



Pollution Prevention and Industrial Ecology

NATIONAL POLLUTION PREVENTION CENTER FOR HIGHER EDUCATION

Industrial Ecology: An Introduction

By Andy Garner, NPPC Research Assistant, and Dr. Gregory A. Keoleian, Assistant Research Scientist, University of Michigan School of Natural Resources and Environment, and NPPC Manager

This portion of the industrial ecology compendium provides an overview of the subject. It further offers guidance as to how one may teach industrial ecology. Exhibits are provided at the end of this introduction that may be used in various parts of an industrial ecology course. Educational resources on industrial ecology are now emerging. Thomas Graedel and Braden Allenby have written the first university textbook on industrial ecology.¹ The text provides a well organized introduction and overview to industrial ecology as a field of study. This book, along with David Allen's book on classroom assignments for pollution prevention, serve as excellent sources of both qualitative and quantitative problems that could be used to enhance the teaching of industrial ecology concepts.² Other sources of information will be noted in this introduction, in the summary of resources, and in the NPPC resources section of this compendium.

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.³

Environmental problems are systemic problems and thus require a systems approach so that the interconnections 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 and can be used to highlight the need and advantages of achieving sustainability. Table 1 depicts ecological and industrial system hierarchies (the figure also shows the hierarchies of political and geographic systems).⁴ Industrial ecology involves the study of 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.

TABLE I. ORGANIZATIONAL HIERARCHIES

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

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 back to the work of Jay Forrester at MIT in the early 1960s and 70s who was one of the first to look at the world as a series of interwoven systems.⁷ Donella and Dennis Meadows and others furthered this work in their seminal book *Limits to Growth* which utilized systems analysis to simulate the trends of environmental degradation in the world which highlighted the unsustainable course of the then current industrial system.⁸

In 1989, Robert Ayres developed the concept of *industrial metabolism* i.e. the use of materials and energy by industry and how these materials flow through industrial systems and are transformed and then dissipated as wastes.⁹ 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 A. Frosch and Nicholas E. Gallopoulos in their important article "Strategies for Manufacturing", published in *Scientific American* in 1989, developed the concept of industrial ecosystems which led to the term *industrial ecology*.¹⁰ They wrote of an ideal industrial ecosystem that would function as "an analogue" of biological ecosystems. This metaphor between industrial and natural ecosystems is fundamental to the foundation of industrial ecology. Such an industrial ecosystem would feature firms producing waste products that would then in turn be utilized as resources by another. No waste would leave the industrial system and they would not negatively impact natural systems.

In 1991, the National Academy of Science's Colloquium on Industrial Ecology constituted a watershed in the development of industrial ecology as a field of study. Since the Colloquium, 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*

Ecosystems.¹¹ The book brings together many earlier initiatives and efforts to use systems analysis to solve environmental problems. Tools of industrial ecology are identified such as design for the environment, life cycle design and environmental accounting. In addition the interactions between industrial ecology and other disciplines such as law, economics and public policy are discussed.

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) has been promoting the systems approach in developing pollution prevention educational materials. The NPPC's research on industrial ecology is a natural outgrowth of our work on pollution prevention.

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:

- 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 towards the future
- working to change linear (open) processes to cyclical (closed) processes so that the waste from one industry is used as an input for another
- seeking to reduce the industrial systems' environmental impacts on ecological systems
- working towards the harmonious integration of industrial activity into ecological systems
- industrial systems being changed to 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 focusing on the tracing of 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 of industrial ecology. Issues that need to be addressed include:

- 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 solutions. Some authors write of industrial ecology as looking for primarily technical, engineered solutions to environmental problems. Others 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 it can be incorporated into existing courses in schools of engineering, business, public health and natural resources. The course can also be offered as an multidisciplinary course (the sample syllabus offered in this compendium gives one example of industrial ecology presented as a multidisciplinary course) which may be of interest due to the multidisciplinary nature of environmental problems. Degrees in industrial ecology might be awarded by universities in the future.¹²

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.¹³ Current research efforts in environmental education are attempting to integrate pollution prevention, sustainable development and

other concepts and strategies into current 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, as industrial ecology 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.¹⁴

In industrial ecology, one focus (or object) of study is the interrelationships among firms as well as their products, 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. Applied ecology has been defined by the Journal of Applied Ecology as the:

... 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 manage-

ment, 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 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.¹⁵

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 and consequently 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*,¹⁶ Eugene Odum's *Ecology and Our Endangered Life-Support Systems*, and *Ecology: Individuals, Populations and Communities* by Michael Begens, John Harper and Colin Townsend.¹⁷

Goals of Industrial Ecology

The primary goal of industrial ecology is to promote sustainable development at the global, regional and local levels.¹⁸ 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.¹⁹ 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).²⁰

Sustainable Use of Resources:

Industrial ecology should promote the sustainable use of resources. This would include the sustainable use of renewable resources and the minimal use of non-renewable resources. Industrial activity is dependent on a steady supply of resources thus industry 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.²¹ Besides solar energy the supply of resources is finite. Thus the depletion of nonrenewable resources and the degradation of renewable resource sources 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, thus their activities can not 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.²²

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/institutional systems and 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, which is "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."²³ The same is true for industrial ecology. If the scope of a study is too broad the results become less meaningful and when too narrow they may be less useful. Refer to Kenneth Boulding's *World as a Complete System* for more information about systems theory or Donella and Dennis Meadows et al.'s *Limits to Growth* and *Beyond the Limits* for a good example of how systems theory can be used to analyze environmental problems on a global scale.²⁴

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 in order to decrease the amount of platinum leaving the system. 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 environmental impacts. The challenge of industrial ecology is to reduce the overall environmental burden of an industrial system that provides some service to society.

It is useful to understand the dissipation of materials and energy (in the form of pollutants) in order to identify areas to target for reduction. We must learn 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 Figure 5, the anthropogenic sources of some materials in natural ecosystems are much greater than natural sources. Tables 2, 3 and 4 provide a good example of how various materials flow through one product system, that of the automobile.

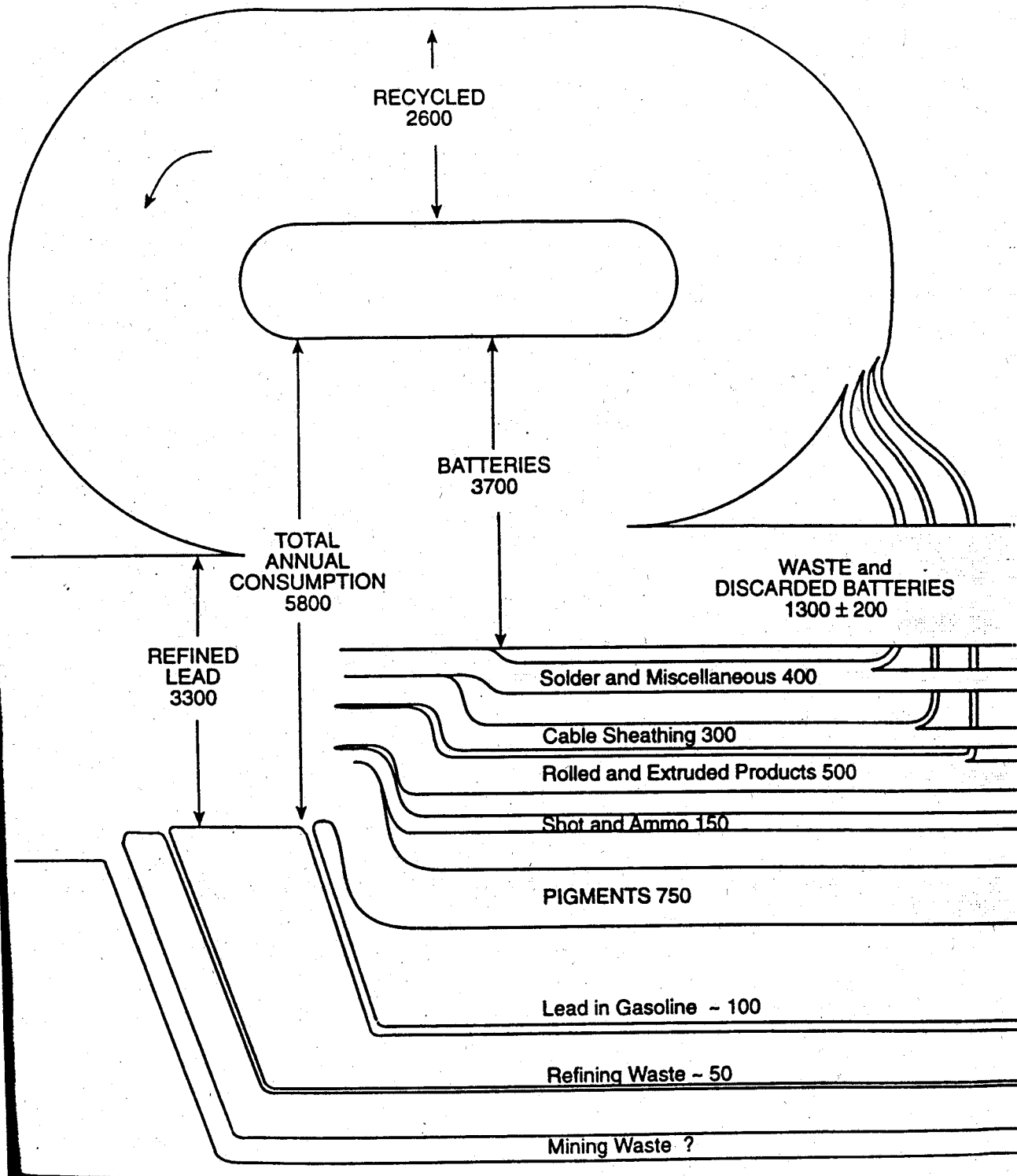


FIG. 2

FIG. 3

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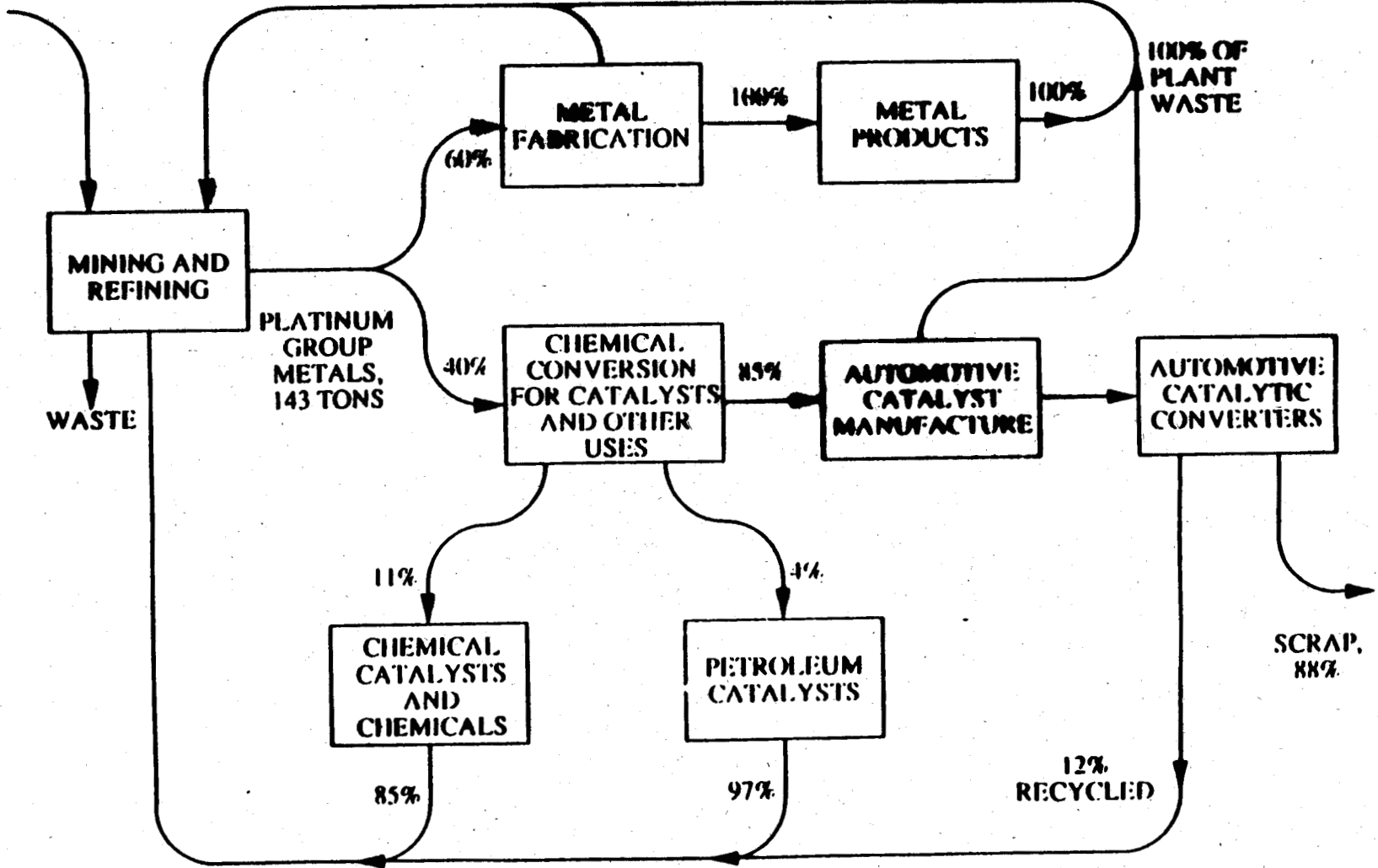


FIG. 4

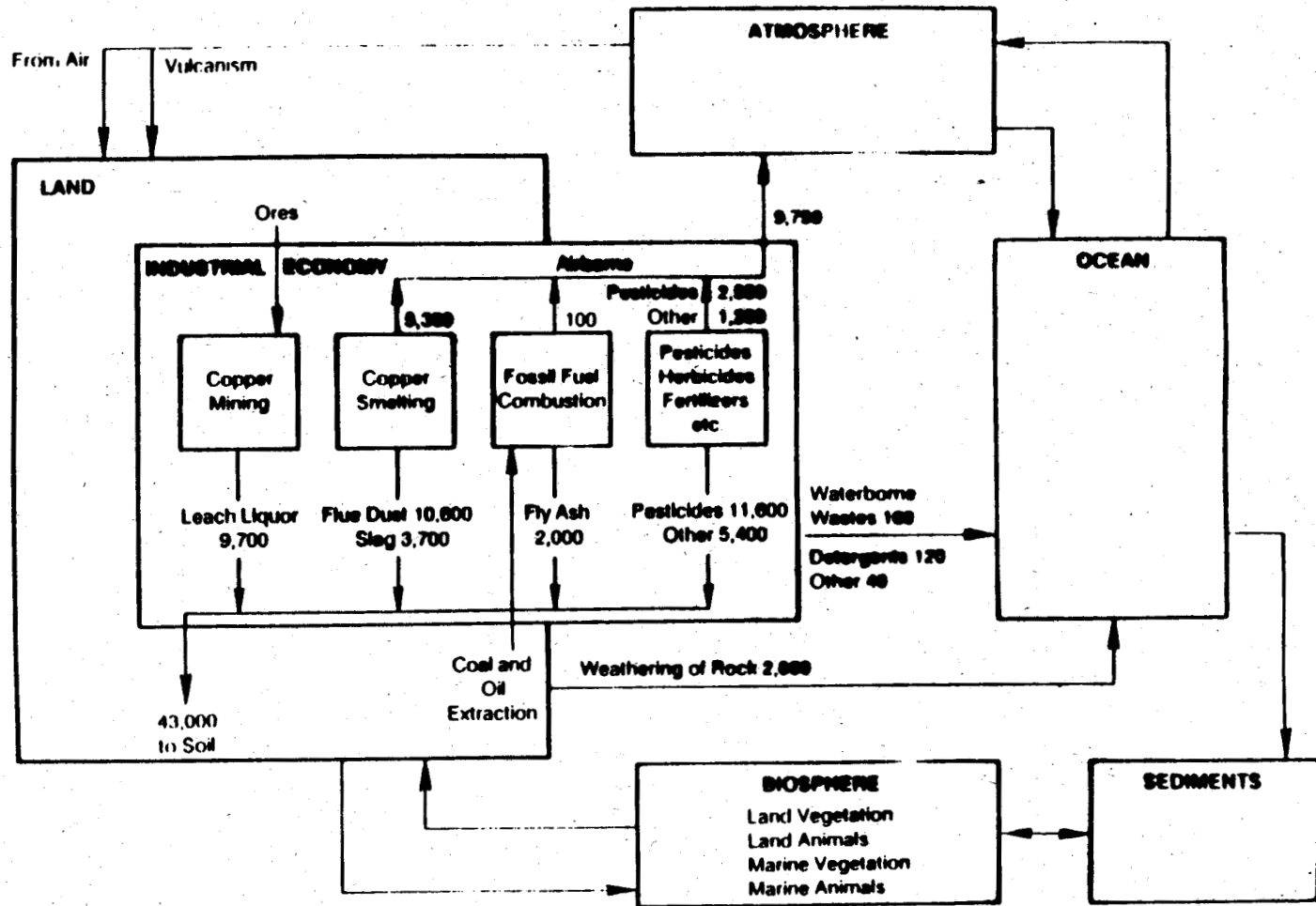


FIGURE 3 Simplified representation of arsenic pathways in the United States (metric tons), circa 1975. SOURCE: Ayres et al. (1988).

Worldwide atmospheric emissions of trace metals
(Thousand tonnes per year)

Element	Energy production	Smelting, refining and mining	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	6.1
Lead	12.7	49.1	15.7	254.9	332.0	28.0
Manganese	12.1	3.2	14.7	8.3	38.0	12.0
Mercury	2.3	0.1	-	1.2	3.6	317.0
Nickel	42.0	4.8	4.5	0.4	52.0	2.5
Selenium	3.9	2.3	-	0.1	6.3	3.0
Thallium	1.1	-	4.0	-	5.1	29.0
Tin	3.3	1.1	-	0.8	5.1	10.0
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?", *Environment*, vol. 32, No. 7 (1990), pp. 7-32.

FIG. 5

TABLE 2

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	
Cu	8.5	
Pb	3.4	
Ni	0.8	
Sn	0.2	
Zn	7.0	
Steel	780	
Fossil Fuels	1.6	
Coal	3200	
Lignite	1200	
Oil 2800		
Gas	920	
Water	41,000,000	8200

* 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).

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

TABLE 3**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%

Material **Percent of Total U.S. Consumption (1988)**

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

The previous tables taken from the Draft Report "Design and the Environment—The U.S. Automobile. The authors of this report obtained the information from the Motor Vehicle Manufacturers Association Annual Data Book, 1990.

TABLE 4

Global Mobilization Factors Based on Annual Emission Rates
Emissions (10^8gy^{-1})

Natural	Anthropogenic	Mobilization Factor
Arsenic (As)	28 [210]	780 28 [3.3]
Chromium (Cr)	580	940 1.6
Copper (Cu)	190	2,600 14
Lead (Pb)	59	20,000 340
Mercury (Hg)	0.40 [250]	110 275 [0.44]
Nickel (Ni)	280	980 3.5
Zinc (Zn)	360	8,400 23

Note: Natural emissions = soil dust + volcanic dust and volcanic-emanation fluxes. For elements with known volatile species in the atmosphere (As, Hg, and Se), vapor emissions (in brackets) from land and sea were added to the dust emissions of Lantzy and Mackenzie (1979). Anthropogenic emissions = fossil-fuel and industrial-particulate fluxes.

From: Galloway, James N., J. David Thornton, Stephen A. Norton, Herbert L. Volchok and Ronald A. N. McLean, "Trace Metals in Atmospheric Deposition: A Review and Assessment," *Atmospheric Environment*, Vol 16, No. 7, pp. 1677-1700, 1982.

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' life 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 Chapter's 3 and 4 in Graedel and Allenby's text *Industrial Ecology* for exercises in this subject area.

Multidisciplinary Approach:

Since industrial ecology is based on a holistic, systems view, it is important that there is input and participation from many different disciplines. Furthermore, given the complexity of most environmental problems a variety of expertise will be needed. Experts from law, economics, business, public health, natural

resources, ecology, and engineering will need to contribute to the development of industrial ecology and the resolution of the 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, technologically based solutions to environmental problems. How industrial ecology should balance the need for technological change with consumer behavioral changes is still subject to debate. Some see industrial ecology as narrowly focused on industrial activity whereas others see it as a way to view the entire global economic system.

Analogies to Natural Systems:

There are several useful analogies between industrial and natural ecosystems.²⁵ 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 since 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 the Odum or the Ricklefs texts 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.

In both natural and industrial systems, cycling of nutrients/materials and energy occur. In nature, the carbon, hydrogen and nitrogen cycles are integral to the functioning and the 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.

The eco-industrial park in Kalundborg, Denmark represents an attempt to model an industrial park after an ecological system. The firms in the park are highly integrated and utilize the waste products from one as an energy or raw material source for another firm (see Figure 1 and Appendix A).

Linear (open) versus Cyclical (closed) Loop Systems:

The evolution of the industrial system from a linear system, where resources are consumed and wastes are dissipated into the environment inducing damage, 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 5.²⁶

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. This type I system relies on a large, constant supply of raw materials since wastes and byproducts are not recycled or reused. This system is unsustainable unless the supply of materials and energy is infinite. Further the ability for natural systems to assimilate wastes (known as "sinks") is also finite. In a type II system, some wastes are recycled or reused in the system while other wastes still leave the system (this characterizes much of our present day industrial system). 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 closed industrial system only solar energy would come from outside the system 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 by 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. Others are wary of placing well established strategies under the rubric of industrial ecology which is still being developed. Strategies that are 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 activities have generally occurred at the firm level and constitute specific actions to reduce pollution. It focuses on actions by individual firms, not on the collective activities of the industrial system (nor on the collective reduction of environmental impacts) as a whole. The section in this compendium entitled "Pollution Prevention Concepts and Principles" provides a detailed description of pollution prevention and related concepts.²⁷



Fig. 1. Type I system

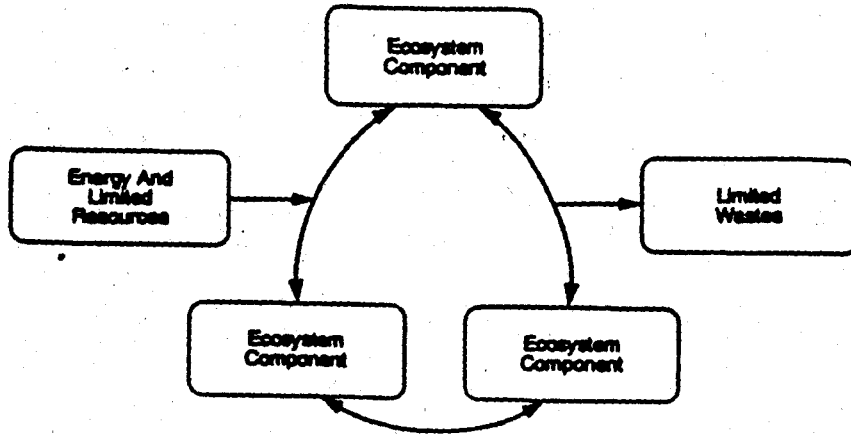


Fig. 2. Type II system

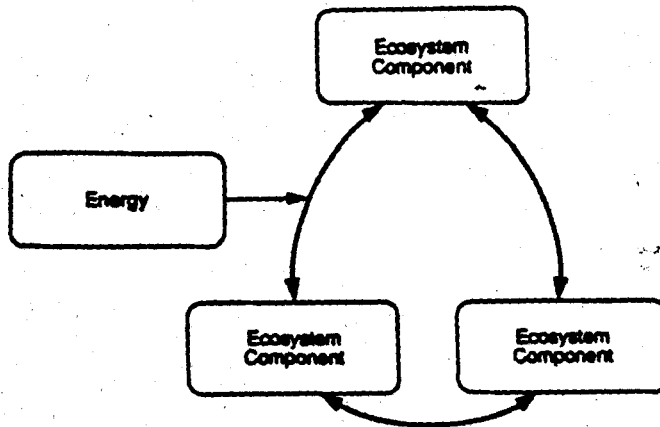


Fig. 3. Type III system

-Allenby, Braden.

FIG. 5.

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."²⁸ *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 environment prior to recycling, treatment or disposal.²⁹

Total quality environmental management (TQEM) is a management system used to monitor, control and improve environmental performance within individual firms. Based on well established total quality management principles, TQEM attempts to integrate environmental considerations into all aspects of a firm's decision-making, operations, processes and products. All employees are responsible for implementing TQEM principles. It is a holistic approach, albeit at the individual firm, not the industrial system, level.

Many additional terms have been used to address strategies for sustainable development. *Cleaner production*, a term coined by UNEP in 1989, is widely used in Europe. It has a similar meaning to pollution prevention. Tim Jackson writes in his book *Clean Production Strategies*, 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."³⁰

These strategies represent approaches that individual firms can take to reduce the environmental impacts of their activities. Along with reducing environmental impacts, 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 individual actions by firms in order 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):

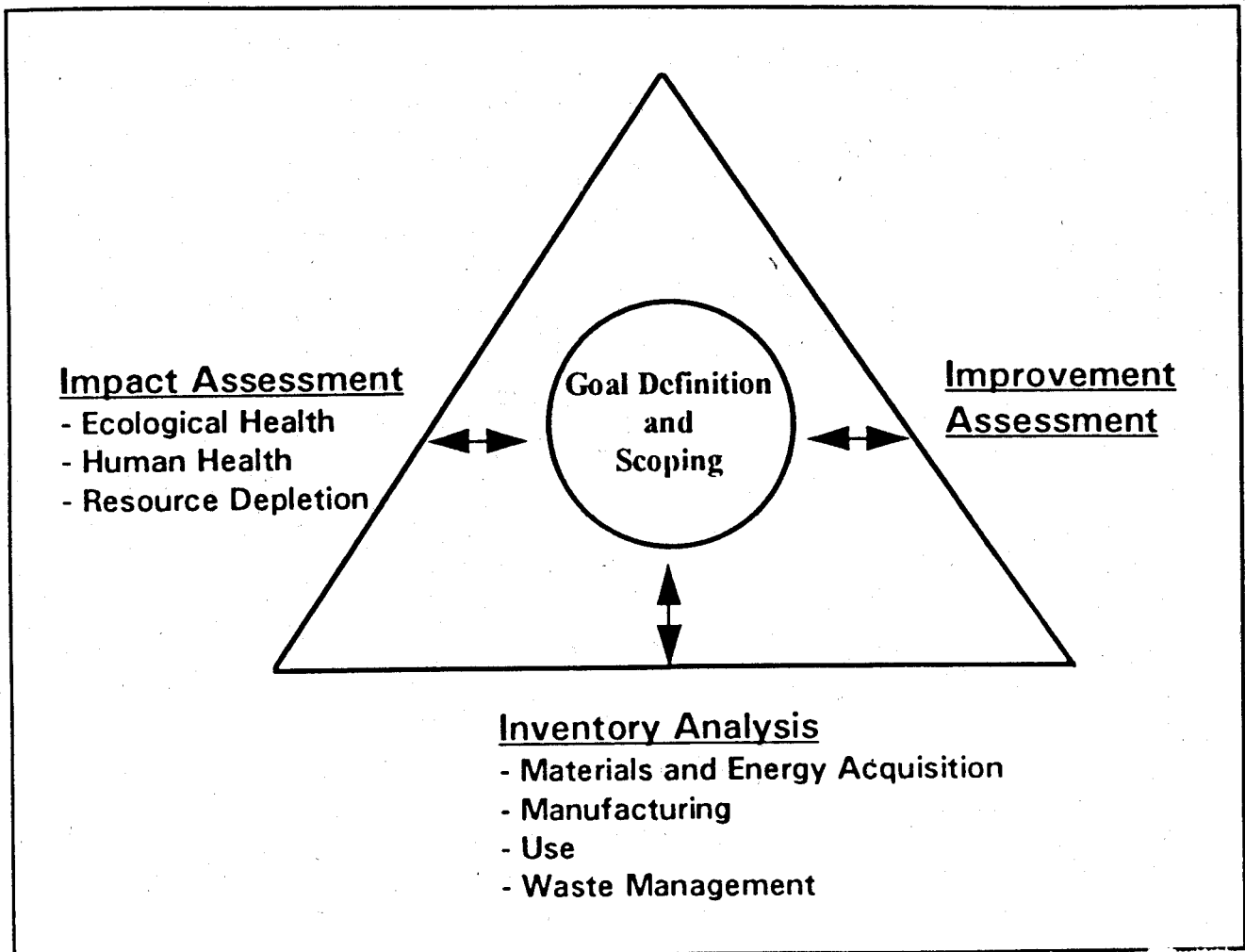
Life cycle assessment, along with "ecobalances" and resource environmental profile analysis (REPA), are methods developed to evaluate the life cycle environmental consequences of a product or process from "cradle to grave".^{31 32 33} The Society for Environmental Toxicology (SETAC) defines LCA as "a process used to evaluate the environmental burdens associated with a product, process, or activity...".³⁴ The U.S. EPA has stated that a "...Life cycle assessment is a tool to evaluate the environmental consequences of a product or activity holistically, across its entire life."³⁵ In the U.S., SETAC, the U.S. EPA and consulting firms are active in developing LCAs.

COMPONENTS OF AN LCA

LCA methodology is still evolving. However the methodology that distinguishes three distinct components of an LCA, as defined by SETAC and the U.S. EPA and shown in **Figure 6**, is most widely recognized. The three separate but interrelated components of a life cycle assessment include: (1) **the inventory analysis**, which is the identification and quantification of energy and resource use and environmental releases to air, water, and land, (2) **the impact analysis**, which is the technical qualitative and quantitative characterization and assessment of the consequences on the environment and (3) **the improvement analysis**, which is the evaluation and implementation of opportunities to reduce environmental burdens. 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.³⁶ 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**.



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FIG. 6

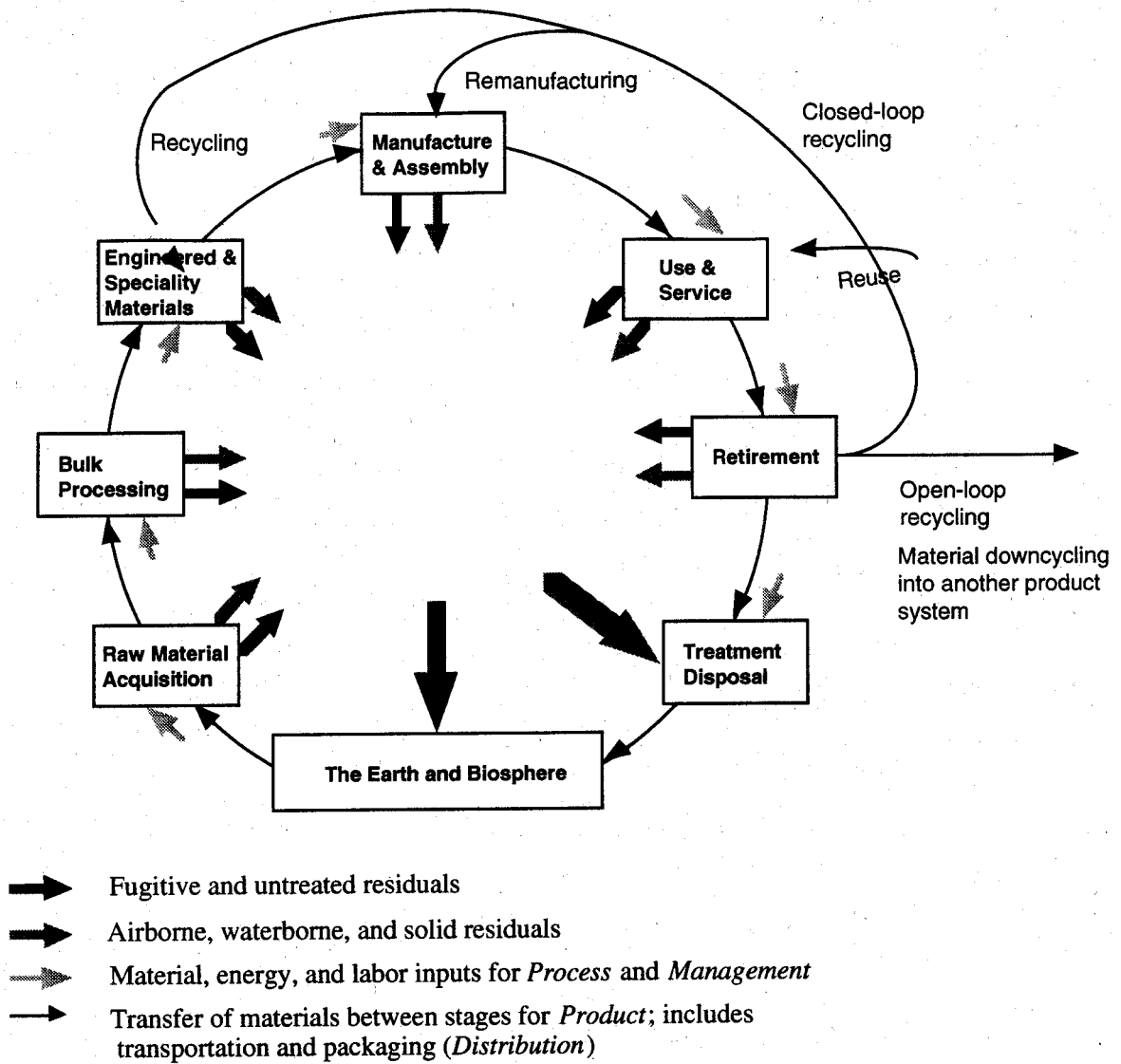


FIG. 7

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. Checklists such as those in Figures 9 and 10 may then be used in order to further define the study, set the system boundaries, and to gather the appropriate information concerning inputs and outputs. A template for constructing a detailed flow diagram for each life cycle subsystem is shown in Figure 11. Figure 12 shows the many stages involved in the life cycle of a bar of soap. This example of a relatively simple product illustrates how quickly the inventory stage can become especially as products increase in number of components and in complexity.

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 13. 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 however 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 improve-

ment for several products.³⁷ 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.³⁸ 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.

APPLICATIONS OF LCA

Life cycle assessments can be used both internally to an organization and externally by both the public and private sectors.³⁹ Internally, LCAs can be used to establish a comprehensive baseline i.e. requirements, that product design teams should meet. LCAs can further be used to identify the major impacts of a product's life cycle. They can also be used to guide the improvement of new product systems towards 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

Many methodological problems and difficulties in applying LCAs exist which inhibit their use particularly for smaller companies. For example, LCAs can be very expensive because of the amount of data needed and the staff time required to perform the analysis. It may also be difficult to obtain all of the necessary data. Further it can be difficult to properly define system boundaries and to 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 often 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. These problems are summarized in Table 5.

Life-Cycle Stages

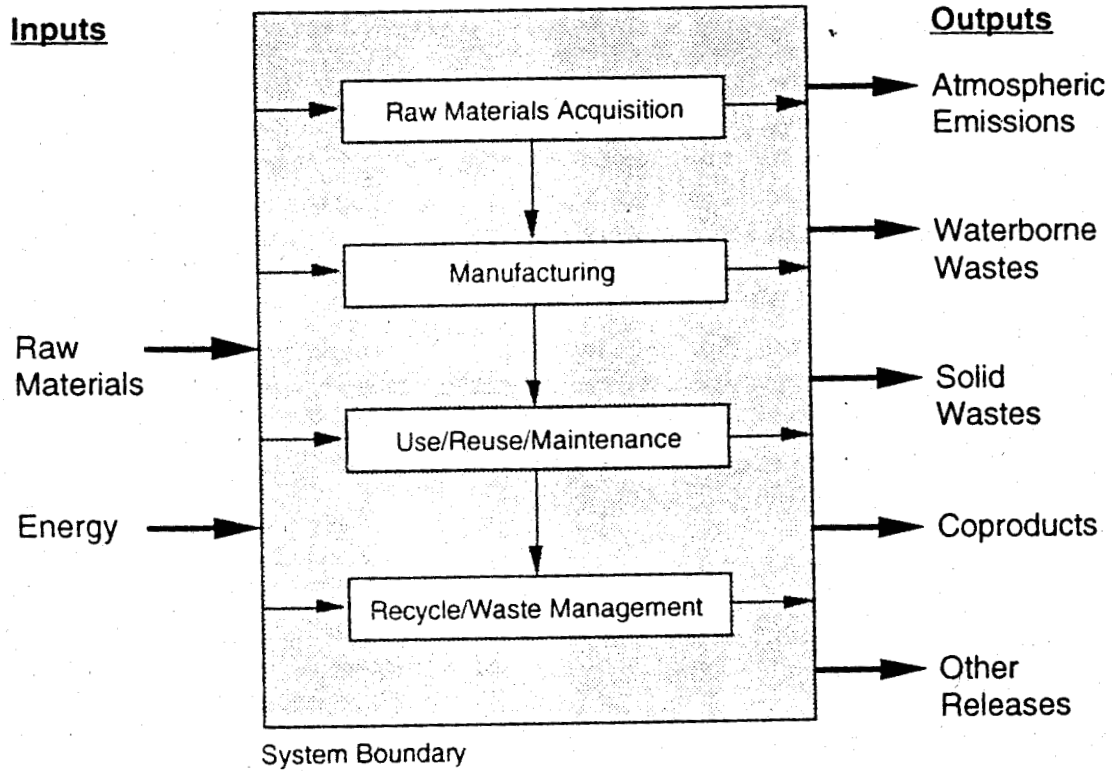


FIG. 8

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 Evaluation
- 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 product/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.

- | | |
|---|--|
| <input type="checkbox"/> Landfill _____ | <input type="checkbox"/> Open-loop Recycling _____ |
| <input type="checkbox"/> Combustion _____ | <input type="checkbox"/> Closed-loop Recycling _____ |
| <input type="checkbox"/> Composting _____ | <input type="checkbox"/> Other _____ |

Basis for Comparison

- This is not a comparative study.
- This is a comparative study.

State basis for comparison between systems: (Example: 1000 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: | <input type="checkbox"/> Data Gathering Techniques _____ | <input type="checkbox"/> Input Data _____ |
| | <input type="checkbox"/> Coproduct Allocation _____ | <input type="checkbox"/> Model Calculations and Formulas _____ |
| | | <input type="checkbox"/> Results and Reporting _____ |

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

- | | | |
|----------------------|--|--|
| Review performed on: | <input type="checkbox"/> Scope and Boundary _____ | <input type="checkbox"/> Input Data _____ |
| | <input type="checkbox"/> Data Gathering Techniques _____ | <input type="checkbox"/> Model Calculations and Formulas _____ |
| | <input type="checkbox"/> Coproduct Allocation _____ | <input type="checkbox"/> Results and Reporting _____ |

Results Presentation

- Methodology is fully described.
 - Individual pollutants are reported.
 - Emissions are reported as aggregated totals only.
- Explain why: _____

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: _____

Report is sufficiently detailed for its defined purpose.

FIG. 9

LIFE-CYCLE INVENTORY CHECKLIST PART II—MODULE WORKSHEET

Inventory of: _____ Preparer: _____

Life-Cycle Stage Description: _____

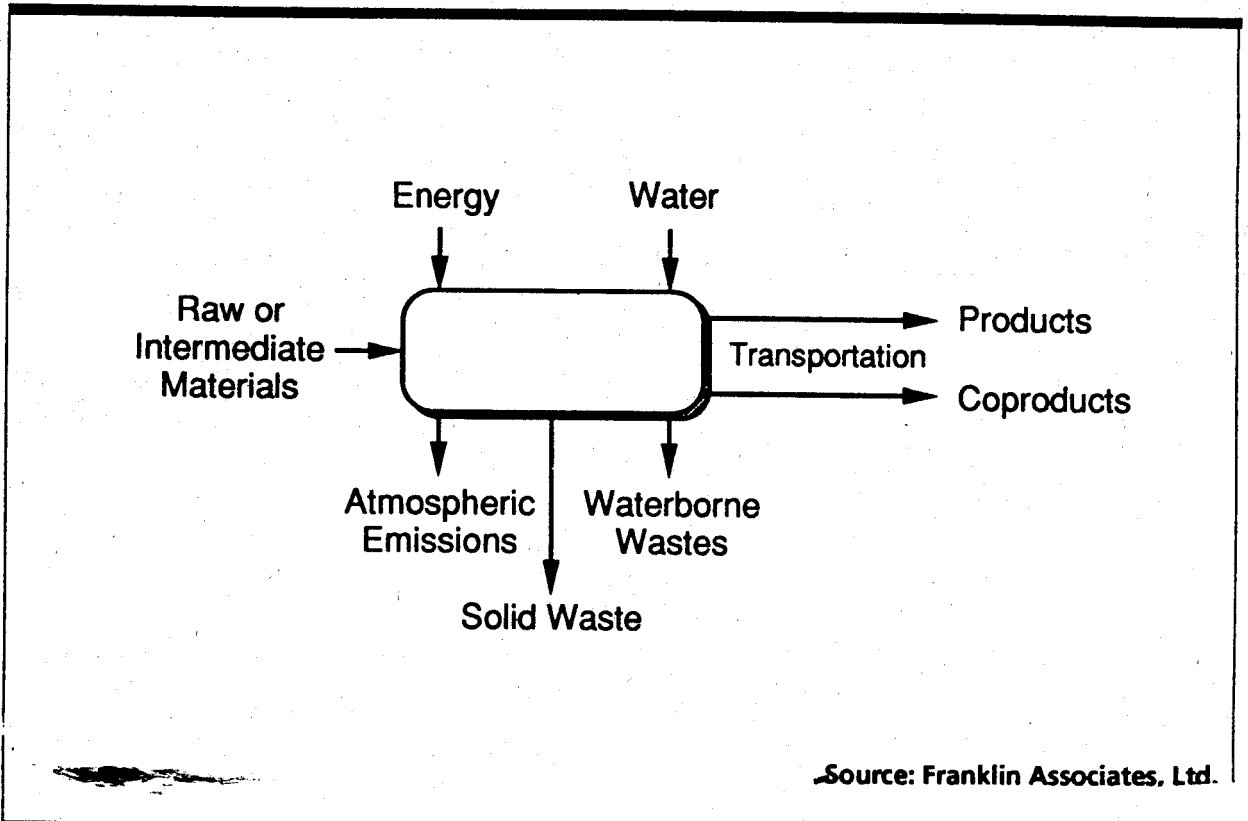
Date: _____ Quality Assurance Approval: _____

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				

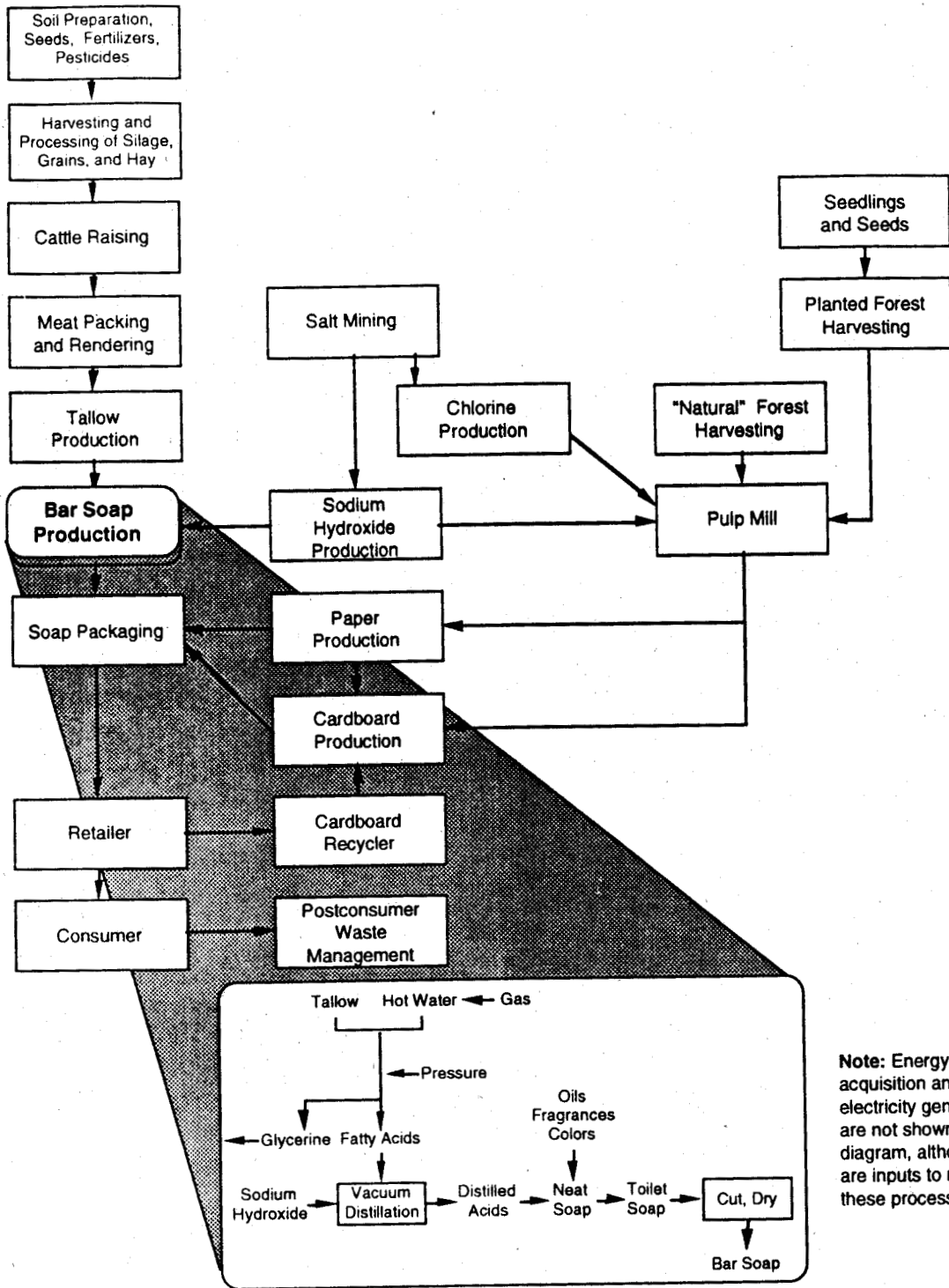
- (a) Include units.
- (b) Indicate whether data are actual measurements, engineering estimates, or theoretical or published values and whether the numbers are from a specific manufacturer or facility, or whether they represent industry-average values. List a specific source if pertinent, e.g., "obtained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

FIG. 10



Source: Franklin Associates, Ltd.

FIG. 11



Note: Energy acquisition and electricity generation are not shown on this diagram, although they are inputs to many of these processes.

Bar Soap Production

Figure 7 Detailed system flow diagram for bar soap

FIG 12

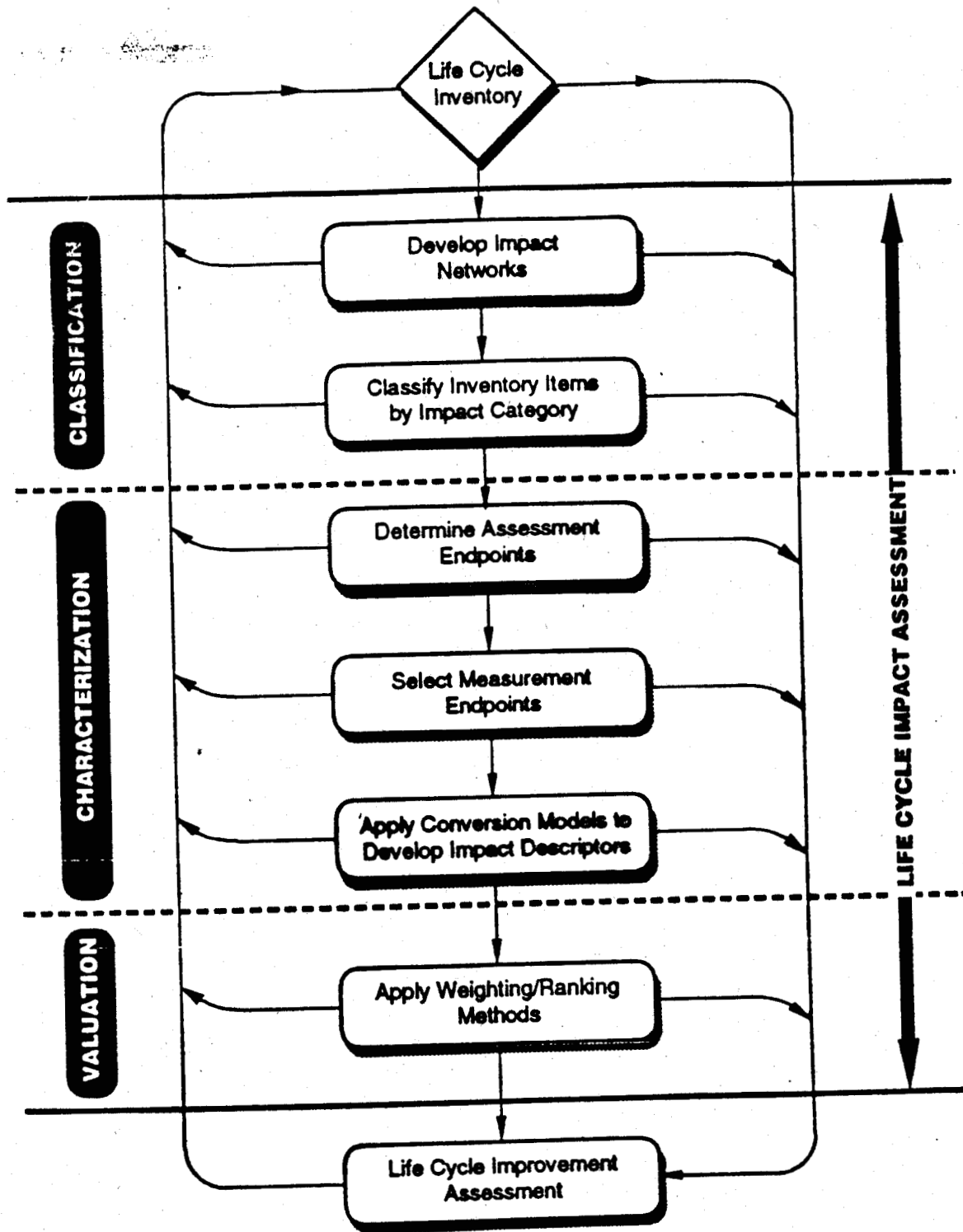


FIG. 13

TABLE 5

From *Journal of Cleaner Production*:

General Difficulties and Limitations of the LCA Methodology

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 including 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 decision makers often lack knowledge about environmental effects, and aggregation and simplification techniques may distort results. Synthesis of environmental effect categories is limited because they are incommensurable.

Absent 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.⁴⁰ Environmental concerns need to be more effectively addressed in the design process in order to reduce the environmental impacts associated with a

product over its life cycle. Life Cycle Design (LCD), Design For the Environment (DFE) and other similar initiatives that are based on the product life cycle are being developed to systematically incorporate these environmental concerns into the design process. *Life Cycle Design* is "a system's oriented approach for designing more ecologically and economically sustainable product systems. It couples the product development cycle used in business with the physical life cycle of a product and integrates environmental requirements into the stages of design so total impacts caused by the product systems can be reduced".⁴¹

Design For the Environment (DFE) is another design strategy which can be used to design products with reduced environmental burden. DFE and LCD can be difficult to distinguish. Although DFE and LCD have similar goals, they evolved from different sources. DFE evolved from the design for X (DFX) approach, where X can represent manufacturability, testability, reliability, or other downstream design considerations.⁴² Braden Allenby has developed a DFE

framework to address the entire product life cycle. DFE's goals are similar to those of LCD and also use 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.

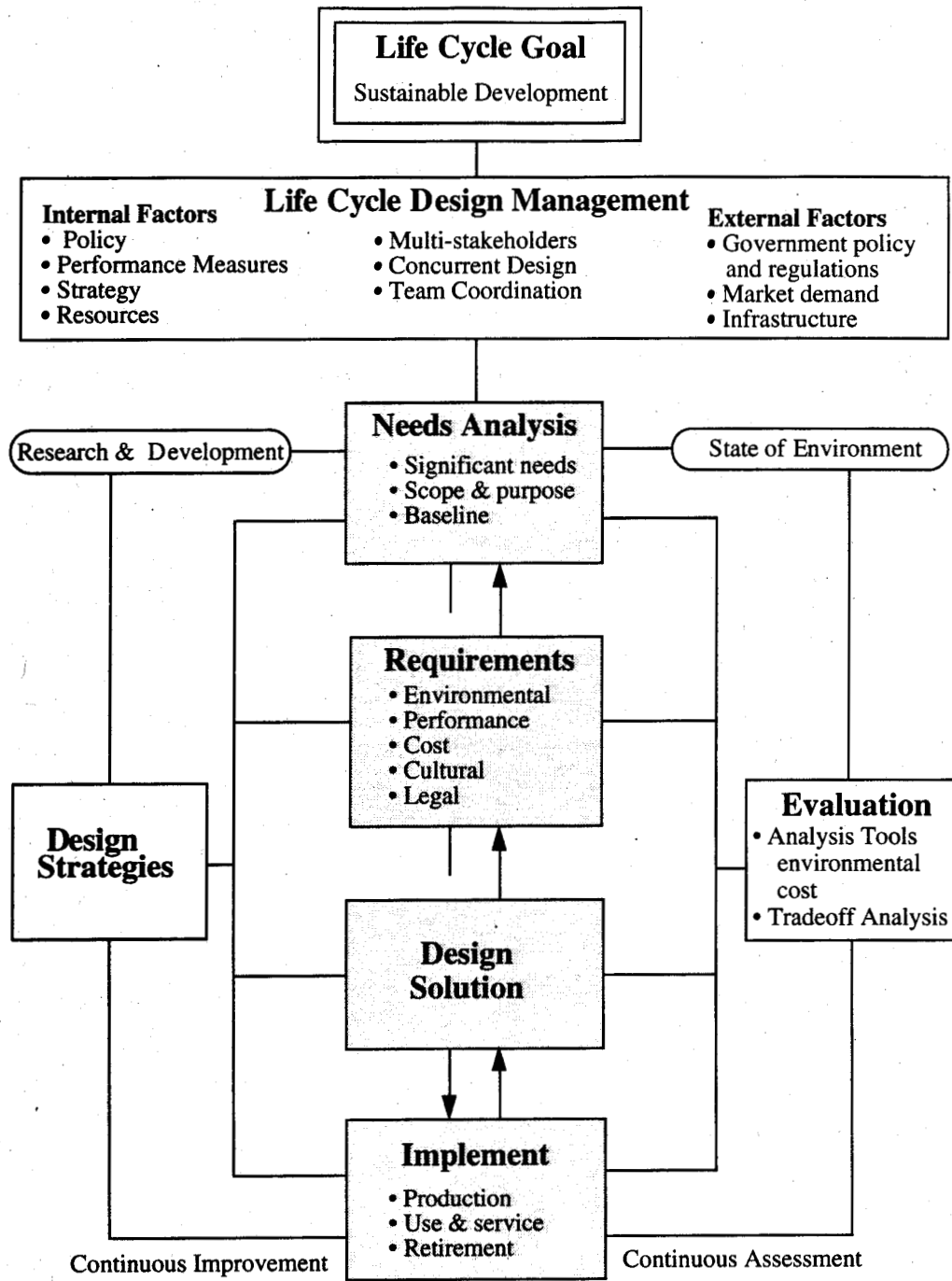


FIG. 14

FIG 15

Environmental Issue to Consider

Materials and Energy

<i>Amount Type</i>	<i>Character</i>	<i>Resource Base</i>	<i>Impacts Caused By Extraction and Use</i>
Renewable	Virgin	Location	Material /energy use
Nonrenewable	Reused/recycled Reusable/ recyclable	local vs. other Scarcity Quality Management/ restoration practices	Residuals Ecosystem health Human health

Residuals

<i>Type</i>	<i>Characterization</i>	<i>Environmental Fate</i>	<i>Treatment/Disposal impacts</i>
Solid waste	Constituents, amount, concentration, toxicity:	Containment	
Air emissions	Nonhazardous	Bioaccumulation	
Waterborne	Hazardous Radioactive	Degradability Mobility/transport	

Ecological Health

<i>Ecosystem Stressors</i>	<i>Impact Categories</i>		<i>Scale</i>
Physical	Diversity	System structure and function	Local
Biological	Sustainability, resilience to stressors	Sensitive species	Regional
Chemical			Global

Human Health and Safety

<i>Population at Risk</i>	<i>Exposure Routes</i>	<i>Toxic Character</i>	<i>Accidents</i>
Workers	Inhalation, skin contact, ingestion	Acute effects	Type & frequency
Users	Duration & frequency	Chronic effects	Nuisance Effects
Community		Morbidity /mortality	Noise, odors, visibility



THE DESIGN PROCESS

Life cycle design seeks to minimize the environmental consequences of each of the four components: product, process, distribution and management, of a product system.⁴³ Figure 14 shows the life cycle design and indicates the complex set of issues and decisions required in LCD.

The goal, sustainable development, is located at the top of the figure. As this figure shows, both internal and external factors affect the design process. Internal factors including corporate policies and the companies' mission, product performance measures, product strategies as well as the resources available to the company during the design process, all affect the ability to utilize LCD. The type of corporate environmental management system, if any, that a company has, greatly affects the company's designer's ability to utilize LCD principles. External factors such as government policies and regulations, the demand for a product and consumer preferences, the state of the economy, and competition affect the design process. The scientific understanding and the public perception of risks associated with the product, also influence the design process.

As shown in the figure, a typical design project begins with a needs analysis, followed by the formulation of requirements, conceptual design, preliminary design, detailed design, and implementation. During the needs analysis or initiation phase, the purpose and scope of the project is defined, and customer needs and market demand are clearly identified.⁴⁴ The system boundaries (the scope of the project) can either be

comprehensive, (e.g. a full life cycle system), a partial life system or individual stages of the life cycle.

Understandably, the more comprehensive the system of study is, the more opportunities for reducing environmental impact that will be identified. Finally *benchmarking* of competitors can be used during the needs analysis process to identify opportunities to improve environmental performance. This involves comparing a company's product's 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 adjustments later on that can be costly and time consuming. 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.

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 Figure 15, 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 16.

FIG. 16

	Legal	Cultural	Cost	Performance	Environmental		
	Raw Material Acquisition	Bulk Processing	Engineered Materials Processing	Assembly & Manufacture	Use & Service	Retirement	Treatment & Disposal
Product • Inputs • Outputs							
Process • Inputs • Outputs							
Distribution • Inputs • Outputs							
Management • Inputs • Outputs							

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 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.

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 various stakehold-

ers such as manufacturers, suppliers, users and end of life managers. Cultural requirements include the 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.⁴⁵ 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 effectively synthesized in order to translate these requirements into solutions. A wide range of possible 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 [Figure 17](#). Recycling is often over emphasized.

FIGURE 17 STRATEGIES FOR MEETING ENVIRONMENTAL REQUIREMENTS

Product Life Extension	<ul style="list-style-type: none"> • Extend useful life • Make appropriately durable • Ensure adaptability • Facilitate serviceability by simplifying maintenance and allowing repair • Enable remanufacture • Accommodate reuse
Material Life Extension	<ul style="list-style-type: none"> • Specify recycled materials • Use recyclable materials
Material Selection	<ul style="list-style-type: none"> • Substitute materials • Reformulate products
Reduced Material Intensity	<ul style="list-style-type: none"> • Conserve resources
Process Management	<ul style="list-style-type: none"> • 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

DESIGN EVALUATION

Finally, it is critical that the design is evaluated and analyzed throughout the design process. Design evaluation might utilize LCAs or other more singlely focused environmental metrics. Tools for design evaluation range from 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.

DFE methods developed by Allenby use a semi-quantitative matrix approach for evaluating life cycle environmental impacts.^{46 47} 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.

Although it has been used by companies like AT & T and Allied Signal, LCD is not yet widely practiced but is recognized as an important approach for reducing environmental burdens. To enhance the use of LCD, in reducing environmental burdens, 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 6.)

TABLE V. 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 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. 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.

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.

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**THE INDUSTRIAL SYMBIOSIS AT KALUNDBORG, DENMARK
PRESENTED AT
THE NAE INTERNATIONAL CONFERENCE ON INDUSTRIAL
ECOLOGY
IRVINE, CALIFORNIA, MAY 9 - 13, 1994
BY
HENNING GRANN, STATOIL**

Background

The concept of sustainable development is being widely referred to by politicians, authorities, industrialists and by 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 4 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.

- 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 2 years later and acquired by Statoil in 1987 along with Esso's Danish marketing facilities. To ensure adequate water supply a pipeline from the Lake Tissø was constructed.
- In 1972 Gyproc established a plaster board manufacturing plant. A pipeline for supply of excess refinery gas was constructed.
- In 1973 the Asnæs power plan was expanded. The additional water requirements were supplied through a connection to the Tissø pipeline following an agreement with the refinery.
- In 1976 Novo Nordisk started delivery by special tank trucks of biological sludge to the neighbouring farming community.
- 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.

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.

- 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 an 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.

KALUNDBORG INDUSTRIAL SYMBIOSIS

INDUSTRIAL SYMBIOSIS IS:

" A cooperation between different industries whereby the presence of each of them increases the viability of the others, while at the same time demands from society for resource conservation and environmental protection are duly considered."

KALUNDBORG INDUSTRIAL SYMBIOSIS

STATOIL REFINERY



- Denmark's largest oil refinery
- Capacity 3.200.000 tons/year
currently being expanded to about 5.000.000 tons/year
- Production of the full range of fuel products
- Present manning level about 250 people

KALUNDBORG INDUSTRIAL SYMBIOSIS

ASNÆSVÆRKET, ANNUAL RESOURCE CONSUMPTION



Water:	400.000 m ³	(treated)
	100.000 m ³	(raw)
	700.000 m ³	(re-used cooling water from Statoil)
	500.000 m ³	(re-used waste water from Statoil)
Coal:	1.600.000 tons	
Oil:	25.000 tons	
Gas:	5.000 tons	(flare gas from Statoil)

KALUNDBORG INDUSTRIAL SYMBIOSIS

ASNÆSVÆRKET



- ◆ Denmark's largest power plant
- ◆ Energy source mainly coal
- ◆ Installed capacity 1500 MW
- ◆ Number of employees about 600

KALUNDBORG INDUSTRIAL SYMBIOSIS

STATOIL REFINERY ANNUAL EMISSIONS



SO ₂	1.000	tons
NOX	200	tons
Waste water	500.000	M3
Oil	1.80	tons
Phenol	0.02	tons
Oily waste	300	tons ^{*)}

*) Being biologically degraded in own sludge farming facilities

KALUNDBORG INDUSTRIAL SYMBIOSIS

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

KALUNDBORG INDUSTRIAL SYMBIOSIS

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	



KALUNDBORG INDUSTRIAL SYMBIOSIS

TYPICAL CHARACTERISTICS OF THE SYMBIOSIS

- ◆ The participating industries must fit together, but be different
- ◆ Individual agreements are based on commercially sound principles
- ◆ Environment, resource conservation and economics go hand in hand
- ◆ Voluntary development, but close co-operation with authorities
- ◆ Short physical distance between plants; a definite advantage
- ◆ Short "mental" distances equally important
- ◆ Mutual management understanding and co-operative commitment is essential
- ◆ Effective operative communication is required
- ◆ Significant side benefits achieved in other areas such as safety and training

KALUNDBORG INDUSTRIAL SYMBIOSIS

ACHIEVED RESULTS

* Reduction of resource consumption

Oil	19.000 tons/year
Coal	30.000 tons/year
Water	1.200.000 m ³ /year

Development of a symbiosis concept, which has application to many other industries

* Kalundborg has achieved an image of a clean industrial city

KALUNDBORG INDUSTRIAL SYMBIOSIS

FUTURE DEVELOPMENTS

The Kalundborg symbiosis may be extended
between existing industries
new industries may join it

The symbiosis concept has general application and is recommended as a
practical approach to minimize the environmental impact from existing
and new industrial complexes

Appendix B

Selected Definitions of Industrial Ecology

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

"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."

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

"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."

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

Patel, C. Kumar N. "Industrial Ecology." *Proceedings, 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."

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

"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."

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

"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".

Lowe, Ernest. "Industrial Ecology-An Organizing Framework for Environmental Management." *Total Quality Environmental Management*, Autumn 1993

"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 of industrial ecology is bringing the industrial system as close as possible to being a closed-loop system, with near complete recycling of all materials."

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

Hawken, Paul. *The Ecology of Commerce*. New York: Harper Business, 1993.

..."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".

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