Source: Gregory A. Keoleian, "The Application of Life Cycle Assessment to Design," *Journal of Cleaner Production* 1, no. 3–4 (1994): 143–149.

Goal Definition and Scoping

Costs to conduct an LCA may be prohibitive to small firms. Time required to conduct LCA may exceed product development constraints, especially for short development cycles. Temporal and spatial dimensions of a dynamic product system are difficult to address. Definition of functional units for comparison of design alternatives can be problematic. Allocation methods used in defining system boundaries have inherent weaknesses. Complex products (e.g., automobiles) require tremendous resources to analyze.

Data Collection

Data availability and access can be limiting (e.g., proprietary data). Data quality concerns such as bias, accuracy, precision, and completeness are often not well-addressed.

Data Evaluation

Sophisticated models and model parameters for evaluating resource depletion and human and ecosystem health may not be available, or their ability to represent the product system may be grossly inaccurate. Uncertainty analyses of the results are often not conducted.

Information Transfer

Design decisionmakers often lack knowledge about environmental effects. Aggregation and simplification techniques may distort results. Synthesis of environmental effect categories is limited because they are incommensurable.

In the absence of an accepted methodology, results of LCAs can differ. Order-of-magnitude differences are not uncommon. Discrepancies can be attributed to differences in assumptions and system boundaries.

Regardless of the current limitations, LCAs offer a promising tool to identify and then implement strategies to reduce the environmental impacts of specific products and processes as well as to compare the relative merits of product and process options. However, much work needs to be done to develop, utilize, evaluate, and refine the LCA framework.

Life Cycle Design (LCD) and Design For the Environment (DfE)

The design of products shapes the environmental performance of the goods and services that are produced to satisfy our individual and societal needs.[28] Environmental concerns need to be more effectively addressed in the design process to reduce the environmental impacts associated with a product over its life cycle. Life Cycle Design, Design for Environment, and other similar initiatives based on the product life cycle are being developed to systematically incorporate these environmental concerns into the design process.

Life Cycle Design (LCD) is a systems-oriented approach for designing more ecologically and economically sustainable product systems. Coupling the product development cycle used in business with a product's physical life cycle, LCD integrates environmental requirements into each design stage so total impacts caused by the product system can be reduced.[29]

Design for Environment (DfE) is another design strategy that can be used to design products with reduced environmental burden. DfE and LCD can be difficult to distinguish. They have similar goals but evolved from different sources. DfE evolved from the "Design for X" approach, where X can represent manufacturability, testability, reliability, or other "downstream" design considerations.[30] Braden Allenby has developed a DfE framework to address the entire product life cycle. Like LCD, DfE uses a series of matrices in an attempt to develop and then incorporate environmental requirements into the design process. DfE is based on the product life cycle framework and focuses on integrating environmental issues into products and process design.

Life cycle design seeks to minimize the environmental consequences of each product system component: product, process, distribution and management.[31]

Figure 13 indicates the complex set of issues and decisions required in LCD. When sustainable development is the goal, the design process can be affected by both internal and external factors.

Internal factors include corporate policies and the companies' mission, product performance measures, and product strategies as well as the resources available to the company during the design process. For instance, a company's corporate environmental management system, if it exists at all, greatly affects the designer's ability to utilize LCD principles.

External factors such as government policies and regulations, consumer demands and preferences, the state of the economy, and competition also affect the design process, as do current scientific understanding and public perception of risks associated with the product.

THE NEEDS ANALYSIS

As shown in the figure, a typical design project begins with a needs analysis. During this phase, the purpose and scope of the project is defined, and customer needs and market demand are clearly identified.[32] The system boundaries (the scope of the project) can cover the full life cycle system, a partial system, or individual stages of the life cycle. Understandably, the more comprehensive the system of study, the greater the number of opportunities identified for reducing environmental impact. Finally, *benchmarking* of competitors can identify opportunities to improve environmental performance. This involves comparing a company's products and activities with another company who is considered to be a leader in the field or "best in class."

DESIGN REQUIREMENTS

Once the projects needs have been established, they are used in formulating design criteria. This step is often considered to be the most important phase in the design process. Incorporating key environmental requirements into the design process as early as possible can prevent the need for costly, time-consuming adjustments later. A primary objective of LCD is to incorporate environmental requirements into the design criteria along with the more traditional considerations of performance, cost, cultural, and legal requirements.

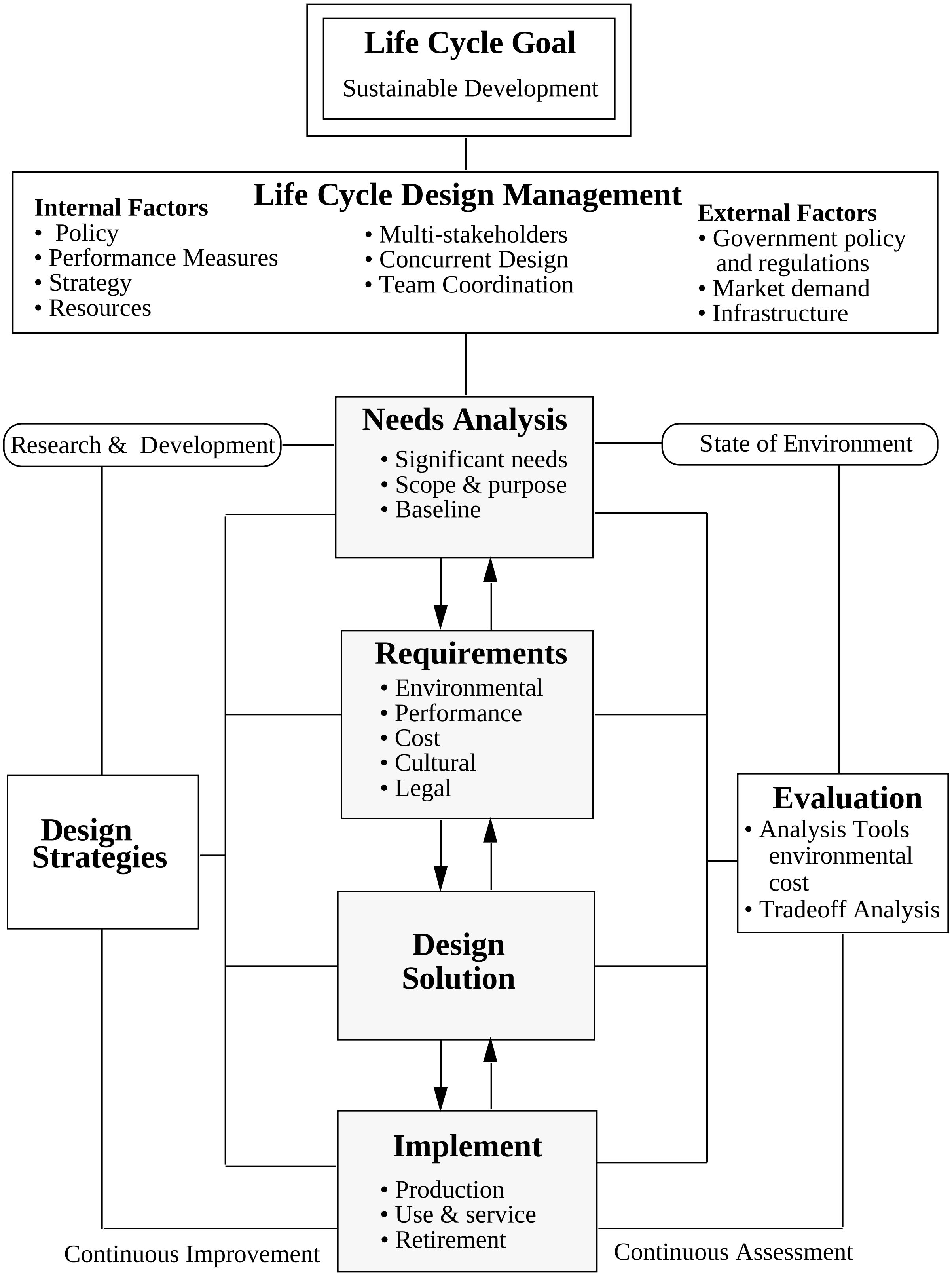


FIGURE 13: LIFE CYCLE DESIGN

Source: Keoleian and Menerey, *Life Cycle Design Guidance Manual* (Cincinnati: U.S. EPA Risk Reduction Engineering Laboratory, January 1993), 23.

Design checklists comprised of a series of questions are sometimes used to assist designers in systematically addressing environmental issues. Care must be taken to prevent checklists, such as the one in **Table 7**, from being overly time-consuming or disruptive to the creative process. Another more comprehensive approach is to use requirement matrices such as the one shown in **Figure 14.**

TABLE 7: ISSUES TO CONSIDER WHEN DEVELOPING ENVIRONMENTAL REQUIREMENTS

Materials and Energy

Amount & Type
- renewable
- nonrenewable

Character
- virgin
- reused/recycled
- reusable/ recyclable

Resource Base
- location
- local vs. other
- availability
- quality
- management
- restoration practices

Impacts From Extraction and Use
- material/energy use
- residuals
- ecosystem health
- human health

Residuals

Type
- solid waste
- air emissions
- waterborne

Characterization
- constituents
- amount
- concentration
- toxicity
- hazardous content
- radioactivity

Environmental Fate
- containment
- bioaccumulation
- degradability
- mobility/transport
- ecologial impacts
- human health impacts

Ecological Health

Stressors
- physical
- biological
- chemical

Impact Categories
- diversity
- sustainability
- resilience
- system structure
- system function

Scale
- local
- regional
- global

Human Health and Safety

Population at Risk
- workers
- users
- community

Exposure Routes
- inhalation, contact, ingestion
- duration & frequency

Accidents
- type
- frequency)

Toxic Character
- acute effects
- chronic effects
- morbidity/mortality

Nuisance Effects
- noise
- odors
- visibility

Source: Keoleian et al., *LIfe Cycle Design Framework and Demonstration Projects* (Cincinnati: U.S. EPA Risk Reduction Engineering Lab, July 1995), 45.

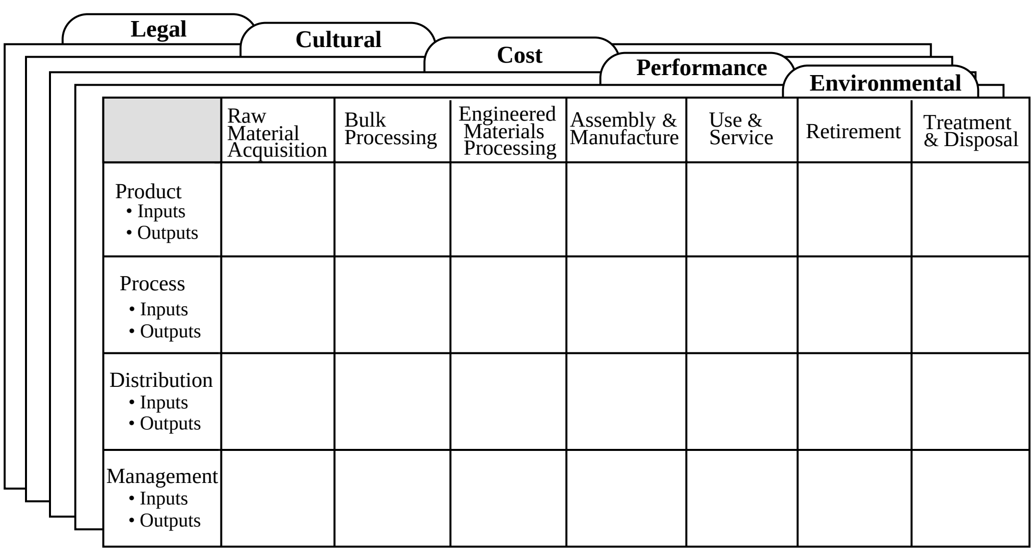


FIGURE 14: REQUIREMENTS MATRICES

Source: Keoleian and Menerey, *Life Cycle Design Guidance Manual* (Cincinnati: U.S. EPA Risk Reduction Engineering Lab, January 1993), 44.

Matrices can be used by product development teams to study interactions between life cycle requirements and their associated environmental impacts. There are no absolute rules for organizing matrices. Development teams should choose a format that is appropriate for their project. The requirements matrices shown 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 on requirements in more depth.

Government policies, along with the criteria identified in the needs analysis, also should be included. It is often useful in the long term to set environmental requirements that exceed current regulatory requirements to avoid costly design changes in the future.

Performance requirements relate to the functions needed from a product. Cost corresponds to the need to deliver the product to the marketplace at a competitive price. LCD looks at the cost to stakeholders such as manufacturers, suppliers, users and end-of-life managers. Cultural requirements include aesthetic needs such as shape, form, color, texture, and image of the product as well as specific societal norms such as convenience or ease of use.[33] These requirements are ranked and weighed given a chosen mode of classification.

DESIGN STRATEGIES

Once the criteria have been defined, the design team can then use design strategies to meet these requirements. Multiple strategies often must be synthesized in order to translate these requirements into solutions. A wide range of strategies are available for satisfying environmental requirements, including *product system life extension, material life extension, material selection,* and *efficient distribution*. A summary of these strategies are shown in **Table 8**. Note that recycling is often overemphasized.

TABLE 8: STRATEGIES FOR MEETING ENVIRONMENTAL REQUIREMENTS

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
- use substitute processes
- increase energy efficiency
- process materials efficiently
- control processes
- improve process layout
- improve inventory control and material handling processes
- plan efficient facilities
- consider treatment and disposal too

Efficient Distribution
- choose efficient transportation
- reduce packaging
- use low-impact or reusable packaging

Improved Management Practices
- use office materials and equipment efficiently
- phase out high-impact products
- choose environmentally responsible suppliers or contractors
- label properly
- advertise demonstrable environmental improvements

Source: Keoleian et al., *LIfe Cycle Design Framework and Demonstration Projects* (Cincinnati: U.S. EPA Risk Reduction Engineering Lab, July 1995), 51.

DESIGN EVALUATION

Finally, it is critical that the design is evaluated and analyzed throughout the design process. Tools for design evaluation range from LCA to single-focus environmental metrics. In each case, design solutions are evaluated with respect to a full spectrum of criteria, which includes cost and performance.

DfE methods developed by Allenby use a semi-quantitative matrix approach for evaluating life cycle environmental impacts.[34 35] A graphic scoring system weighs environmental effects according to 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.

Although LCD is not yet widely practiced, it has been used by companies like AT&T and AlliedSignal and is recognized as an important approach for reducing environmental burdens. To enhance the use of LCD, appropriate government policies must be evaluated and established. In addition, environmental accounting methods must be further developed and utilized by industry (these methods are often referred to as Life Cycle Costing or Full Cost Accounting — see **Table 9.**)

TABLE 9: DEFINITIONS OF ACCOUNTING AND CAPITAL BUDGETING TERMS RELEVANT TO LCD

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 only include costs that affect the firm’s bottom line; 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. Further, educational institutions must work to continue the development and the dissemination of the LCD methodology and related approaches. Key issues in environmental accounting that need to be addressed include: measurement and estimation of environmental costs, allocation procedures, and the inclusion of appropriate externalities.

Source: Robert S. Kaplan, “Management Accounting for Advanced Technical Environments,” *Science* 245 (1989): 819–823; cited in Keoleian et al., *LIfe Cycle Design Framework and Demonstration Projects* (Cincinnati: U.S. EPA Risk Reduction Engineering Lab, July 1995), 62.

Future Needs for the Development of Industrial Ecology

Industrial ecology is an emerging framework. Thus much research and development of the field and its concepts need to be done. Future needs for the further development of industrial ecology include:

- A clearer definition of the field and its concepts. The definition of industrial ecology, its scope and its goals need to be clarified and unified in order to be more useful. The application of systems analysis must be further refined.
- A clearer definition of sustainable development, what constitutes sustainable development, and how it might be achieved, will help define the goals and objectives of industrial ecology. Difficult goals to address, along with the maintenance of ecological system health, are intergenerational and intersocietal equity.
- More participation from a cross section of fields such as ecology, public health, business, natural resources and engineering should be encouraged in order to meet some of the vast research and information requirements needed to identify and implement strategies to reduce environmental burdens.
- Increased curriculum development efforts on sustainable development in professional schools of engineering, business, public health, natural resources, and law. The role of industrial ecology in these efforts should be further explored and defined. Determining whether industrial ecology courses should be discipline specific, interdisciplinary or integrated as modules into existing courses.
- Further research on the impacts of industrial ecosystem activities on natural ecosystems in order to identify what problems need to be resolved and how.
- Greater recognition of the importance of the systems approach to identifying and resolving environmental problems.
- Further development of tools such as life cycle assessment and life cycle design and design for the environment.
- The improvement of governmental policies that will strengthen incentives for industry to reduce environmental burdens.

Further Information

Further resources, references and sources of information are provided in other sections of this compendium. Please forward any comments or concerns directly to the National Pollution Prevention Center. Your input is encouraged and appreciated.

Endnotes

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Appendix A: "The Industrial Symbiosis at Kalundborg, Denmark"

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Background

The concept of sustainable development is being widely referred to by politicians, authorities, industrialists, and the press. Although there is agreement in principle about the meaning of this concept, there are many and differing opinions as to what it means in practice and how the concept should be translated into specific action.

The subject for my presentation is "Industrial Symbiosis," and I think that this could well be viewed as a practical example of application of the sustainable development concept. The industrial symbiosis project at Kalundborg (100 km west of Copenhagen) in Denmark has attracted a good deal of international attention, notably by the EC Commission, and the project has been awarded a number of environmental prizes.

The symbiosis project is originally not the result of a careful environmental planning process. It is rather the result of a gradual development of co-operation between four neighbouring industries and the Kalundborg municipality. From a stage where things happened by chance, this co-operation has now developed into a high level of environmental consciousness, where the participants are constantly exploring new avenues of environmental co-operation.

What is industrial symbiosis? In short, it is a process whereby a waste product in one industry is turned into a resource for use in one or more other industries. A more profound definition could be:

> "A co-operation between different industries by which the presence of each of them increases the viability of the others and by which the demands from society for resource conservation and environmental protection are taken into consideration."

Participants in the Kalundborg symbiosis are:

- Asnæsværket, Denmark's largest power plant. The plant is coal-fired with a capacity of 1,500 MW. It employs about 600 people.
- The Statoil oil refinery, Denmark's largest refinery with a capacity of about three million tons/year. The refinery is currently being expanded to a capacity of five million tons/year with a manning level of about 250 people.
- Gyproc A/S, a plaster board manufacturing plant producing about 14 million m^2/year of plaster board for the building industry. The employment is about 175 people.
- Novo Nordisk, a biotechnological industry producing about 45% of the world market of insulin and about 50% of the world market of enzymes. In addition, there is substantial production of growth hormones and other pharmaceutical products. Novo Nordisk is operating in several countries, but the Kalundborg plant with its 1,100 people is the largest production site.
- The Kalundborg municipality, who through its technical administration is the operator of all distribution of water, electricity, and district heating in the Kalundborg city area.

Development of the symbiosis

- In 1959 Asnæsværket, who is the central partner in the symbiosis, was started up.
- In 1961 Tidewater Oil Company commissioned the first oil refinery in Denmark. The refinery was taken over by Esso two years later and acquired by Statoil in 1987 along with Esso's Danish marketing facilities. To ensure adequate water supply, <u>a pipeline from the Lake Tissø was constructed.</u>
- In 1972 Gyproc established a plaster board manufacturing plant. <u>A pipeline for supply of excess refinery gas was constructed.</u>
- In 1973 the Asnæs power plan was expanded. The additional <u>water requirements were supplied through a connection to the Tissø pipeline</u> following an agreement with the refinery.
- In 1976 Novo Nordisk started delivery by special tank trucks of <u>biological sludge to the neighbouring farming community.</u>

- In 1979 the power plant started supply of fly ash (until then a troublesome waste product) to cement manufacturers (e.g., Aalborg Portland).
- In 1981 the Kalundborg municipality completed a district heating distribution network within the city of Kalundborg utilising waste heat from the power plant.
- In 1982 Novo Nordisk and the Statoil refinery completed the construction of steam supply pipelines from the power plant. The subsequent purchase of process steam from the power plant enabled the shut-down of their own inefficient steam boiler capacity.
- In 1987 the Statoil refinery completed a pipeline for supply of cooling water effluent to the power plant for use as raw boiler feed water.
- In 1989 the power plant started to use the waste heat in salt cooling water (+7–8°C) for fish production (trouts and turbot).
- In 1989 Novo Nordisk entered into an agreement with the Kalundborg municipality, the power plant, and the refinery for supply of Tissø water to meet Novo's rising demand for cooling water following several expansions.
- In 1990 the Statoil refinery completed the construction of a sulphur recovery plant for production of elemental sulphur being sold as a raw material for sulphuric acid manufacture.
- In 1991 the Statoil refinery commissioned a pipeline for supply of biologically treated refinery effluent water to the power plant for use in various cleaning purposes and for fly ash stabilisation.
- In 1992 the Statoil refinery commissioned a pipeline for supply of refinery flare gas to the power plant as a supplementary fuel.
- In 1993 the power plant completed a stack flue gas desulphurisation project. This process converts flue gas SO_2 to calcium sulphate (or gypsum) which is sold to the Gyproc plaster board plant, where it replaces imports of natural gypsum as raw material. The new raw material from the power plant results in increased plaster board quality characteristics.
- The construction of green houses are being considered by the power plant and by the refinery for utilisation of residual waste heat.

Typical characteristics of an effective symbiosis

- The participating industries must fit together, but be different.
- The individual industry agreements are based on commercially sound principles.
- Environmental improvements, resource conservation, and economic incentives go hand in hand.
- The development of the symbiosis has been on a voluntary basis, but in close co-operation with the authorities.
- Short physical distances between participating plants are a definite advantage.
- Short "mental" distances are equally important.
- Mutual management understanding and co-operative commitment is essential.
- Effective operative communication between participants is required.
- Significant side benefits are achieved in other areas such as safety and training.

Achieved results of the symbiosis

The most significant achievements of the industrial symbiosis co-operation at Kalundborg may be summarised as:

- Significant reductions of the consumption of energy and utilities in terms of coal, oil, and water.
- Environmental improvements through reduced SO_2 and CO_2 emissions and through reduced volumes of effluent water of an improved quality.
- Conversion of traditional waste products such as fly ash, sulphur, biological sludge, and gypsum into raw materials for production.
- Gradual development of a systematic environmental "way of thinking" which is applicable to many other industries and which may prove particularly beneficial in the planning of future industrial complexes.
- Creation of a deservedly positive image of Kalundborg as a clean industrial city.

Future developments

Traditionally, increase of industrial activity has automatically meant in increased load on the environment in an almost straight line relationship. Through the application of the industrial symbiosis concept this no longer needs to be the case. By carefully selecting the processes and the combination of industries, future industrial complexes need in theory not cause any pollution of the environment at all. Although this obviously is an ideal situation which in reality is impossible to achieve, it may be a good and challenging planning assumption.

At Kalundborg all future projects and/or process modifications will be considered for inclusion in the industrial symbiosis network. A number of interesting ideas have been identified for further study. In the meantime, the concept of industrial symbiosis is recommended as a practical approach to minimise the environmental impact from existing and new industrial complexes.

Additional data

ASNÆSVÆRKET, ANNUAL PRODUCTION

Electricity	4,300,000,000 tons
Process steam	355,000 tons
District heating	700,000 GJ
Fly ash	170,000 tons
Fish	200 tons
Gypsum	80,000 tons

ASNÆSVÆRKET, ANNUAL RESOURCE CONSUMPTION

Water	400,000 m^3	(treated)
	100,000 m^3	(raw)
	700,000 m^3	(reused coolingwater from Statoil)
	500,000 m^3	(reused wastewater from Statoil)
Coal	1,600,000 tons	
Oil	25,000 tons	
Gas	5,000 tons	(flare gas from Statoil)

ASNÆSVÆRKET, ANNUAL EMISSIONS

CO_2	4,300,000	tons
SO_2	17,000	tons
NO_x	14,000	tons

STATOIL REFINERY, ANNUAL RESOURCE CONSUMPTION

Water	1,300,000	m^3	(raw)
	50,000	m^3	(treated)
Steam	140,000	tons	(from Asnæsværket)
	180,000	tons	(own waste heat)
Gas	80,000	tons	
Oil	8,000	tons	
Electricity	75,000,000	kWh	

STATOIL REFINERY, ANNUAL EMISSIONS

SO_2	1,000	tons
NO_x	200	tons
Waste water	500,000	m^3
Oil	1.80	tons
Phenol	0.02	tons
Oily waste	300	tons*

*Being biologically degraded in own sludge farming facilities

GYPROC, ANNUAL RESOURCE CONSUMPTION

Gypsum, from Asnæsværket	80,000 tons
" , other industrial	33,000 tons
" , recycled	8,000 tons
Cardboard	7,000 tons
Oil	3,300 tons
Gas	4,100 tons
Water	75,000 m^3
Electricity	14,000,000 kWh

NOVO NORDISK, ANNUAL RESOURCE CONSUMPTION

Water	1,400,000 m^3 (treated)
	300,000 m^3 (raw)
Steam	215,000 tons
Electricity	140,000,000 kWh

NOVO NORDISK, ANNUAL EMISSIONS

Waste water	900,000 m^3
COD	4,700 tons
Nitrogen	310 tons
Phosphorus	40 tons

ACHIEVED ANNUAL RESULTS

Reduction of resource consumption	
Oil	19,000 tons
Coal	30,000 tons
Water	1,200,000 m^3
Reduction in emissions	
CO_2	130,000 tons
SO_2	25,000 tons
Re-use of waste products	
Fly ash	135,000 tons
Sulphur	2,800 tons
Gypsum	80,000 tons
Nitrogen from biosludge	800 tons
Phosphorus from biosludge	400 tons

Appendix B: "Selected Definitions of Industrial Ecology"

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.

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

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.

> *— Braden Allenby, "Achieving Sustainable Development Through Industrial Ecology,"* International Environmental Affairs *4, no.1 (1992).*

Industrial Ecology is a new approach to the industrial design of products and processes and the implementation of sustainable manufacturing strategies. It is a concept in which an industrial system is viewed not in isolation from its surrounding systems but in concert with them. Industrial ecology seeks to optimize the total materials cycle from virgin material to finished material to component, to product, to waste products, and to ultimate disposal. . . . Characteristics are: (1) proactive not reactive, (2) designed in not added on, (3) flexible not rigid, and (4) encompassing not insular.

> *— L.W. Jelinski, T. E. Graedel, R. A. Laudise, D. W. McCall, and C. Kumar N. Patel, "Industrial Ecology: Concepts and Approaches,"* Proceedings of National Academy of Sciences, USA *89 (February 1992).*

Industrial ecology can be best defined as the totality or the pattern of relationships between various industrial activities, their products, and the environment. Traditional ecological activities have focused on two time aspects of interactions between the industrial activities and the environment — the past and the present. Industrial ecology, a systems view of the environment, pertains to the future.

> *— C. Kumar N. Patel, "Industrial Ecology,"* Proceedings of the National Academy of Sciences, USA *89 (February 1992).*

Industrial Ecology is the study of how we humans can continue rearranging Earth, but in such a way as to protect our own health, the health of natural ecosystems, and the health of future generations of plants and animals and humans. It encompasses manufacturing, agriculture, energy production, and transportation — nearly all of those things we do to provide food and make life easier and more pleasant than it would be without them.

> *— Bette Hileman, "Industrial Ecology Route to Slow Global Change Proposed,"* Chemical and Engineering News *(Aug. 24 ,1992): 7.*

Industrial ecology involves designing industrial infrastructures as if they were a series of interlocking manmade ecosystems interfacing with the natural global ecosystem. Industrial ecology takes the pattern of the natural environment as a model for solving environmental problems, creating a new paradigm for the industrial system in the process. . . . The aim of industrial ecology is to interpret and adapt an understanding of the natural system and apply it to the design of the manmade system, in order to achieve a pattern of industrialization that is not only more efficient, but that is intrinsically adjusted to the tolerance and characteristics of the natural system. The emphasis is on forms of technology that work with natural systems, not against them.

> *— Hardin B. C. Tibbs, "Industrial Ecology: An Environmental Agenda for Industry,"* Whole Earth Review *77 (December 1992).*

The heart of industrial ecology is a simple recognition that manufacturing and service systems are in fact natural systems, intimately connected to their local and regional ecosystems and the global biosphere. . . the ultimate goal . . . is bringing the industrial system as close as possible to being a closed-loop system, with near complete recycling of all materials.

> *— Ernest Lowe. "Industrial Ecology — An Organizing Framework for Environmental Management."* TQEM *(Autumn 1993).*

Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to waste product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital.

— Braden Allenby and Thomas E. Graedel, Industrial Ecology *(New York: Prentice Hall, 1993; pre-publication edition).*

Industrial ecology provides for the first time a large-scale, integrated management tool that designs industrial infrastructures "as if they were a series of interlocking, artificial ecosystems interfacing with the natural global ecosystem." For the first time, industry is going beyond life-cycle analysis methodology and applying the concept of an ecosystem to the whole of an industrial operation, linking the "metabolism" of one company with that of another.

— Paul Hawken, The Ecology of Commerce *(New York: HarperBusiness, 1993).*

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