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Wrocław University of Technology

Renewable Energy Systems

Zbigniew Leonowicz, Przemysław Janik

INDUSTRIAL ECOLOGY – SELECTED ISSUES

Wrocław 2011

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Contents

Glossary

Abiotic (components) - are non-living chemical and physical factors in the environment

Adaptive management—Management of complex technological—social systems that recognizes the importance of technological information, the inadequacy of predictive activity, and the need to act, nonetheless, to optimize human—natural systems over time.

Anthropogenic— Derived from human activities. Background consumption—Consumption that satisfies basic needs.

Audit - an evaluation

Budget —A balance sheet of the magnitudes of all of the sources and sinks for a particular species or group of species in a single reservoir.

By-product —A useful product that is not the primary product being produced. In life cycle analysis, by-products are treated as coproducts.

Carcinogen—A material that causes cancer.

Cascade recycling —Open-loop recycling Category—Derived from human activities.

CFCs — Chlorofluorocarbon compounds, that is, organic compounds that contain chlorine and/or fluorine atoms. CFCs are widely recognized as hazardous to stratospheric ozone.

Characterization —The process of quantitatively determining the impact resulting from the stress indicated by LCA inventory values.

Chronic—In toxicology, an exposure or effect of an exposure which becomes manifest only after a significant amount of time—weeks, months, or even years—has passed. Many carcinogens (substances causing cancer) are chronic toxins, and low level exposure to many heavy metals, such as lead, produces chronic, rather than acute, effects.

Classification —The process of assigning raw LCA data on flows of materials and energy to particular environmental concerns.

Consumption—The organism-induced transformation of materials and energy.

Cycle —A system consisting of two or more connected reservoirs, where a large part of the material of interest is transferred through the system in a cyclic manner.

Dematerialization—An absolute or relative reduction in the use of materials per unit of value added or output.

Depletion time—The time required to exhaust a resource if the present rate of use remains unchanged.

Design for environment —An engineering perspective in which the environmentally related characteristics of a product, process, or facility design are optimized.

Disposal—Discarding of materials or products at the end of their useful life without making provision for recycling or reuse.

Ecological engineering—The design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both.

Ecology (biological) —The study of the distribution and abundance of organisms and their interactions with the physical world.

Emergent behavior—The behavior of a system at a particular holonic level which is impossible to predict from detailed knowledge of adjacent holonic levels.

Emissions—Losses to the environment from any of a variety of human activities.

Energy audit —An accounting of input flows, output flows, and losses of energy within an industrial process, a facility, a corporation, or a geographical entity.

Exposure—Contact between a hazard and the target of concern, which may be an organ, an individual, a population, a biological community, or some other system. The confluence of exposure and hazard gives rise to risk.

Extent—The size of a scale dimension.

Flux —The rate of emission, absorption, or deposition of a substance from one reservoir to another. Often expressed as the rate per unit area of surface.

Food chain —A sequence in which resources flow in linear fashion from one trophic level to the next.

Food web —A pattern in which resources flow largely from one trophic level to the next but may also flow across trophic levels in nonlinear fashion.

Fossil fuel—A general term for combustible geological deposits of carbon in reduced (organic) form and of biological origin, including coal, oil, natural gas, oil shales, and tar sands.

Global warming—The hypothesis that elevated concentrations of certain anthropogenic atmospheric constituents are causing or will cause an increase in Earth's average temperature.

Green engineering—The design and implementation of engineering solutions that take environmental issues into account throughout the life cycle of the design.

Greenhouse gas —A gas with absorption bands in the infrared portion of the spectrum. The principal assumed greenhouse gases in the Earth's atmosphere are water, carbon dioxide, ozone, methane, etc.

Hazard— (as used in risk assessment) A material or condition that may cause damage, injury, or other harm, frequently established through standardized assays performed on biological systems or organisms. The confluence of hazard and exposure creates a risk.

Hidden flow—The indirect flows of materials such as resources, pollution, or waste that occur upstream in a production process but that are not physically embodied in the product itself.

Holarchy—A network of holons.

Holistic - all-englobing, regarded as greater than the sum of its parts.

Holocene - a geological epoch which began approximately 10,000-12,000 years ago and continues to the present.

Holon—An individual entity in a system of systems.

Indicator—A non-quantitative measure of the status of a chosen parameter, environmental or otherwise.

Industrial ecology —An approach to the design of industrial products and processes that evaluates such activities through the dual perspectives of product competitiveness and environmental interactions.

Industrial enzyme—An industrial process or piece of equipment that results in a transformation of materials or energy.

Industrial symbiosis —See Symbiosis.

Infrastructure—The basic facilities, equipment, and installations needed for the functioning of a community or industrial operation.

Level—A unit of analysis located in a particular position on a scale.

Life cycle—The stages of a product, process, or package's life, beginning with raw materials acquisition; continuing through processing, materials manufacture, product fabrication, and use; and concluding with any of a variety of waste management options.

Life cycle assessment—A concept and a methodology to evaluate the environmental effects of a product or activity holistically, by analyzing the entire life cycle of a particular material, process, product, technology, service, or activity. The life cycle assessment consists of three complementary components — inventory analysis, impact assessment, and improvement analysis — together with an integrative procedure known as scoping.

Material flow analysis —An analysis of the flows of materials within and across the boundaries of a particular geographical region.

Metabolic analysis—The analysis of the aggregate of physical and chemical processes taking place in an organism, biological or industrial.

Metabolism—The physical and chemical processes taking place in an organism, biological or industrial.

Metabolite —An intermediate product of chemical transformations within an organism.

Metric —A quantitative measure of the status of a chosen parameter, environmental or otherwise.

Mineral —A distinguishable solid phase that has a specific chemical composition, for example, quartz or magnetite.

Mutagen—A hazard that can cause inheritable changes in DNA.

Normalization—In life cycle assessment, the process of relating environmental impact values derived at the characterization step to reference values in order to arrive at common indicator values.

NO_x—The sum of the common pollutant gases NO and NO_2 or generic term for mono-nitrogen oxides NO and NO_2.

Omnivore—The acquisition of resources from organisms at several different trophic levels.

Ore —A natural rock assemblage containing an economically valuable resource.

Organism —An entity internally organized to maintain vital activities.

Overburden—The material to be removed or displaced that is overlying the ore or material to be mined.

Overconsumption—Consumption for which choice exists and that undermines a species' own life support system.

Ozone depletion —The reduction in concentration of stratospheric ozone as a consequence of efficient chemical reactions with molecular fragments derived from anthropogenic compounds, especially CFCs and other halocarbons.

Packaging, primary—The level of packaging that is in contact with the product. For certain beverages, an example is the aluminum can.

Packaging, secondary —The second level of packaging for a product that contains one or more primary packages. An example is the plastic rings that hold several beverage cans together.

Packaging, tertiary—The third level of packaging for a product that contains one or more secondary packages. An example is the stretch wrap over the pallet used to transport packs of beverage cans.

Pathway—The sequence of chemical reactions that connects a particular starting material with the final material that is produced.

Plating—The act of coating a surface with a thin layer of metal.

Pollution prevention —The design or operation of a process or item of equipment so as to minimize environmental impacts.

Radionuclide (radioactive isotope or radioisotope) - is an atom with an unstable nucleus, which is a nucleus characterized by excess energy which is available to be imparted either to a newly-created radiation particle within the nucleus, or else to an atomic electron. The radionuclide, in this process, undergoes radioactive decay, and emits a gamma ray(s) and/or subatomic particles. These particles constitute ionizing radiation. Radionuclides may occur naturally, but can also be artificially produced.

Recycling—The reclamation and reuse of output or discard material streams useful for application in products.

Remanufacture—The process of bringing large amounts of similar products together for purposes of disassembly, evaluation, renovation, and reuse.

Reserve —The total known amount of a resource that can be mined with today's technology at today's market prices.

Reserve base —The total known amount of a resource that can be mined, without regard for technology or market prices.

Source —In environmental chemistry, the process or origin from which a substance is injected into a reservoir. Point sources are those where an identifiable source, such as a smokestack, can be identified. Nonpoint sources are those resulting from diffuse emissions over a large geographical area, such as pesticides entering a river as runoff from agricultural lands.

Stock—The contents of a reservoir.

Stratosphere—The atmospheric shell lying just above the troposphere and characterized by a stable lapse rate. The temperature is approximately constant in the lower part of the stratosphere and increases from about 20 km to the top of the stratosphere at about 50 km.

Sustainable engineering —The design and implementation of engineering solutions that take environmental and sustainability issues into account throughout the life cycle of the design.

Sustainability—In the context of industrial ecology, sustainability is the state in which humans living on Earth are able to meet their needs over time while nurturing planetary life-support systems.

Symbiont - is the term that commonly describes an organism with close and often long-term interactions with another organism

Symbiosis—A relationship within which at least two willing participants exchange materials, energy, or information in a mutually beneficial manner.

Thermal pollution - is the degradation of water quality by any process that changes ambient water temperature. A common cause of thermal pollution is the use of water as a coolant by power plants and industrial manufacturers. When water used as a coolant is returned to the natural environment at a higher temperature, the change in temperature impacts organisms by (a) decreasing oxygen supply, and (b) affecting ecosystem composition.

Thermohaline circulation (THC) - refers to the part of the large-scale ocean circulation that is driven by global density gradients created by surface heat and freshwater fluxes. The adjective thermohaline derives from “thermo”- referring to temperature and “haline” referring to salt content, factors which together determine the density of sea water.

Trophic level—A group of organisms that perform similar resource exchanges as part of natural food chains or food webs.

Troposphere—The lowest layer of the atmosphere, ranging from the ground to the base of the stratosphere at 10-15 km altitude, depending on latitude and weather conditions. About 85 percent of the mass of the atmosphere is in the troposphere, where most weather features occur. Because its temperature decreases with altitude, the troposphere is dynamically unstable.

Valuation —In life cycle assessment, the process of assigning weighting factors to different impact categories based on their perceived relative importance.

Visibility—The degree to which the atmosphere is transparent to light in the visible spectrum, or the degree to which the form, color, and texture of objects can be perceived. In the sense of visual range, visibility is the distance at which a large black object just disappears from view as a recognizable entity.

Waste—Material thought to be of no practical value. One of the goals of industrial ecology is the reuse of resources, and hence the minimization of material regarded as waste.

Waste audit—An accounting of output flows and losses of wastes within an industrial process, a facility, a corporation, or a geographical entity.

Water audit —An accounting of input flows, output flows, and losses of water within an industrial process, a facility, a corporation, or a geographical entity.

Weighting —In life cycle assessment, the process of assigning factors to different impact categories based on their perceived relative importance.

This glossary was compiled from various sources, including particularly: T.E. Graedel, B.R Allenby, Industrial Ecology and Sustainable Engineering, Pearson, 2009.

Chapter 1 What Is Industrial Ecology And Sustainable Engineering?

The ecology has reached enormous importance in the last years. The increasing interest in environment in which we live has helped to develop the conscience of problems that affect our planet and demand a quick solution.

The alive beings are in permanent interaction between each other and with the environment in which they live. The ecology analyzes how each element of an ecosystem affects the other components and how it is affected too. It is a synthesis science, because it involves the complex plot of scientific relations: botany, zoology, physiology, genetics, physics, chemistry and geology but also industrial engineering.

Overall, we still have a socioeconomic system in whirl over 90 percent of extracted material ends up as unused waste. Most energy is focused in production and consumption.

In ecosystems, materials are reused, and as much as 91 percent of energy goes directly into the system of decomposition to continually renew the nutrients needed for ongoing life.

The development of industrial ecology is an attempt to provide a new approach for understanding the impacts of industrial systems on the environment. This 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. The aim would be to help restore human systems to a balance more closely resembling that found in ecosystems.

Industrial ecology is the study of the physical, chemical, and biological interactions and interrelationships both within and between industrial and ecological systems. Researchers point out that industrial ecology involves identifying and implementing strategies for industrial systems to produce more harmonious, sustainable, ecological ecosystems.

Environmental problems 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.

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.

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 famous 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.

1.1 Definitions of 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

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.

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.

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.

For the present, a working definition of the field is as follows:

Industrial ecology is the means by which humanity can deliberately approach and maintain sustainability, 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 obsolete product, and to ultimate disposal.

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?

A full consideration of industrial ecology would include the entire scope of economic activity, such as mining, agriculture, forestry, manufacturing, service sectors, and consumer behavior. It is, however, obviously impossible to cover the full scope of industrial. Accordingly, we limit the discussion in most of this book to manufacturing activities

1.2. Principles of industrial ecology

There is a number of general principles suggested for the field:

* Connect individual firms into industrial ecosystems

* Close loops through reuse and recycling.

* Maximize efficiency of materials and energy use.

* Minimize waste generation.

* Define all wastes as potential products and seek markets for them.

* Balance inputs and outputs to natural ecosystem capacities

* Reduce the environmental burden created by releases of energy and material into the natural environment.

* Design the industrial interface with the natural world in terms of the characteristics and sensitivity of the natural receiving environment.

*Avoid or minimize creating and transporting toxic and hazardous materials (when needed, synthesize locally).

* Re-engineer industrial use of energy and materials

* Redesign processes to reduce energy usage.

* Substitute technologies and product design to reduce use of materials that disperse them beyond possibility of recapture.

* Do more with less (technically called dematerialization).

* Align policy with a long-term perspective of industrial system evolution.

SUSTAINABLE DEVELOPMENT has been defined as balancing the fulfillment of human needs with the protection of the natural environment so that these needs can be met not only in the present, but in the indefinite future.

Sustainable development is quoted as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs."

The field of sustainable development can be divided into four general dimensions: social, economic, environmental and institutional. The first three dimensions address key principles of sustainability, while the final dimension addresses key institutional policy and capacity issues.

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.”

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 inter-societal).

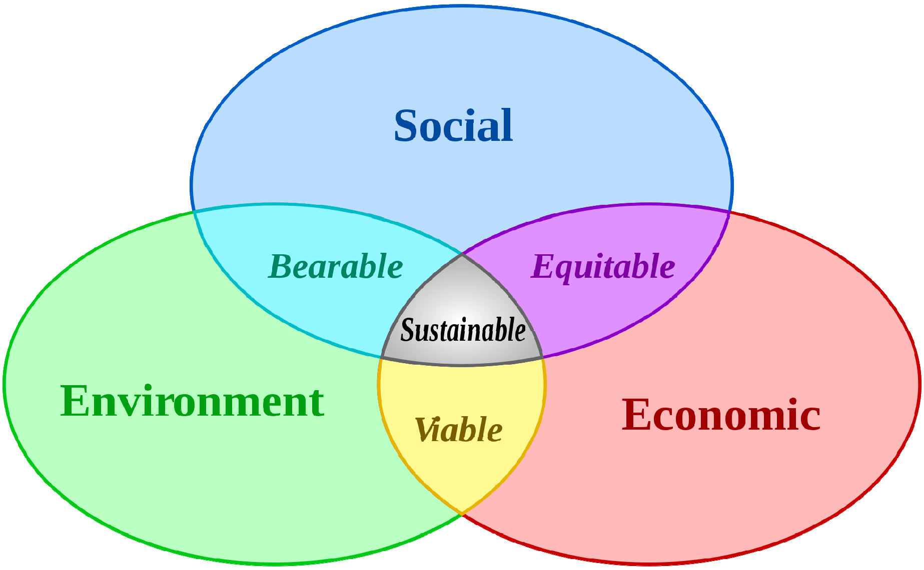


Figure 1. Scheme of sustainable development: at the confluence of three preoccupations.
(http://en.wikipedia.org/wiki/Portal:Sustainable_development)

This chapter and the following were compiled from various sources, including particularly Garner A. G. A. Keoleian Industrial Ecology: An Introduction, University of Michigan School of Natural Resources and Environment, 1995.

Chapter 2 History Of Industrial Ecology

Industrial ecology is based on systems analysis and is a higher level systems approach to 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. 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.

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” (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. Environment Protection Agencies 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 educational materials.

Chapter 3 GOALS AND KEY CONCEPTS OF INDUSTRIAL ECOLOGY

3.1 Goals of industrial ecology

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

3.1.1 Sustainable Use of Resources

Industrial ecology should promote the sustainable use of renewable resources and minimal use of nonrenewable 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 cannot be assumed that substitutes will continue to be found as supplies of certain raw materials decrease or are degraded.

Besides solar energy, the supply of resources is finite. Thus, depletion of non-renewables and degradation of renewables must be minimized in order for industrial activity to be sustainable in the long term.

3.1.2 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.

3.1.3 Environmental Equity

A primary challenge of sustainable development is achieving intergenerational as well as inter-societal 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. Inter-societal 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 a country. Several studies have shown that low income and ethnic communities in many countries., are often subject to much higher levels of human health risk associated with certain toxic pollutants.

A goal of industrial ecology would be to reach 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.

3.2 Key concepts of industrial ecology

3.2.1.Systems analysis

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. 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.

3.2.2.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. 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.

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 a service to society.

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. The anthropogenic sources of some materials in natural ecosystems are much greater than natural sources.

3.2.3. 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.

3.2.4.Analogies to natural systems

There are several useful analogies between industrial and natural ecosystems.

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.

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.

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.

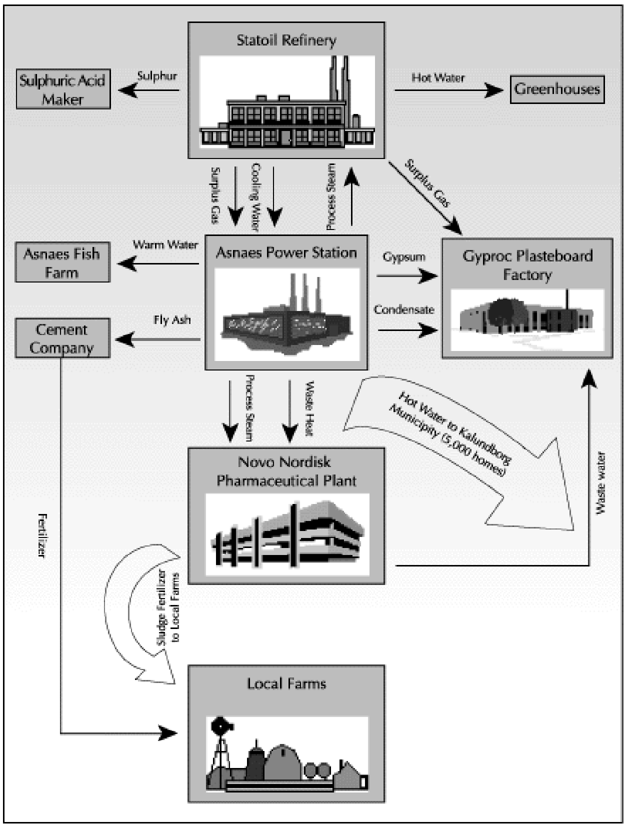


Figure 2 . Kalundborg Industrial Symbiosis. IPTS Report. E. Cohen-Rosenthal and T. N. McGalliard, Eco-Industrial Development: The case of the United States. Reproduction for non-commercial purposes authorized by European Commission.

Chapter 4 Sustainability

4.1. Definitions of sustainability

There are many definitions of sustainability, two of which seem to be particularly summarizing:

1. "Sustainability is the possibility that human and other forms of life will flourish on the planet forever." *(John Ehrenfeld)*

2. [Sustainability is] "a development path that can be maintained indefinitely because it is socially desirable, economically viable, and ecologically sustainable." *(The International Institute of Environment and Development)*

4.2. Basis of the process of sustainability

Given the general agreement that society's current path is not sustainable, we need to decide what we wish to sustain, what we wish to develop, and for how long. A variety of positions have been taken on these topics.

What is to be sustained?

1.NATURE (Earth, Biodiversity, Ecosystems)

2.LIFE SUPPORT (Ecosystem Services, Resources, Environment)

3.COMMUNITY (Culture, Groups, Places)

What is to be developed?

1.PEOPLE (Child Survival, Life Expectancy, Education, Equity, Equal Opportunity)

2.ECONOMY (Wealth, Productive Sectors, Consumption)

3. SOCIETY (Institutions, Social Capital, States, Regions)

For how long?

1.Twenty five years

2. Now and in the future

3. Forever

Notions 2 and 3 are naïve and impracticable choices, because making policy for more than a human adult lifetime is not realistic. Thus most operational planning durations for sustainability fall into the 25-50 year range (notion 1)

4.3. "Weak" and "strong" sustainability.

"Weak" sustainability's adherents judge the total capital stock (the sum of natural capital and human-made capital) is nondecreasing.

"Strong" sustainability's supporters argue that natural capital provides certain important functions for which human-made capital cannot substitute.

Robert Ayres (2007) lists free oxygen, freshwater, phosphorus, thallium or rhenium in this group and argues that "those who espouse the notion of strong sustainability appear to be closer to the truth than the optimists who believe in more or less unlimited substitution possibilities.

4.4. How to evaluate sustainability?

How sustainability guidance can be implemented? We explore in this section of the chapter a few examples of how such guidance might be established and provided.

Realistic and defensible goals for sustainability and their implementation will not be easy to establish in practice, but we can establish some basic principles:

•Establish the limiting rate of use of the environmental, economic, or equity component.

•Allocate the acceptable limit to those who are influenced by that limit.

•Compare the current situation with the permitted allocation.

•Consider potential corrective actions.

4.4.1 Potential factors in the future

By most accounts, the next 50 years will be crucial in determining the long-term sustainability of ecological and human systems. Population is likely to increase dramatically over the next 50 years from 6 billion to 9 billion.

According to some hypothesis, a discernable human-induced climate change on the order of 2-5°C could well occur, and commonly used industrial minerals and both oil and natural gas could become increasingly scarce over the next 50 years.

We further assume that resource consumption should be planned so that existing resources will last for 50 years at current rates. This allows time for substitution of other resources or the development of alternative ways of meeting the needs that are served by resource consumption.

4.4.2. A preliminary measure of sustainability

We assume that the average global population over the next 50 years will be 7.5 billion people. We should:

* Establish the virgin material supply limit by calculating the amount of a resource that can be used per year if that resource is to last for 50 years.

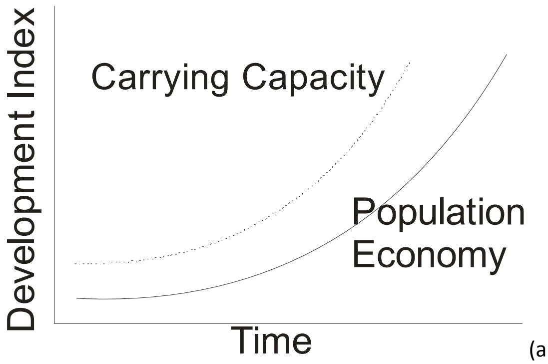
To do so, we must first establish the known quantity of the resource available within the region of interest (the globe, a country, a state, etc.). For a nonrenewable resource, the amount often used is the "reserve base," defined as those resources that can be extracted at a profit plus some resources that are known but are not presently economically viable.

* Allocate the virgin material supply according to a reasonable formula (such as dividing it equally among the global population, perhaps).

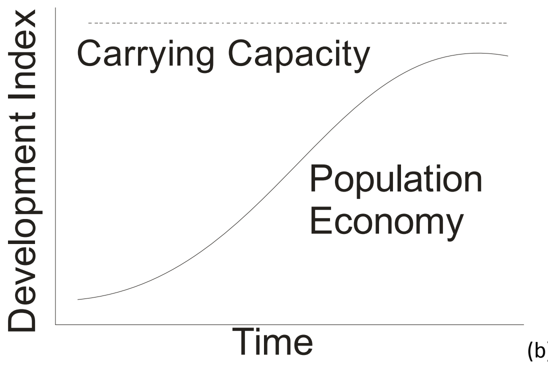
4.5. Sustainability and societal collapse

Societal collapses occurred many times in the history of humanity. The classic case is that of Easter Island in the southeastern Pacific Ocean. When the Polynesians arrived, they began to cut trees to create farmland and to make canoes. Soon they began to erect the large statues for which the island is famous, and trees were used to transport the statues and erect them. Over time, the island's trees were all cut for these purposes. The lack of trees meant that Easter Island had no firewood, mulch, or canoes. Without the ability to catch fish from canoes, and with the depletion of nesting birds, the population came under severe pressure, and the island was too remote for help to come. There were no alternatives to a severe and ultimately permanent population collapse.

This process is exemplified by the Figure 3. The Figure 3a shows the path of social progress for about 200 years. This pattern occurs when there are no limit to growth or when innovation modifies limits. The s-shaped curve (Figure 3b) is characteristic of the system with fixed constraints and distant limits.



(a)



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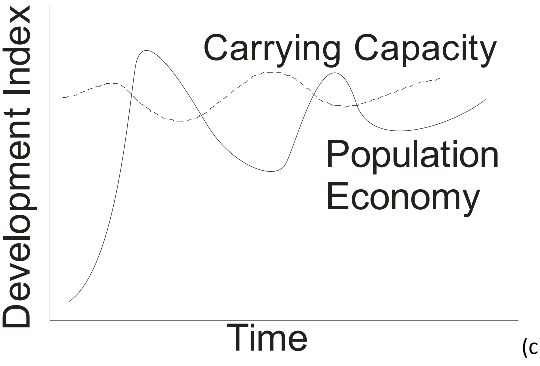
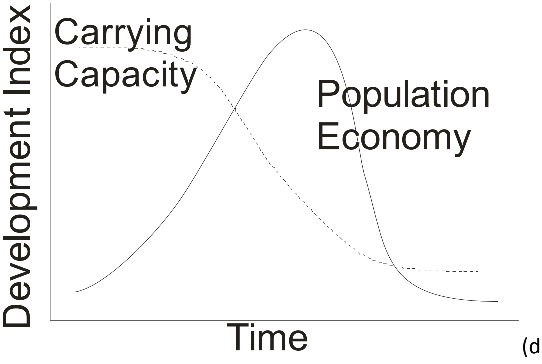


(c)



(d)

Figure 3. Dynamics of complex systems. Adapted from D.H. Meadows, D.L. Meadows, J. Randers, Beyond the Limits, White River Junction, 1992.

The curve showing oscillatory behavior (Figure 3c) is typical of systems where feedback mechanisms are inaccurate and responses are too slow..At the point of awareness of some limit, it is too late to avoid overstepping this limit and the system continues to move. If the resulting stress does not completely degrade the system, subsequent corrections can enable the system to oscillate about and approach the limit. Curve (Fig. 3d) depicts initial behavior similar to the (3c) curve, but with a difference. Here the system is insufficiently robust, corrections are insufficient, and collapse occurs. (the Easter Island trajectory).

It is important to note that the initial stages of these curves are similar. We imagine that we are close to the origin and further imagine that we are on the expansion model. If we are not, we must re-evaluate the sustainability, the robustness and stability of our technological society.

4.6: Example of sustainable production of greenhouse gases

We wish to maintain two major Earth system conditions: a Holocene-style climate and functioning planetary engineering systems (fore; wetlands, etc.). The sustainability of each is closely linked to global climate change.

A doubling of atmospheric CO_2 (the major greenhouse gas of concern for our technological society) would most likely permanently not alter Atlantic Ocean circulation, and would not seriously modify climate conditions. However, although effects of a doubling of atmospheric CO_2 are still uncertain, they has emerged as a political target and a focal point for scientific analysis in most climate change models.

Perhaps one sustainability threshold for climate change would be to limit possible human modifications of climate that will significantly alters ocean circulation patterns, such the North Atlantic thermohaline circulation.

4.6.1. Calculation of a global sustainable limiting rate of carbon dioxide production:

* Virgin material supply limit: in order to level off atmospheric CO_2 concentration below a doubling from the preindustrial level (i.e. below approximately 550 ppmv[1] by the year 2100), global anthropogenic emissions must be limited to ~7-8 Pg[2] of carbon per year.

* Allocation of virgin material: each of the average 7.5 billion people on the planet over the next 50 years is allocated an equal share of CO_2 emissions. This translates to roughly 1 metric ton of carbon per person per year.

* Regional "recaptureable" resource base: "recycling" of carbon in the form of permanent or semipermanent sequestration may eventually be possible through controversial techniques such as deep well injection of carbon dioxide. However, this is still largely theoretical or in the very early stages of experimentation. Future sustainability measures could incorporate carbon recycling.

* Current consumption rate vs. sustainable limiting rate: the United States on average produces 6.6 metric tons of carbon equivalents per person, which is clearly well beyond the global sustainable rate of 1 metric ton of carbon per person per year. Inhabitants of Switzerland produce approximately 2.0 metric tons of carbon equivalents per person, which is still approximately twice our calculated sustainable limit.

Driving an automobile produces approximately 100 g of carbon per vehicle per mile traveled. Drivers in the United States average 12,500 miles per person per year, which translates to 1.25 metric tons of carbon produced per year by driving. Regardless, a person could use all of his or her sustainable carbon credit on driving, but this would leave nothing for home heating, electricity for a computer, or a personal share in the larger industrial-technological systems that support the economy.

Alternative energy sources, carbon sequestration possibilities, less-carbon-intensive production systems, personal driving habits, vehicle technology, public transportation systems, or some combination thereof must all be incorporated into the public discourse.

4.7 The Grand Environmental Objectives

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1 parts per million by volume

2 petagram (Pg), an SI unit of mass based on the kilogram (10^{15} grams)

Although there is a number of environmental issues, there is indisputable evidence that some environmental concerns are regarded universally as more important than others. For example, a major global decrease in biodiversity was recognized as more important than the emission of hydrocarbon molecules from residential heating. The Montreal Protocol and the Rio Treaty demonstrate that minimizing the prospects for ozone depletion and global climate change are issues of universal importance.

Therefore one may postulate the existence of a small number of "Grand Objectives" having to do with environmental issues:

1st Objective: Maintaining the existence of the human species

Environmental concern:

* global climate change

* human organism damage

* water availability and quality

* resource depletion (fossil fuels)

* artificially produced radionuclides

2nd Objective: Maintaining the capacity for sustainable development and the stability of human systems

Environmental concern:

* water availability and quality

* resource depletion (fossil and non-fossil fuels)

* landfill exhaustion

3rd Objective: Maintaining the diversity of life

Environmental concern:

* water availability and quality

* loss of biodiversity

* stratospheric ozone depletion

* acid deposition

* land use patterns

* thermal pollution

4th Objective: Maintaining the aesthetic richness of the planet

Environmental concern:

* smog

* aesthetic degradation

* oil spills

* odor

4.7.1 How to achieve the Grand Environmental Objectives?

There are certain basic societal requirements that must be satisfied if the objectives are to be met.

In the case of 1st Objective, these are:

* the minimization of environmental toxicity,

* the provision of basic needs: food, water, shelter,

* the development of social and environmental capacity of regeneration after possible disasters.

In the case of 2nd Objective, these are:

* a reliable energy supply,

* the availability of suitable material resources,

* the existence of workable political structures,

* minimizing cultural conflict.

In the case of 3rd Objective, these are:

* maintenance of a suitable amount of natural areas,

* maximizing biological diversity on disturbed areas,

In the case of 4th Objective, these are:

* control of wastes of various kinds: minimizing emissions that result in smog, discouraging dumping and other activities leading to the environmental degradation

* encouraging farming and agricultural practices that avoid land overuse and erosion,

* the preservation of commonly held undeveloped land.

In an industrialized society, a number of these requirements are decisions made by product designers and manufacturing engineers. Thus, the Grand Objectives specify means by which favorable decisions can be made.

4.8 Linking the Grand Objectives with an industrialized society

The final step is the improvement of the environmental and social responsibility of their products. This can be done through the four steps' process:

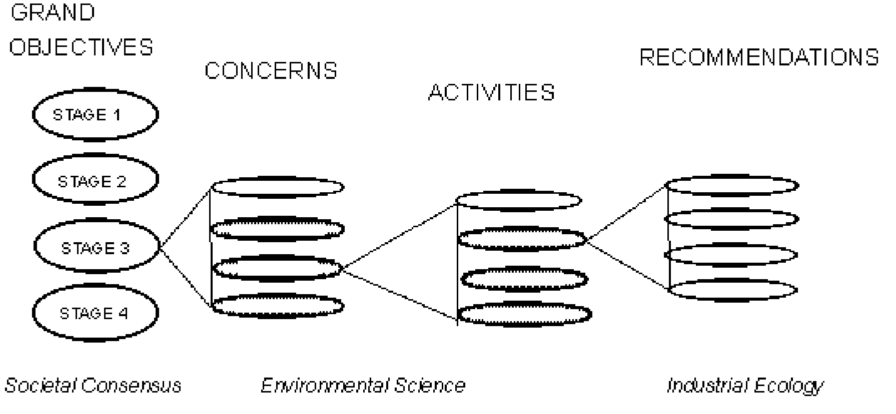

Figure 4. A schematic representation of the conceptual sequence of four stages in life cycle assessment

Each of the four grand stages is related to a number of concerns, such as climate change (each concern suggested be a horizontal ellipse); similarly, each of the concerns is related to a number of activities, such as fossil fuel combustion (again, horizontal ellipses indicate different activities); and each activity is related to a number of recommendations, such as higher-efficiency combustion. As noted at the bottom, different specialist fields treat different stages in the sequence.

EXERCISES

1.Use the information in 4.6.1 to estimate how a driver would have to reduce his or her yearly driving miles in order to achieve the 1 metric ton of carbon per person sustainability goal.

2. Section 4.2 proposes that 25-50 years is the best choice for a sustainability planning timescale. Do you agree? Explain.

3. Present the options for allocating the allowable CO2 emissions, together with problems with the options.

4. Do you agree that four Grand Objectives are the ideal set? If not, present and discuss alternatives.

Chapter 5 WHAT IS GREEN ENGINEERING?

5.1. The concept of green engineering

Engineering has traditionally been regarded as the specialty that employs scientific principles to achieve practical ends. These approaches are now clearly recognized as outdated, and modern engineers acknowledge the need to do better.

The first step in this transformation of the engineering profession is to practice green engineering. Green or sustainable engineering is the design, commercialization, and use of engineering solutions, viewed from the perspective of human and environmental health.

This engineering centers in practice on minimizing pollution and risk as a consequence of product manufacture and product use, that is, of being more environmentally responsible

5.2. Key questions of green engineering

Green engineering is not interested in the functioning of the technological system per se, but on the industrial ecosystem's interactions with and implications for the natural and social systems of the planet. It specifically concentrates on a single species (humans), its relationship with the environment, and the impacts of industrial operations and choices on its social systems. From this position it results a set of key questions:

1. How do modern technological cycles operate?

* How are industrial sectors linked?

* What are the environmental and social opportunities and threats related to specific technologies or products?

* How are technological products and processes designed, and how might those approaches be usefully modified?

* Can cycles from extraction to final disposal be established for the technological materials used by our modern society?

* How do technological cycles interact with culture and society, and what are the implications inherent in these "second order" effects of technology?

2. How do the resource-related aspects of human cultural systems operate?

* How do corporations manage their interactions with the environment and society, and how might corporate environmental management evolve?

* How can the influence of culture/consumption on materials' cycles be modulated?

* How can engineers appreciate their relationships with environment and society?

* How might IE[3] systems be better understood?

3. What are the limits to the interactions of technology with the world within which it operates?

* What limits are imposed by nonrenewable, nonfossil resource availability?

* What limits are imposed by the availability of energy?

* What limits are imposed by the availability of water?

* What limits are imposed by environmental and/or sustainability concerns?

* What limits are imposed by institutional, social, and cultural systems?

4. What is the future of the technology—environment—society relationship?

* What scenarios for development over the next several decades form plausible

pictures of the future of technology and its relationship to the environment

and social systems?

* Should systems degraded by technological activity, local to global, be restored, and if so how?

5.3. The concept of waste

Industrial ecology, like the biological system, rejects the concept of waste. Waste is defined as useless or worthless material. In nature, however, nothing is eternally discarded; in various ways all materials are reused, generally with great efficiency.

5.4. Characteristics of green engineering

Green (ecological) engineering is defined as the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both.

Green engineering is most often encountered in the design of water treatment systems, where the filtration and cleansing activities of plants and soil substitute for a conventional water treatment plant.

The key feature of green engineering is that the engineer abandons the concept of total control and instead aims to enable functionality by the ecosystems themselves.

Three attributes separate green engineering from other engineering specialties:

Green engineering is based on self-organizing hierarchical open (SOHO) systems. The goal of the green engineer is to initiate and enable a suitable SOHO system by seeding appropriate species into the area being engineered and then allowing self-organization to occur.

3 Industrial ecology is abbreviated to IE

Green engineering designs and enables systems that are primarily or entirely self-sustaining. These systems are usually solar based, requiring minimal or negligible energy from traditional, human-engineered sources such as fossil fuels or electricity. As a result, SOHO systems are generally less costly than conventional systems but require more land. Green engineering supports ecosystem conservation and development, thus providing benefits to nature as nature provides benefits to humans.

Green engineering is also employed in the restoration of ecosystems that have been degraded or destroyed by traditional engineering approaches.

However, green engineering neither includes the cleanup of contaminated sites so that they can be used by humans again, nor the dredging of rivers, lakes, and harbors to facilitate human use, because in these cases ecosystem restoration and function are not taken into account, at least not in any central way.

It does, however, encompass activities such as the restoration of wetlands degraded or destroyed by human development projects. In such restorations, functionality useful to humans such as water purification or erosion control may result so long as ecosystem integrity is among the primary project goals.

5.5. Practicing green engineering

5.5.1. Earth Systems Engineering and Management (ESEM)

The main goal of green engineering is altering our technological society so that we balance social, environmental, and economic domains and reduce or eliminate impacts on the environment. Another approach consists of trying to manage major Earth systems that are already affected by human activity: We term this "Earth system engineering and management" (ESEM).

ESEM arises from the realization that many fundamental natural systems are increasingly dominated by the activities of a single species — ours. This concept is made vital by the increasing scale of human impact on the environment.

ESEM is defined as "the engineering and management of Earth systems (including human systems) so as to provide desired human-related functionality in an ethical manner."

Thus ESEM treats human and natural systems as coherent complexes. ESEM considers that the desired output of the technological system is bound with respect for, and protection of, the relevant aspects of coupled natural systems. This can include things valued by humans, such as aesthetics, or ecosystem services such as flood control, as well as respecting biodiversity or the global water cycle.

5.5.1.1. The principles of ESEM

One can draw the complex systems engineering projects and related fields such as adaptive management to generate a basic set of ESEM principles that, although still illustrative, create an operational foundation. These principles can be sorted into three categories: theory, governance, and design and engineering.

1) Theoretical principles of ESEM

The theoretical principles of ESEM are cautionary and reflect the complexity of the systems involved and our current levels of ignorance.

Only intervene when necessary, and then only to the extent required, because minimal interventions reduce the probability and potential scale of unanticipated and undesirable system responses.

ESEM projects and programs are not just scientific and technical in nature, but unavoidably have powerful economic, political, cultural, ethical, and religious dimensions. Social engineering— efforts to change cultures, values, or existing behavior—and technical engineering both need to be integrated in ESEM projects, but they draw on different disciplines and knowledge domains and involve different issues and world views. An ESEM approach should integrate all these factors in order to arrive at a satisfactory outcome.

ESEM requires a focus on the characteristics and dynamics of the relevant systems as systems, rather than as sums of individual components.

Boundaries around ESEM initiatives should reflect real-world linkages through time, rather than disciplinary simplicity.

Major shifts in technologies and technological systems should be evaluated before, rather than after, implementation of policies and initiatives designed to encourage them.

For example, it is apparent that corn-based ethanol as a biomass fuel leads to higher-cost food and, in some countries, political unrest.

2) Governance Principles of ESEM

The global governance system is rapidly evolving and becoming more complex. This gives rise to a second category of principles involving ESEM governance.

ESEM initiatives by definition raise important scientific, technical, economic, political, ethical, theological, and cultural issues in the context of global polity. Given the need for consensus and long-term commitment, the only workable governance model is one that is inclusive, transparent, and accountable.

ESEM governance models that deal with complex, unpredictable systems must accept high levels of uncertainty as inherent in the process. ESEM policy development and deployment must be understood as a continuing dialog with the relevant systems rather than a definitive endpoint and should thus emphasize flexibility. Moreover, the policy maker must be understood as part of an evolving ESEM system, rather than an agent outside the system guiding or defining it.

Because Earth systems are self-organizing and open and are thus capable of emergent behavior, continual learning at the personal and institutional level must be built into the process.

There must be adequate resources available to support both the project, and the science and technology research and development that are necessary to ensure that the responses of the relevant systems are understood.

3) Design and engineering principles of ESEM

Finally, there is a set of principles that informs the design and engineering of ESEM systems:

Know from the beginning what the desired and reasonably expected outcomes of any intervention are and establish quantitative metrics by which progress may be tracked.

Unlike simple, well-known systems, the complex, information dense and unpredictable systems that are the subject of ESEM cannot be centrally or explicitly controlled. Rather than being outside the system, the Earth systems engineer will have to see herself or himself as an integral component of the system itself, closely coupled with its evolution and subject to many of its dynamics.

Whenever possible, engineered changes should be open to discussion and reversible, rather than fundamental and irreversible. Green engineering should allow for the fact that in complex systems, discontinuities and emergent characteristics are the rule, not the exception.

An important goal in Earth systems engineering projects should be to support the evolution of resiliency, not just redundancy, in the system. Thus, inherently safe systems are to be preferred to engineered safe systems.

5.5.2. Considering the ESEM

ESEM is not something that humans should now begin to do, because we have been overtly influencing natural systems for centuries. Similarly, it is not unreasonable to view global agricultural and energy systems, tightly linked as they now are by trade and commodity markets, as an ESEM process —and, obviously, another one that has been going on for centuries. Today ecological engineering and ESEM emphasize broad systems thinking. They thus enhance the technological society—environment interaction in potentially useful ways.

Examples of prospective ESEM include among others: the global climate change, the efforts to manage the Baltic Sea, managing regional forests to be sustainable, restricting exploitation of local and regional fisheries, understanding the dynamics of powerful emerging technology systems (nanotechnology, biotechnology, robotics, ICT, and cognitive science), and meeting continued challenges from invasive species.

It is interesting to ask why some ESEM proposals are being implemented and others are not. The implementation is not related to the potential severity of the environmental challenge, nor to the spatial scale of the proposed ESEM activity, nor to the spatial scale of the impact. It is related, however, to the public visibility of the environmental challenge and (to a lesser extent) to the degree of scientific understanding.

ESEM will assume the discussions' move from a goal of environmental improvement to one of sustainability. The latter implies some sort of targets for technology—environment interactions, together with adequate policies, monitoring to evaluate progress toward those targets, and periodic review to assess whether mid-course corrections are needed.

There are numerous ways in which humans are restoring degraded systems. Nonetheless, this often is controversial, time-consuming, and costly. In some cases, with global climate change, for example, it remains unclear whether amelioration can even be accomplished.

5.5.2.1. Practical examples of ESEM

5.5.2.1.1. Regional scale ESEM

1) The Florida Everglades

Figure 5. The map of the Everglades (from Wikipedia "The Evergaldes")

The Everglades are subtropical wetlands located in the southern portion of the U.S. state of Florida. The ecological degradation of the Florida Everglades occurred because South Florida is an area of significant agricultural activity, rapidly increasing population and economic activity.

Nearly 1800 miles of canals have been built over the past 50 years, diverting some 1.7 billion gallons a day of water flow to service agriculture and people and to manage flooding. Equally important, water quality has changed significantly over the same period, and a number of invasive species are increasingly successful.

It is worth noting that a critical technology shaping Southern Florida was air conditioning for both homes and cars, without which highly uncomfortable hot and humid summers would discourage many potential immigrants.

The Everglades ecosystem and the associated human communities that depend upon it became increasingly unsustainable. In response, the Comprehensive Everglades Restoration Plan (CERP), an effort spearheaded by the U.S. Army Corps of Engineers and the South Florida Water Management District, was developed in 1999. Some idea of the magnitude of such an effort is indicated by CERP's scale: it includes more than 40 major projects and 68 project components, at a cost estimated at $10.9 billion in 2004 dollars, over a timeframe of three decades. Its goal is to restore water quality and flow in natural systems to functional levels, while continuing to support industrial, agricultural, settlement, and other human activities.

5.5.2.1.2. Global scale ESEM

1) Stratospheric ozone and CFCS

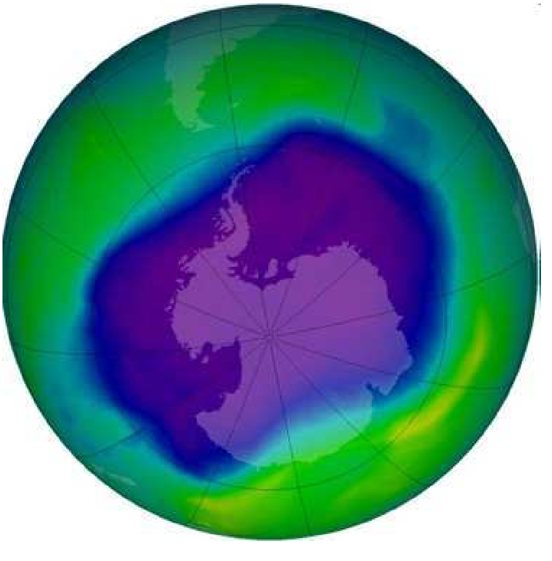

Figure 6. Image of the largest Antarctic ozone hole ever recorded (September 2006). (Wikimedia)

Since 1930’s chloroflurocarbons, or CFCs have proved to be important industrial cleaning compounds and propellants as well as refrigerants. Unfortunately, their stability meant that upon release they migrated through the troposphere to the stratosphere where, upon absorbing high energy photons, they split off chlorine radicals that catalyzed the destruction of stratospheric ozone.

Stratospheric ozone performs the important function of absorbing high ultraviolet (UV) energy before it strikes Earth's surface. Because life at the Earth's surface evolved without significant high energy UV exposure, it was significantly affected by such radiation, which had the potential to kill algae and plankton and generate high levels of cataracts and skin cancer in humans.

The catalytic action of chlorine released from CFCs on stratospheric ozone was first described by Molina and Roland in 1973. Their work and that of others eventually led to the Montreal Protocol on Substances that Deplete the Ozone Layer, which focused on stratospheric ozone recovery to pre-CFC levels. This agreement and subsequent actions have come to be a prime example of a significant positive achievement of international environmental policy.

CFCs were not only a case of a relatively small human activity destabilizing a major Earth system. They were also a classic example of how human, natural, and industrial systems are now integrated at regional and global scales: industrial economics and human values (e.g., health of workers, safety of refrigerant systems), stratospheric physics and chemistry, radiation balances and living systems, international politics—all were coupled.

But perhaps the most important thing to note in this case study is that it is a successful example of ESEM. A problem was identified, a transparent and active political dialog resulted, agreement was accomplished before critical tipping points in the Earth system were reached, and subsequent tracking of the size of the annual ozone hole above Antarctica—helped ensure that the policy initiatives were having the desired effects.

2) Combating global warming

Global warming is the phenomenon in which human-associated emissions of gases to the atmosphere result in increased trapping of outgoing infrared radiation.

The principal anthropogenic "greenhouse" gas is carbon dioxide, though methane, CFCs, nitrous oxide, and other gases also contribute. Because greenhouse gases are directly related to the use of energy, and because energy is the enabler of modern technology and modern life and culture, an ESEM approach to climate is much more complicated and challenging than was the case with CFCs. A further complication is that the climate system is tightly coupled to a great many other parts of Earth systems functioning.

Strictly speaking, CO2 sequestration from power plant stacks is not ESEM, but pollution control, just as is the capture of volatile organic gases before they can leave an industrial facility.

In common usage, however, all proposals for dealing with global warming tend to be lumped into an ESEM framework. Regardless of how it is classified, if a fossil fuel power plant is designed to combust carbon-based feedstock, transfer the combustion products directly to long life reservoirs and produce energy in the form of electricity or hydrogen, the perspective on power generation and the environment undergoes fundamental change.

Rather than being part of a significant environmental problem— a large emitter of greenhouse gases—the power plant becomes part of the solution — a factor in the control of greenhouse gas atmospheric concentrations.

Because of the potential severity of global warming, a number of approaches have been proposed:

a) Capturing carbon dioxide

Human emissions of carbon dioxide, the main anthropogenic greenhouse gas, are not just a phenomenon of the Industrial Revolution. In fact, initial perturbations to atmospheric CO2 concentrations arose from the deforestation of Europe and North Africa between the tenth and fourteenth centuries.

Much later, the development of the internal combustion engine and, as a result, the automotive industry, greatly accelerated emissions of carbon dioxide. As fossil fuel use increases in our modern world, atmospheric CO2 concentrations continue to increase as well.

A possible ESEM alternative is to capture carbon dioxide from stack gases, liquify it, and inject it into underground or undersea aquifers and geologic formations. There, it may remain almost indefinitely.

b) Sequestering carbon in vegetation

CO2 sequestration, as described above, is an approach that aims to prevent CO2 from being emitted into the atmosphere. Once it is there, however, another potential ESEM approach is to remove a portion of it.

One technique that has been fairly widely embraced has been the planting of fast-growing trees, since atmospheric CO2 is the building block for the cellulose from which trees are made. It is clear that reforestation of previously forested areas will indeed store CO2 for at least a period of time, though the absorption rate slows as the trees age.

Although the degree of long-term gain is imperfectly understood, tree planting has many beneficial aspects besides carbon storage, and may be increasingly adopted. Increased biomass proposals raise other issues, however: Can significant increases in biomass production be done in such a way as to avoid destabilizing the global nitrogen cycle? How critical are genetically engineered forms of biomass (e.g., trees designed to fix their own nitrogen) to the implementation of this plan? Once again we are challenged to think of any action from a very broad , systems perspective.

c) Sequestering carbon in marine organisms

CO2 is a building block for phytoplankton, the tiny marine organisms that carry out nearly half of the photosynthesis on Earth. The reproduction and growth of those organisms is limited in most parts of the oceans by the availability of nutrients, particularly iron. It was thus proposed in the early 1990s that if the oceans were fertilized with iron, the resulting growth of organisms would remove considerable CO_2 from the atmosphere.

Spreading fertilizer on the ocean surface on a regular and widespread basis is an enormously ambitious project, but a few tests have been made to assess the feasibility of the idea.

In the most extensive of these, a seeding experiment in the Southern Ocean south of Tasmania, increased phytoplankton growth was stimulated and maintained for over a month. It was not clear that the CO_2 that was incorporated was then transferred to the deep ocean, as would be required for the approach to be effective.

In addition, there is concern for unintended side effects such as deoxygenating the deep ocean and disrupting the structure of marine food webs. Given the current scientific uncertainty, it remains unclear whether, and at what scale, this approach should be employed.

d) Scattering solar Radiation with sulfur particles

Another potential ESEM approach to the mitigation of global warming avoids dealing with CO_2, but rather with preventing incoming solar radiation from reaching the planet's surface.

This idea was proposed some years ago by Russian climatologist Mikhail Budyko, who envisioned injecting some 35 Gg of sulfur dioxide annually, about 25 percent of the amount presently released by fossil fuel burning, directly into the stratosphere. He calculated that such an amount, once converted there to sulfate aerosol particles, should significantly enhance the backscattering of solar radiation to space. The success of the technique depends on an accurate assessment of stratospheric sulfur dioxide to sulfate transition rates at all latitudes and seasons, and it is uncertain whether this information can be precisely derived. Still more challenging, however, are the logistical difficulties of delivering many gigagrams of gases or particles to an altitude near the limit of modern aircraft by fleets of thousands of planes. A possible alternative is to load sulfur particles into ballistic shells and shoot them into the stratosphere using the guns of the world's large naval vessels (several thousand rounds per day, day after day, year after year). By either method, the cost would be in the tens of billions of U.S. dollars annually, and the potential environmental impacts appear highly problematic.

e) Reflecting solar radiation with mirrors in space

An alternative to injecting scattering particles into Earth's upper atmosphere is to send mirrors or other reflective devices by space satellite to the Lagrangian Ll point (a point along the Earth—Sun line where no net forces act on a small object), so that the objects might remain at that location and reflect radiation away from Earth indefinitely.

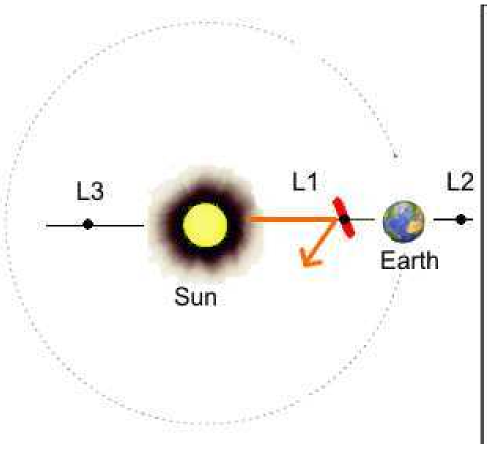

Figure 7. Conceptual diagram for solar reflectors placed at Lagrangian point Ll of the Earth—Sun system to decrease the amount of solar radiation incident on Earth. There are five Lagrangian points, three of which are shown (the other two are at the points of equilateral triangles from the Earth—Sun line). Objects located at these points are stable, or nearly so, because gravitational acceleration and centrifugal acceleration are exactly in balance. Ll is approximately 1 percent of the distance from the Earth to the Sun.

Unfortunately for the concept, gravitational displacement forces from planets and other celestial objects are to be expected at the Ll point, so the objects would require an active positioning system in order to remain in place. Active positioning systems may be impractical. In addition, the enterprise would be extremely expensive, not to mention political intricacies, and the size and reflectivity of the devices would have to be determined very precisely in order not to heat or cool Earth more than desired.

As we have seen, there are many ways in which technologies, economic practices, and cultures can be used to modify human impacts on the carbon cycle and climate systems. It is important to recognize that these options address symptoms rather than root causes, and thus do not adequately address other implications of global climate change.

In particular, none of these geoengineering approaches would reduce the increasing acidification of the ocean as it continues to absorb CO2 and create carbonic acid, thereby affecting marine organisms that use calcium carbonate for their shells. This is evidence of the high degree of interconnections among fundamental natural and human cycles. Imperfectly understood couplings and complexities raise caution flags for most or all geoengineering ideas.

EXERCISES

1. Choose a room of your apartment, dormitory, or house. Conduct an inventory of the physical items or "artifacts" in the room. Divide them into four categories: (1) The artifact is necessary for survival; (2) The function performed by the article is necessary, but the artifact represents

unnecessary environmental impact (e.g., clothes may be necessary, but a fur coat or 10 pairs of shoes may not be); (3) The artifact is unnecessary for survival but is culturally required; (4) The artifact is both physically and culturally unnecessary (albeit probably desirable, or it wouldn't be there). Based on these results, what percentage of your consumption represents unnecessary environmental impact?

2. Technology brings benefits, such as food, home heating, and medications. It also brings potential problems, such as air pollution and ecosystem disruption. Considering your interactions with the products of technology (see Exercise 1) and those of others, what sort and scope of technology's products do you think is appropriate for Earth in the twenty-first century?

3. What are the relationships among industrial ecology, ESEM, and sustainable development?

4. Successful response to the challenge of stratospheric ozone depletion is often given as a model for policy formulation regarding global climate change. Do you think the comparison between the ozone depletion situation and global climate change is valid? Why or why not?

5. You have been selected as the technologist in charge of Everglades engineering and management, with the task of creating a South Florida regional policy that meets the ESEM requirements.

(a) What elements will you involve in your planning process, and why?

(b) How will you monitor the system to determine when relevant changes are occurring, and how will you respond to them?

(c) An important stakeholder demands that the Everglades be returned to the state it was in before Europeans arrived in the New World. How will you respond?

6. You are the technologist in charge of global climate change mitigation for the United Nations. Unexpectedly, global climate change appears to be getting much worse, and you have been asked to recommend one of three geoengineering responses:

1. major iron fertilization of the ocean;

2. installing mirrors in space to reduce incoming radiation; or

3. injection of sulfur particles into the atmosphere.

Analyze your choices using ESEM principles, select the best option of the three, and defend your selection.

Chapter 6 CONSIDERING BIOLOGICAL AND INDUSTRIAL ORGANISMS

6.1. Linking biological ecology and industrial ecology

In both terms the word "ecology" has a reference to biological systems. However, the modern concept of industrial ecology (IE) originated from the idea of conceptualizing human industrial systems from an organismic point of view.

A working definition of biological ecology (BE) is the study of the distribution and abundance of organisms and their interactions with the physical world.

Accordingly, IE can be defined as follows:

Industrial ecology is the study of technological organisms, their use of resources, their potential environmental impacts, and the ways in which their interactions with the natural world could be restructured to enable global sustainability.

IE has an appealing analogy to BE because it encourages the idea of the cycling (i.e., the reuse) of materials.

6.2.Biological organisms

Biological organisms are defined as "entities internally organized to maintain vital activities." These organisms shares several characteristics:

1) Are capable of independent activity.

2) Utilize energy and materials resources. Expend energy to transform materials into new forms suitable for use. They also release waste heat and material residues (excess energy).

3) Are capable of reproduction.

4) Respond to external stimuli (e.g. temperature, humidity, resource availability, potential reproductive partners).

5) All multicellular biological organisms originate as one cell and move through stages of growth.

6) Have a finite lifetime.

6.3. Industrial organisms

The word "organism" does not only refer to living things, but also to industrial activities (e.g. a factory) and theoretical concepts (e.g. "social organisms"), analogous in structure and function to a living thing.

6.3.1. Why the factory meets the criteria of industrial organism?

1) Factories (through their employees) clearly undertake many essentially independent activities on their own behalf: acquisition of resources, transformation of resources, and so forth. **Thus an industrial organism is capable of independent activity**.

2) Factories expend energy for the purpose of transforming materials of various kinds into new forms suitable for use. Energy residues are emitted by industrial organisms into the surroundings, as are material residues (solid waste, liquid waste, gaseous emissions, etc). **Thus industrial organisms use energy and material resources and release waste heat and material residues.**

3) Clearly all factories are constructed not for the purpose of reproduction (re-creating itself), but to create a nonorganismic product (such as a pencil). Generally their aim is not the generation of their more or less exact copies, thus industrial organisms do not meet the precise definition of biological organisms. However, some characteristic of reproduction (multiplication) can be observed in industrial organisms (e.g. construction of similar new factories).

Thus industrial organism's reproduction is not a function of each individual organism itself, but of specialized external actors.

4) Factories relate readily to such external factors as resource availability, potential customers, prices, and so on. **Thus industrial organisms respond to external stimuli.**

5) **Generally all factories move through stages of growth.** Few factories are unchanged during their lifetimes, and are constantly modernized.

6) **All factories have a finite lifetime.**

A factory thus seems to be an appropriate candidate as an industrial organism, since it utilizes energy to transform materials just as does a biological organism.

6.4. Differences between biological and industrial organisms:

* There is no primary producer in the economic system analogous to photosynthesizers.

* In the biosphere there are no products as such.

* In the biosphere there are no markets.

* Biological evolution is driven by random variations, in industry by directed invention.

Nevertheless, the wide acceptance of the term "industrial ecology" has proven that it is more than a convenient label; rather, it is a reflection of similarities that have resulted from explorations of the linkages between fields of study once thought to be completely distinct.

6.5. Examples of Ecosystem Engineering and Industrial Engineering:

The simplest case of true ecosystem engineering (EE) occurs when an organism transforms (or shapes or rearranges) materials into resources useful to other organisms. There is an example of a bird's nest in the muskrat lodge, constructed by the muskrat without the thought of providing such an opportunity for birds. In the similar way industrial engineering (IE) influences the environment.

1) Activities done to maintain organism function but not to manufacture products for others. Examples:

IE: fixing the roof of a factory, or repainting its interior.

EE: rabbits eat grasses.

2) Activities resulting in an alteration in the flows of resources.

Examples:

IE: urban areas alter water flows.

EE: beavers build dams.

3) Activities resulting in the modulation of one or more abiotic forces of nature

IE: urban areas raise regional temperatures which increases cloudiness and precipitation

EE: mussels' colonies protect and stabilize sediments on the seabed

4) Activities influencing major abiotic forces on a global scale

IE: CFC4 emissions create ozone hole.

EE: plankton emit cloud-forming dimethyl sulfide

6.6. Metabolism in biological and industrial organisms

6.6.1.Metabolism in biological organisms

Metabolism is the set of chemical reactions that happen in living organisms to maintain life. These processes allow organisms to grow and reproduce, maintain their structures, and respond to their environments. Metabolism is usually divided into two categories. Catabolism breaks down organic matter, for example to harvest energy in cellular respiration. Anabolism, uses energy to construct components of cells such as proteins and nucleic acids.

The chemical reactions of metabolism are organized into metabolic pathways, in which one chemical is transformed through a series of steps into another chemical, by a sequence of enzymes. Enzymes are crucial to metabolism because they allow organisms to drive desirable reactions that require

4 Chlorofluorocarbon : a class of chemical compounds that deplete ozone.

energy and will not occur by themselves, by coupling them to spontaneous reactions that release energy. As enzymes act as catalysts they allow these reactions to proceed quickly and efficiently. Enzymes also allow the regulation of metabolic pathways in response to changes in the cell's environment or signals from other cells.

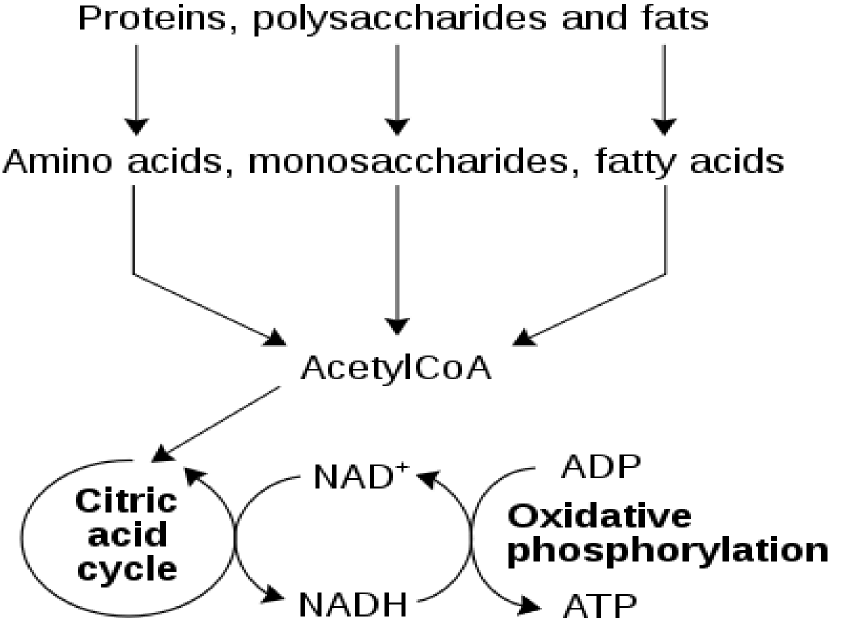

Figure 8. Biological metabolism: a simplified outline of the catabolism of proteins, carbohydrates and fats.

6.6.2. Metabolism in industrial organisms

Just as for all biological organisms, we can analyze the metabolism of an industrial organism (e.g. the factory or corporation). To do so, we need to revise somewhat the definitions of metabolic terminology:

* *Industrial metabolite* is an intermediate product in the transformation of resources into final products. Industrial metabolites can also be termed "parts," "subassemblies," and so on.

* *Industrial enzyme* is an industrial process or piece of equipment that results in a transformation, also termed "reactor," "milling machine," "lathe," and so on. an industrial enzyme may enable a physical transformation (e.g., drilling, shaping) as well as a chemical one.

* *Industrial pathway* is the sequence of transformations that convert resources into final products.

An industrial pathway diagram shares many characteristics with biochemical pathway analysis, as can be seen in Figure 5.4.

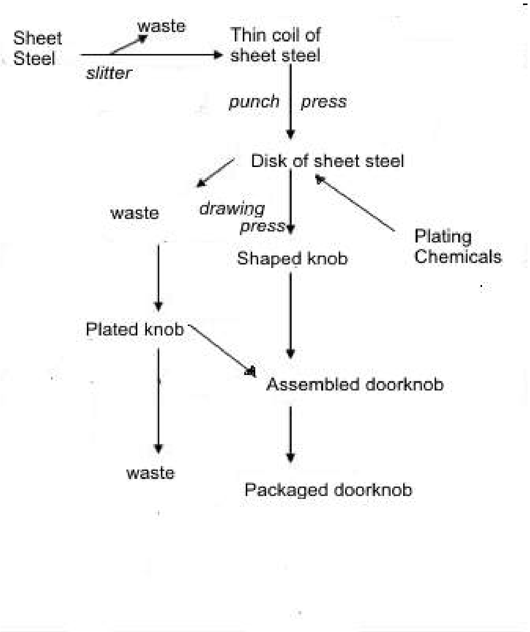

Figure 9. The doorknob cycle. Industrial metabolic reaction pathways, from simple to complex.

In overview, at the top of the figure, steel parts and chemicals enter the facility, and a packaged product emerges. To construct the diagram for a given material one needs to know which process transforms or transports the material and which final products contain the material. To specify the fluxes, one needs to know the mass fluxes of the material inputs, the material concentrations in the inputs, and the details of the transformation process. This information then generates the industrial metabolic diagram which indicates the metabolites, enzymes, and by-products.

EXERCISES:

1 Do you agree that a factory meets the criteria of industrial organism? Why or why not?

2. Besides a factory there are other possible candidate organisms however. Evaluate the following as industrial organisms, compare their characteristics to those of a factory, and determine analogies and differences: a)multinational corporation, b) a city of one million people.

3. Use the information in 6.5 and propose your own examples of IE and EE activities.

4. Use the information in 6.6.2. and draw your own scheme of industrial metabolic reaction pathways for another product.

Chapter 7 ECOSYSTEMS

7.1. Linking biological ecosystem and industrial ecosystem

7.1.1. Biological ecosystem

Biological ecosystem (BE) consists of the interacting parts of the physical and biological worlds. By analogy, an industrial ecosystem consists of the interacting parts of the technological and nontechnological worlds.

The figure below demonstrates the typical interactions among participants in a BE which involve the transfer of resources from one participant to another, or the sharing of resource acquisition or disposal. Such a structure constitutes a food chain.

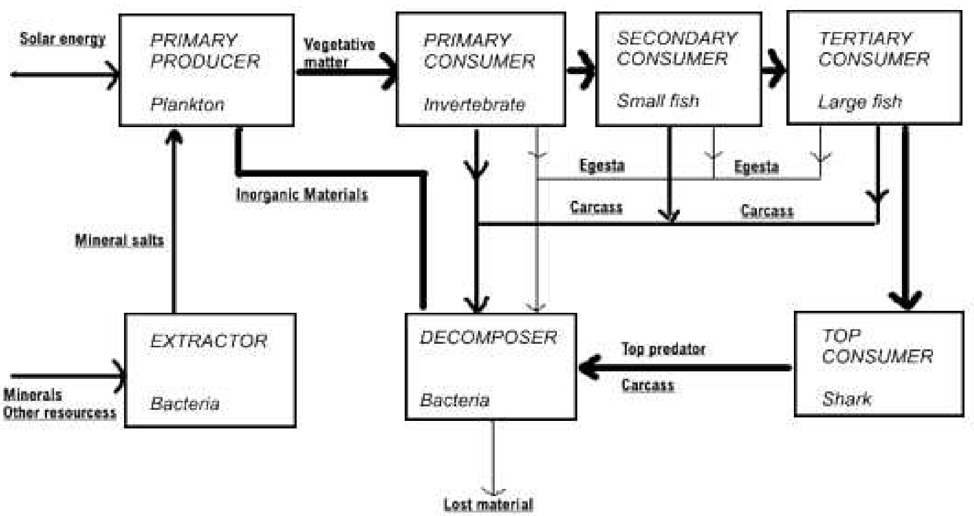

Figure 10. This simplified[5] marine biological food chain consists of the boxes indicating the principal elements of the hierarchy, called "trophic[6] levels". Note that the food chain is not completely sequential: decomposers receive egested material from several trophic levels, for example. Bacteria act as both extractors and decomposers, receiving carbon in one activity, minerals in the other.

The cycle begins with primary producers, who use energy and materials to generate resources usable to higher trophic levels. The final consumer stage is that of the top predator or ultimate consumer. Decomposers return materials to the primary producers, thus completing the cycle. At the bottom of

5 Omnivory is not incorporated into the figure, because it complicates the diagram.

6 from the Greek word for „food"

each box is an example of an organism in an aquatic ecosystem that plays the trophic level role. Types of resources are indicated along the flow arrows.

7.1.2. Industrial ecosystem

It appears that the biological trophic levels and industrial trophic levels can be described with the similar terminology. What are differences between the two ecosystems? Let us compare.

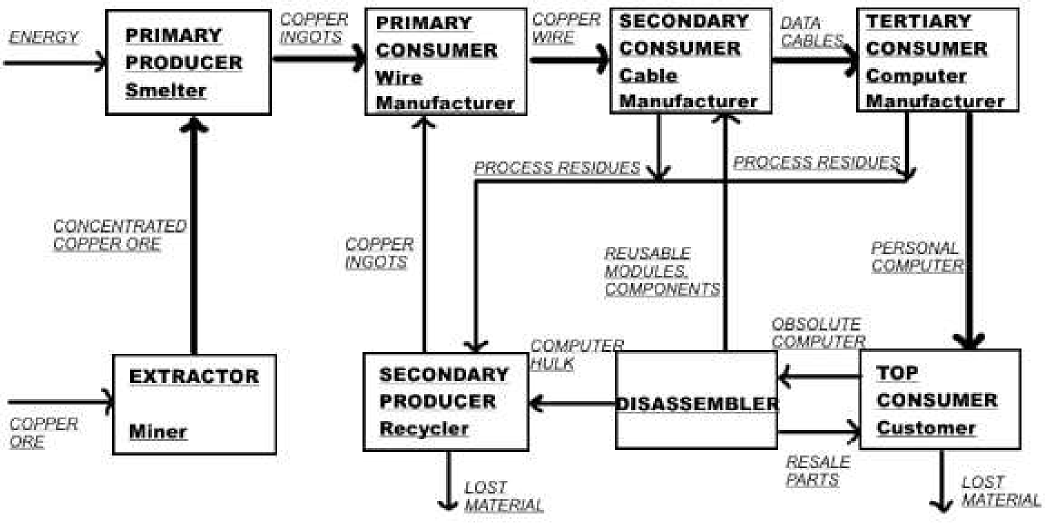

Figure 11. The industrial food chain- the use of copper in personal computers. Examples of organisms that play specific trophic-level role appear at the bottom of each box. The widths of the arrows are very rough indicators of typical relative quantities of materials flow.

The recycler is the IE food chain equivalent of the BE decomposer. Unlike the biological decomposer who furnishes reusable materials to primary producers, recyclers can often return resources one trophic level higher, to primary consumers.

In practice, of course, the system is seldom this prescribed; many recyclers send intermediate materials to the same smelters used for primary production and are thus more like biological decomposers.

The disassembler is an additional actor in the IE food chain. Its goal is to retain resources at high trophic levels, passing as little as possible on to the recycler.

Share of resources from outside. In the industrial food chain a lot of resources is lost. As a consequence, the industrial ecosystem must extract a substantial portion of its resources from outside the system, the biological ecosystem only a small amount.

Speed in adapting to change. If the nutrient supply is restricted or disrupted the industrial organism can quickly develop an alternative nutrient supply (by process or product redesign or by negotiation with new suppliers). The biological species can do the same, but generally over timescales of decades to millennia, rather than days to weeks.

Response to increased need for resources. If conditions become favorable for multiplication (due to a lack of competition, for example) in the IE case extractors and primary producers can generally supply the needed materials, perhaps with lag times of days to a few years.

In the BE case, little capacity exists for substantially increasing the flow of nutrients, and the result is that individual growth and/or population increase does not take place, or does so at the expense of another species.

Approach to initiative. Biological organisms are expert at working within the environment in which they find themselves. In contrast, industrial organisms strive to define the environment for themselves. BE systems are *responders*; IE systems are *initiators*.

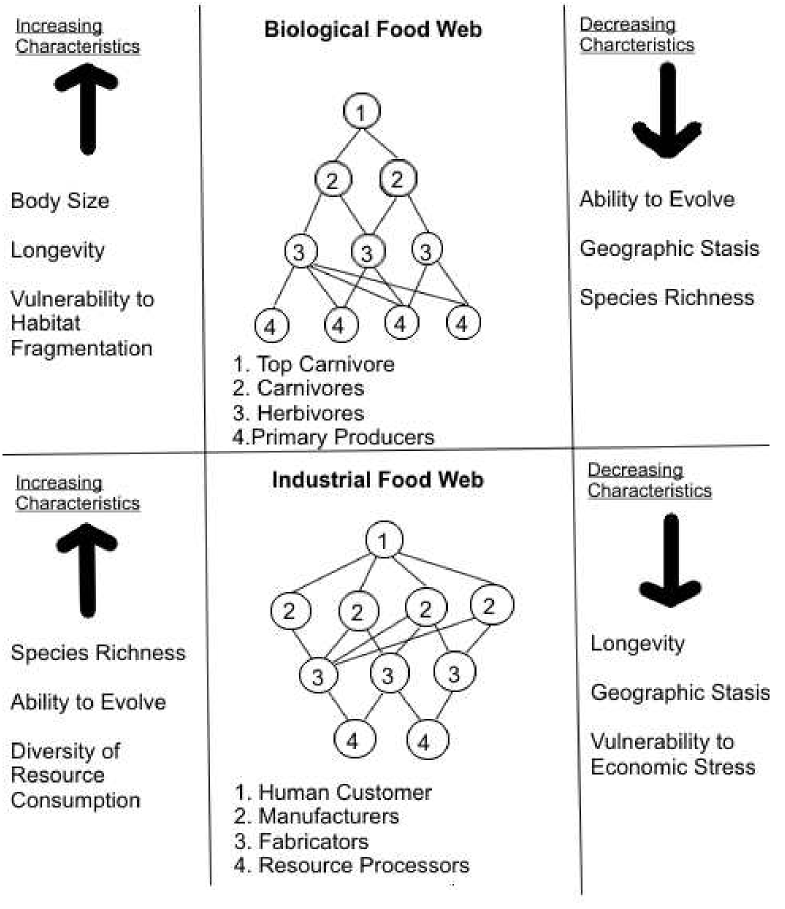

Figure 12. Biological and industrial food webs.

It is instructive to compare the forms and characteristics of typical biological and industrial ecosystems. Those for biological ecosystems tend to have richness, geographic stasis, and the ability to evolve rapidly increasing downward, size, longevity, and vulnerability to habitat fragmentation increasing upward.

In the industrial ecosystem the pyramid is invert. There are few extractors (mining companies, crude oil extractors, etc.), many more fabricators (of rolls of steel, cables of copper, etc.), and many more manufacturers still.

The characteristics tend to follow the inversion of the pyramid in terms of longevity, ability to evolve, vulnerability to stress (economic in this case), and geographic stasis.

The top predator in the industrial system, the human customer, is not a good match for the top predator in biology, because he or she does not transform resources but only receives and "stores" them. Thus, the concept of trophic levels is similar in both ecosystems, but the food webs that result are completely inverse.

7.1.3. Symbiosis in technological systems

Symbiosis is the intimate association of two species, either for the benefit of one of them (parasitic symbiosis) or for both of them (mutualistic symbiosis). It is a frequent situation in BE. However, this concept can be applied as well to technological systems.

Industrial symbiosis (IS) is a process in which the unwanted by-products of one industry become the new materials for another. For example: the sharing of utilities or infrastructure such as wastewater treatment plants, or the joint provisioning of services such as transportation or worker training. IS can develop environmentally superior industrial ecosystems.

Industrial symbiotic systems can be divided into five categories:

1) *Through waste exchanges*.

In these situations, recovered materials are donated or sold to other organizations. A common example is the automobile scrap yard, which recovers and sells automobile components and prepares the bulk metal body and chassis for recycling.

2) *Materials or products are exchanged within a single organization, but among different organizational entities.*

In petrochemical complexes a by-product from one process serves as the feedstock to another.

3) *Exchange among collocated firms in a defined industrial area.*

Corporations or other entities located close together (e.g. in an industrial park) exchange energy, water, materials, and/or services. For example a brewery waste can be used as a resource for mushroom, pig, fish, and vegetable farming.

4) *Exchange among nearby firms not collocated*

For example a number of firms within a 3-km radius exchange steam, heat, fly ash, sulfur, and a number of other resources.

5) Exchange among firms organized across a broader region.

It consists of exchanges across a broad spatial region. In principal, it can incorporate any or all of the types described above. This category (which have not yet been fully realized anywhere) would probably require an active management organization.

Thus industrial symbiotic systems are evolutionary, not static. Simple Category 1 systems can become Category 4 or even Category 5 over time, for example.

7.1.3.1. Making of symbiotic industrial ecosystems

What is evident that industrial ecosystems are not creations of technology; rather they result from the interplay of technology, economics, government, and society. It is this complexity that probably accounts for the difficulty in developing planned ecosystems.

There is debate over whether industrial ecosystems can be planned, but it is clear that existing ecosystems can be discovered. The discovery frequently begins by sharing the acquisition, exchange, or disposal of the most universal of resources—water and energy. Processed water from one facility may be used as cooling water to another, or excess steam in one may provide heat or power to another. Shared construction of a water treatment facility is an often-encountered example.

Industrial ecosystems are in earlier evolutionary states than biological ecosystems, and coherence generally increases as an ecosystem matures.

IE organisms have much broader feeding habits than BE organisms- some desire petrochemicals, some metals, some forest products.

Categories IS have a variable degree of design applicability:

* Category 1 IS would seem not to qualify, because the exchanges are unplanned and episodic.

* Category 2 IS probably fails as well, because symbiosis involves more than a single actor and is not preplanned.

7.1.3.2. Drivers for and barriers to industrial ecosystems

Drivers:

1) <u>Financial opportunities</u>

Most IS exchanges make good business sense in terms of lower input costs, lower operating costs, and/or increased revenues.

2) <u>Resource scarcity</u>

Water is the most common example.

3) <u>Reduced liability</u>

Potentially problematic discards or by-products that are exchanged become the responsibility of others.

4) Sustainability focus

Industrial symbiosis is a natural component of increasing corporate attention to sustainability.

5) Staff Mobility

Technically trained people moving from one facility to another, especially in a different industry, . often see symbiotic opportunities not visible to others.

Barriers:

1) Informational

A lack of understanding of the process inputs and outputs of potential symbionts often inhibits exchange possibilities.

2) Economic

Exchanges or joint approaches to acquisition or disposal may carry with them excessive economic costs.

3) Technical

The set of potential symbionts may not "fit together" so far as inputs and outputs are concerned.

4) Regulatory

In some cases, regulations may prevent or inhibit the exchange of potentially hazardous resources.

5) Motivational

Firms, regulators, and others must be willing to commit to symbiotic relationships

Notwithstanding all of the above, industrial ecosystems can be fragile. One of the symbionts may go out of business, or a resource flow valued by one symbiont may no longer be produced by another, or a symbiosis champion may retire without a suitable successor on hand. When they succeed, however, industrial ecosystems are financially beneficial, environmentally sound, and socially satisfactory.

EXERCISES:

1. Select a local industrial park for study and identify the principal input and output flows. Determine any existing "green twinning" relationships and propose others for consideration.

Chapter 8 URBAN METABOLISM

We understand plants and animals in part because their metabolic information allows us to understand the functioning of those organisms. The same potential holds true for studies of urban physical metabolisms. It will allow researchers and policy makers to examine what (and how much) enters a city, how long it is retained, and when and how it is discarded. This information has potential for informing discussions of resource availability, recycling, energy use, and environmental impact. It could enable the comparison of one city's performance with that of another, or with itself over time.

A comprehensive characterization of urban metabolism includes the need to measure not only the combined flows of all forms of materials, but the flows of each form. This is crucial because for recycling and reuse purposes the viability of the stock of a material generally depends on the efficiency with which it can be recovered.

As with any organism, a city's metabolism is characterized by the quantities of flows of resources, their distribution throughout the organism, and the dynamic nature of the flows.

8.1.Urban organisms

Cities can be compared to biological organisms. They are born; they grow; and they utilize resources from various sources e.g. apples from New Zealand, electronics from Japan, automobiles from Germany, leather from Argentina, lobsters from the United States. Cities also dissipate resources after use, sometimes to the local air and water, often to landfills, generally close to home. Cities are accomplished attracters and poor dispersers.

8.1.1. The metabolic cycle of biological organisms

The metabolic cycle of biological organisms consists of 3 phases:

* ingestion (I)

* assimilation of the ingested material. Some is not utilized at all (NU), the remainder (the assimilated portion), consists of two parts: that devoted to respiration (R), thus providing energy for the organism, and that devoted to the maintenance and growth of the organism's parts.

* egestion (E)

The change in mass (M) of the biological organism (its growth) is given by

$\Delta M = I — E — R — NU$

8.1.2. The metabolic cycle of urban organisms

A city can be regarded as an industrial ecology organism. Thus, the urban metabolic analysis consists of the knowledge about the uses and fates of "urban nutrients" —their rates of flow, their degree of spatial concentration, their modes of loss, their potential for reuse.

The metabolic cycle of urban organisms consists of 3 phases as well:

* ingestion (I) (of crushed stone, diesel fuel, coffee makers, etc.)

* assimilation of the ingested material. The assimilated material, as with the organismal analog, is of two parts. One is the energy sources—coal, fuel oil, natural gas—that provide energy to the urban system and generate respiratory products such as carbon dioxide. The second consists of the materials and products that enable our modern technological world to function.

* egestion (E) (of garbage, discarded cellular telephones, etc.).

* "hidden flows" (H); these represent the mobilization of waste rock and soil and the use of energy in the generation of the urban nutrients. These flows occur away from the city and so are hidden from it, but are properly chargeable to it.

The change in mass (M) of the urban organism with time is given by

$\Delta M = I — E — R$

The difference between this formula and that for natural organisms is that there is no "not used" portion, and secondly, there are “hidden flows” of materials and energy.

A biological organism's metabolic flow consists largely of organic matter (which is often expressed in energy terms) and water. The flows connected to a city are much more complex. They include five components at minimum: nutrients, materials, water, energy, and dissipative flows, but these categories can be disaggregated considerably for various purposes. Nutrients can be subdivided into many food types, for example, and materials into a diversity of product groupings.

The urban metabolism concentrates on resource consumption and waste generation. This is linked to the population’s growth, the per capita consumption of food, water, and materials, total air emissions, CO_2 outputs, municipal solid waste, and sewage. Therefore major investments in infrastructure are required in order to sustain these increased flows without major environmental and human health consequences.

8.1.2.1. Urban resources recovery

People are located increasingly in cities. In consequence, materials in urban use present a potentially attractive opportunity for resource recovery.

The specter of the exhaustion of the resources seems increasingly possible, although it is difficult to predict the epoch in which exhaustion (or at least scarcity) of virgin geological resources will occur.

In-use stock is discarded only when it no longer has utility for the owner, and this occurs after quite different lengths of service, depending on the product. “Urban-oriented recycling," has a number of specific benefits for society. These include

* Mitigating problems of resource depletion by providing an alternative source

* Avoiding (for recycled materials) the environmental impacts of mining

* Saving energy

* Saving water

The practical requirements for implementing the extensive recycling in cities are as follows:

* An accurate determination of in-use stocks of urban materials, good estimates of the discard flow rates as a function of time, and specification of the physical and chemical forms of the discards

* An accurate determination of the spatial distributions of the urban stocks

* The design of buildings, equipment, and products of all kinds so as to facilitate disassembly and reuse

* A system of efficient collection and sorting of discards

* The provision of incentives, monetary or otherwise, for material reuse

This situation can approach sustainability only as the total annual requirements for materials approach constancy.

8.2. Creating industrial ecology scenarios

They are mechanisms to predict complex systems’ future behavior , and to understand them, and prepare potential responses. In industrial ecology, scenarios provide the inspiration for the development of corporate and governmental policy involving technology, society, and the environment. Scenarios foresee possible futures. Scenarios have long been used by corporations, military organizations, and many others.

Most conceptual scenarios are forward-looking, and need not to be complex. They might be as simple as "Suppose the price of one of the principal materials used to make our products doubles in price—what are our options?"

In practice, scenarios that are most useful are fairly detailed, and every feature is examined carefully to make sure it is potentially realistic. A common approach is to construct a mathematical model of the present or the past, in order to get an appreciation of the details of the system under study, and then develop the scenario(s) from that framework.

Scenarios can be divided in another way as well. Some treat evolutionary situations such as the gradual change in climate and ecosystems resulting from the emissions of greenhouse gases. Others are directed to disruptive events, such as the consequences of a national disaster.

Scenarios offer the opportunity to perform experiments on paper or with a computer, rather than in real life. They have the potential to provide very much improved perspective on issues of importance and to give a framework for the consequences of impulsive and disruptive events of various kinds. One can readily imagine industrial ,ecology scenarios addressing such topics as:

* The future of metal use given decision choices on individual products by potential customers

* Changes in energy use

* The development of ecoindustrial parks

* Industrial relationships over time given a changing water cycle

*And many others

Despite this promise, industrial ecology scenarios present substantial challenges in scope, data availability, and implementation. This is especially true with Class 2 and Class 3 scenarios. Nonetheless, here are evidence that the development of industrial ecology scenarios has begun and will continue to be an important part of the science in the future.

8.2.1. Developing a scenario

Because good scenarios generally rest on a foundation of reliable information, industrial ecologists did not really consider scenario building until they had generated such a foundation by extensive field work, data mining, and so forth.

In developing a scenario the first task is to determine the project goal.

In the world of science, the goal is one of exploration, to investigate how a holarchic system might change over time.

In the world of business, the goal is to be decision support, to provide enhanced perspective on a potential situation.

In the world of policy, the goal is a hybrid of these two, as policy makers seek options that respond to changing conditions while meeting political constraints and practical limitations. Industrial ecology scenarios might have any of these aims.

Process design depends on the project goals and on the availability of information. The task here is to determine what information is needed in order to get a solid footing for a future scenario - the current price of oil, for example. If social or cultural features are to be included, methods for developing that information must be characterized as well.

The final topic is scenario content—the timescale, the exact nature of the variables, the level of integration, and so forth. This stage is where a decision would be made as to how many scenario variations are desired and how multidisciplinary the scenarios will be. This last attribute establishes the industrial ecology scenario class.

EXERCISES

1. Is the movement of people from rural to urban locales positive or negative for the environment? Why?

2. Some cities around the world refer to themselves as "sustainable cities." If you were mayor of one of them, how could you justify this appellation?

3. Develop three scenarios for the next three decades for the geographical region of which you are a part. (You may choose the scale, but no larger than national.) What are the characteristics of your scenarios? What governmental policies might be suggested, and when should they be considered?

4. Repeat Exercise 3, but for a multinational manufacturing firm instead of a government.

Chapter 9 IMPLEMENTATION OF GREEN ENGINEERING

9.1.Green Engineering

Green engineering (GE) is the design and implementation of engineering solutions that take environmental issues into account throughout the life cycle of the design. This implementation can take place wherever engineers are transforming materials and using energy.

Green engineering has its set of 12 principles

1) Designers should ensure that all material and energy inputs and outputs are as nonhazardous as possible.

2) It is better to prevent waste formation than to treat it after it is formed.

3) Separation and purification operations should be designed to minimize energy consumption and materials use.

4) Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.

5) Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.

6) Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.

7) Targeted durability, not immortality, should be a design goal.

8) Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.

9) Material diversity in multicomponent products should be minimized so as to promote disassembly and value retention.

10) Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.

11) Products, processes, and systems should be designed for performance in a commercial "afterlife." a Material and energy inputs should be renewable rather than depleting.

Engineering is a diverse profession which operates at many different levels:

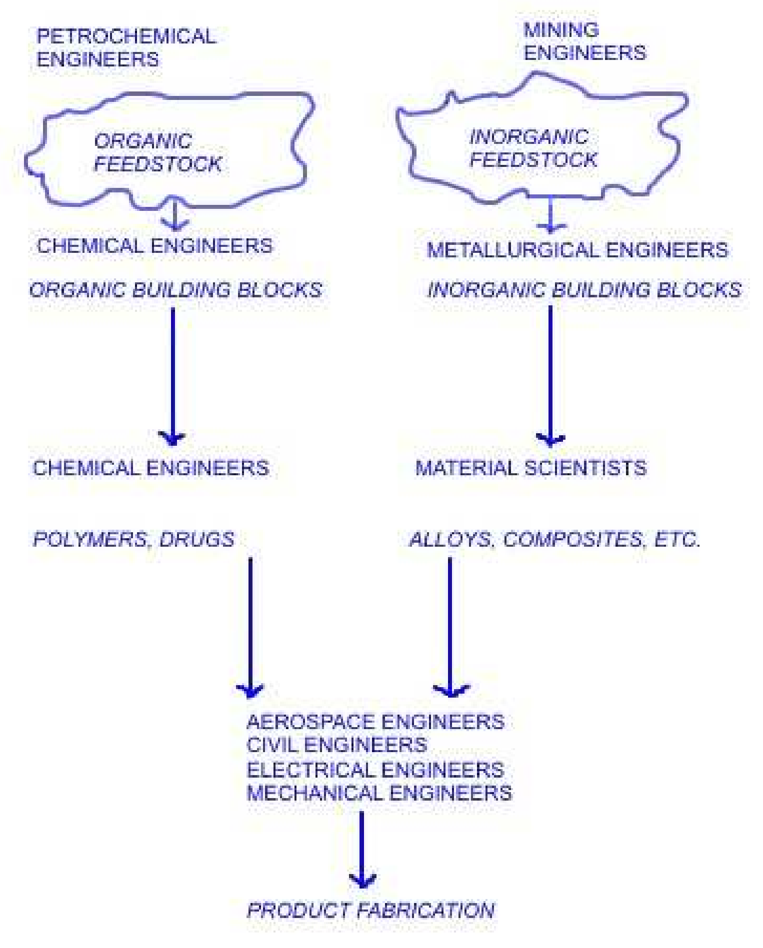

Figure 13. Different levels of engineering and their interrelations.

It is worth noting that the products of these engineering specialties have quite different typical lifetimes: 2-5 years for electrical engineers (e.g., cellular telephones), 5-15 years for mechanical engineers (e.g., automobiles), 10-30 years for aerospace engineers (e.g., helicopters), 15-50 years for civil engineers (e.g., bridges and buildings). These time bands are generalities but they suggest that in her or his career an electrical engineer gets many more opportunities to create fresh designs than does a civil engineer, has more opportunities to employ new materials and new concepts, and has more chances

9.2. Modification of industrial processes

The industrial processes needed to accomplish manufacture constitute a sequence of operations designed to achieve a specific technological result, such as the manufacture of a telephone from metallic and polymeric starting materials. Typical goals for an industrial process designer have traditionally included the following:

*Accomplish the desired technological result.

*Achieve high precision by manufacturing products that consistently fall within desired tolerance limits.

*Achieve high efficiency by manufacturing products in a minimum amount of time.

*Design a process for high reliability over a long period of time.

*Make the process safe for the workers who will use it.

*Design the process to be modular and upgradable.

*Design for minimum first cost (equipment purchase and installation).

*Design for minimum operating cost.

Sustainable engineering imposes on the process designer several additional goals:

*Prevent pollution.

*Reduce risk to the environment.

*Perform process design from a life cycle perspective.

It is seldom that each of these goals can be optimized independently. Rather, the aim is to achieve the optimum balance among the goals.

9.2.1. Pollution prevention

Pollution prevention or "cleaner production" is the main goal of green engineering. The objective of this activity is to reduce impacts or risk of impacts to employees, local communities, and the environment at large by preventing pollution where it is first generated.

The sequence to accomplish this goals is:

*identification of a problem or potential problem, *location of its source within the manufacturing process,

*changing of the source so as to reduce or eliminate the problem.

Process evaluation deals with sequence flow, the consumption of materials, energy, water, and other resources; the manufacture of desired products; and the identification and quantification of residues.

After evaluation, the techniques are as follows:

1) Process modification—changing a process to minimize or eliminate waste generation

2) Technology modification—changing manufacturing technology to minimize or eliminate waste generation

3) Good housekeeping— changing routine maintenance or operation routine to minimize or eliminate waste generation

4) Input substitution—changing process materials to minimize quantity or potential risk of generated waste

5) On-site reuse—recycling residues within the facility

6) Off-site reuse—recycling residues away from the original facility

With the target identified and its flows determined green engineering approaches can be employed in a straightforward manner:

*Redesign the process to substitute low toxicity materials for those that are highly toxic, or to generate high toxicity materials on-site as needed.

*Minimize process residues.

*Reuse process residues.

*Redesign the process so that unwanted residue streams become streams of useful by-products.

In the case of a process already existing or newly begun, a *waste audit* is generally useful. The approach is to study all waste flows from the facility to determine which can be decreased, and how. Industrial solvents, cleaning solutions, and etchants are often good places to begin. An approach that has proven beneficial in a number of cases is the regeneration of chemical solutions, which can often be accomplished by filtration, changes to relax purity requirements, the addition of stabilizers, redesign of process equipment, and so on.

9.2.2. The life cycle of industrial processes

Industrial processes have life cycles, and green engineering approaches should treat all stage of those cycles. The process cycle is comprised of three epochs (Figure 8.6): resource provisioning and process implementation occur simultaneously; primary process operation and complementary process operation occur simultaneously as well; and refurbishment, recycling, and disposal is the end-of-life stage. The characteristics of these stages are described below.

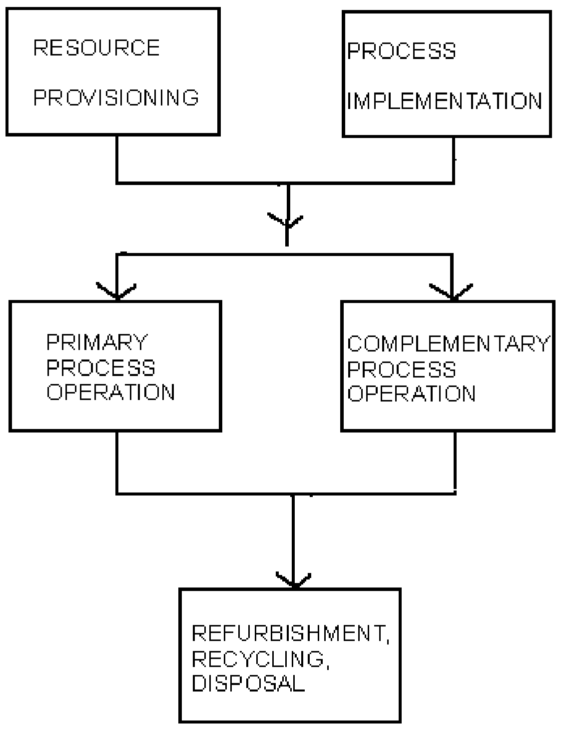

Figure 14. Stages of industrial processes.

9.2.2.1 Resource provisioning

The first stage in the life cycle of any process is the provisioning of the materials used to produce the consumable resources.

Green engineering approaches:

* The source of the materials: instead of materials extracted from their natural reservoirs (virgin materials), recycled materials should be used.

* The methods used to prepare the materials for use in the process (supplier operations, development and implementation of this process). This should be done be done in an environmentally responsible manner.

Activities coincident with resource provisioning. These principally involve the manufacture and installation of the process equipment and installing other resources that are required such as piping, conveyer belts, exhaust ducts, and the like.

9.2.2.2. Primary process operation

A process should be designed to be environmentally responsible in operation. Ideal target is that every molecule that enters a manufacturing process should leave that process as part of a salable product. Such a process would ideally limit the use of hazardous materials; minimize the consumption of energy; avoid or minimize the generation of solid, liquid, or gaseous residues; and ensure that any residues that are produced can be used elsewhere in the economy.

9.2.2.3. Complementary process operation

A comprehensive process evaluation needs to consider not only the environmental attributes of the primary process itself, but also those of the complementary processes that precede and follow. The responsible primary process designer will consider to what extent his or her process imposes environmentally difficult requirements for complementary processes, both in their implementation and their operation.

For example, a process of metal cleaning traditionally required the use of ozone-depleting chlorofluorocarbons. Changes in any element of this system—flux, solder, or solvent—usually require changes to the others as well if the entire system is to continue to perform satisfactorily.

9.2.2.4. Refurbishment, recycling, disposal

All process equipment will eventually become obsolete. It must therefore be designed so as to optimize disassembly and reuse, either of modules (the preferable option)-or materials.

The process designer can control or discourage many environmentally responsible equipment recycling actions by his or her choice of features.

9.3. Requirements of green technology

In the case of technology, there are three overarching requirements:

a) Substances extracted from the lithosphere must not systematically accumulate in the ecosphere.

b) Society-produced substances must not systematically accumulate in the ecosphere.

c) The physical conditions for production and diversity within the ecosphere must not become systematically deteriorated.

9.4. Industrial ecology models

Models are necessary for efficient Green Engineering. A model is a representation or description designed to show the structure or operation of an object or a system. Thus, a model represents the components of the object or system of interest, and the potential for interaction among the components. Models require data which are very often limited.

9.4.1. Realization of models in industrial ecology

Such models typically take one of three forms: system dynamics, programming, or agent-based modeling. In all cases, the system of interest is defined by the mathematical relationships linking the exogenous and endogenous variables. In system dynamics case, the goal is to solve a set of equations of the form:

$e_i = F_i(x_1, x_2,\ldots,x_n)$

where no limits are placed on the form of F. In most cases in industrial ecology, however, the equations are linear.

The goal in linear programming, a technique often employed in economic models, is to, maximize a linear function whose variables are required to satisfy a system linear constraints, that is,

$z = F(x_1, x_2,\ldots,x_n)$

Where

$a_i, x_1 + a_i, 2x_2 \ldots + a_{i,n}x_n \leq b_i$

and z is the quantity to be maximized.

In the case of agent-based models, the equations in the form: $e_i = F_i(x_1, x_2,\ldots,x_n)$ represent the sums of decisions made by individual agents, who might be potential customers for a specific product, managers deciding whether to build a new facility, or automobile owners deciding when to discard their vehicle and replace it.

The mathematical functions are thus the probabilities that certain decisions will be made.

9.4.2. Model validation

How do we know whether model results are valid? A validated model does not contain known or detectable flaws and is internally consistent.

That is not to say that the model results perfectly reflect the real world. However, a model might generate results that are reasonable and useful on one spatial or temporal scale, but not at another. Depending on the purpose of the model, such performance may be perfectly satisfactory. Models are representations, useful for guiding further study but not a proof.

The typical output of a model consists of computed values for a number of dependent variables. Ideally, these results are compared with actual data for conditions similar to those simulated by the model. In our example, one might investigate whether the actual flows of lead scrap are consistent with the model results. If so, an initial measure of confidence is provided.

If the model fails to reproduce the data then the model is faulty in some way, and studying those discrepancies often provides clues to increased understanding.

Finally, the model can be used to make a prediction (e.g., lead recycling in 2010), and the prediction evaluated by actual measurement.

When a large number of such steps have been carried out, more or less successfully, the model is said to have been validated. The model results can then be regarded as likely to be good representations of the actual situation.

9.4.3. Role of models

Models can corroborate a hypothesis by offering evidence to strengthen what may be already partly established through other means. Models can elucidate discrepancies in other models. Models can be also be used for sensitivity analysis—for exploring "what if" questions— thereby illuminating which aspects of the system are most in need of further study, and where more empirical data are most needed.

9.4.4. Types of conceptual models

Definitions of terms related to model building and data acquisition term:

1) Scales -the spatial, temporal, quantitative, or analytical dimensions used to measure and study an object or process of interest.

2) Extent - the size of a scale dimension.

3) Resolution - the precision used in measurement.

4) Levels - the units of analysis that are located in the same position on a scale. Many conceptual scales contain levels that are ordered hierarchically, but not all levels are necessarily linked to one another in a hierarchical system.

9.4.4.1. The Class 1 Industrial Ecology Model

Ideally, a model is realized in a sequential process, initiated by defining the question we wish the model to answer. The first step, for example, is to ask: "What fraction of lead in discarded computers in Country A was recycled in year 2000 within the country?"

Answering the question requires only two pieces of information: how much lead was discarded in computers in year 2000, and how much of it entered the recycling stream.

In practice, we may instead know how many computers were discarded but not their lead content, and we may know how much lead was recycled in the country but not how much of it came from computers. Nonetheless, the answer to this question could be of interest for any of a number of reasons: (1) a lead recycler in another country wants to evaluate a business opportunity; (2) an environmental organization wants to estimate damage from lead loss; (3) computer manufacturers want to understand their potential liability, and so on. We thus have identified a question whose answer requires a model.

The second step in model building is that of “scale”. In our example, four scales are required: the number of discarded computers, the lead content ,of the computers, the number of computers recycled, and the total lead recycling flow.

Next, we consider the extent of the information. In all cases it is for year 2000 and, if available, for the country as a whole. The number of computers discarded and recycled is straightforward as to extent, as is the total recycling flow. However, computers are made by different manufactures and have differing lead contents. It is unrealistic to determine the elemental composition of every computer, so a decision on extent is required—perhaps to take the average lead content of computers made by the top four manufacturers from 1993 to 1997 (the approximate manufacturing period for computers discarded in 2000).

The resolution relates to how accurately we need to know the information we seek. This decision often has major implications for the time required to gather and verify the information. In the present case, we may choose to be satisfied with lead content figures and computer counts with estimated uncertainties of 20 percent.

A further consideration is of the level from which information is needed. In our example, the entire country is the desired level because that corresponds precisely to the question.

With the decision regarding level having been made, our conceptual model is complete. The analytical model is then constructed by defining the mathematical relationships among the data entities (e.g., discarded lead equals number of discarded computers multiplied by the average lead content).

The model described above is a Class 1 model, because it directly addresses only the technological aspects of lead use.

9.4.4.2. The Class 2 Industrial Ecology Model

Such models are an expansion of the Class 1 model, and answer broader questions, such as: "What are the environmental impacts of the human use of lead in Country A in 2000?"

First, we are asked to consider all the ways in which humans use lead, not just in computers, and we asked a detailed environmental question as well .

Then we decide to address lead toxicity in humans and animals, rather than all possible lead impacts. We then consider scale and immediately realize that people and animals are not distributed uniformly in Country A, nor are lead emissions, so the model must have two spatial dimensions.

The scales for which spatially resolved information will be needed are: (1) human population, (2) animal population, (3) lead emissions.

We also need nonspatial information on two other scales: lead sensitivity of humans and lead sensitivity of animals. And, of course, we need to retain the scales from the computer-centered Class 1 model we described earlier.

There will be questions of extent (what is the minimal lead concentration to be considered), of resolution (what spatial resolution is required, and are data available at that resolution), of exposure (are dose-response data available), and perhaps of level (can lead from gasoline be considered on anything but a regional basis and can animal toxicity be considered on anything but a patch basis).

9.4.4.3. The Class 3 Industrial Ecology Model

Such models address an additional set of scale dimension, answering still broader questions, such as: "How do human choices produce the environmental impacts of lead in Country A in 2000?" Here the question retains the features that were addressed by the Class 1 and Class 2 models, but the addition of the human element elevates the challenge to that of a Class 3 model. These models require detailed interdisciplinary knowledge of technological implications, human dynamics, and environmental processes.

We must now address an additional dimensions: the human choice of how much to drive, how much lead paint to use, and whether to buy a computer with a (leaded) cathode ray tube display or a (lead-free) liquid crystal display, for example. Extent issues may emerge as well (sampling only a portion of the population), as do those of resolution (state or neighborhood) and level (educational level of the responders).

With the entry of human behavior into the picture, the mathematical model must add stochastic[7] aspects. This is generally done with "agent-based models," in which each decision maker (the agent) is given a certain probability of making a decision.

This approach recognizes that different agents aim for different goals and so do not necessarily make the same decisions, yet interact directly by sharing information and services and indirectly by sharing the resources of the system. The model creates an assembly of agents, their interactions, and connections between those interactions, their associated technologies, and the environment.

9.5. Sociological aspects of green engineering

Green engineering as complex and interdisciplinary domain should consider sociological aspects as well:

a) At the *micro* level (the individual):

* What do people really need?

---

7 Stochastic means random

* Why do we want so much these days?

* How can people get what they need without so much stuff?

b) At the *meso* level (the firm):

* How can products be designed to minimize resource closure problems?

* What can firms do to produce authentic but dematerialized satisfaction?

* How can firms understand their roles in the holarchic systems within which they function?

c) At the macro level (society):

* How far can ecoefficiency take us before absolute limits set in?

* What are the regulatory, economic, and institutional barriers to improving humanity's path to sustainability?

* How can industrial ecology develop optimal solutions in technologies related to sustainable development?

* Where are the most opportunistic power points for improving humanity's path to sustainability?

These are interdisciplinary topics in which progress will only be made by groups of colleagues willing to cross disciplinary boundaries.

It is clear that for engineering and technology the scope of the environmentally related approaches are the following:

* Not looking to the past, but to the future

* Not fragmented, but systemic

* Emphasizing not gross insults, but microtoxicity

* From focusing on environmental improvement to focusing on sustainability

These approaches need to consider a dramatic increase in global population and an equally vigorous reliance on technology. Our upcoming planetary population, the majority of which will live in urban areas, is likely to have increased income and thus increased demands for resources (or the services thereof). Five features will characterize this societal evolution:

* Not local, but global

* Not pastoral, but urban

* Not isolated, but connected

* Not more technology, but better technology

* Not emphasizing the developed world, but the developing world

The twentieth century has turned out to be one of major anthropogenic change on the planet on which we live. The twenty-first century must be one in which we do better —measuring our every action against its impacts on the environment, on society, and on sustainability. It is the supreme challenge to the human species, and one in which industrial ecology and sustainable engineering must be the enablers.

EXERCISES:

1. Which of the twelve principles of green engineering seem to you to be the most important? Why?

2. You are the industrial ecologist for a manufacturing company whose leading product is cables for personal computers. The principal components of the cable are copper wire, flexible plastic wire coating, and rigid plastic connectors. What by-product or residue streams do you anticipate? About which should you be most concerned?

3. Choose a manufacturing process, historic or modern, about which you can locate considerable detail concerning a specific industrial facility. Evaluate the process, pointing out its strengths and weaknesses from an industrial ecology standpoint.

4. Develop a detailed conceptual model for the operation of a toaster. What question do you wish to answer with your model? What is the model's class? Discuss issues of scale, extent, resolution, and level. Diagram your model.

5. What industrial ecology model class is each of the following? Why?

- Characterizing the Japanese annual cycle of tin.
- Describing the chemistry of the Antarctic ozone hole.
- Understanding human demand for water in Arizona, the way in which water is provided, and the environmental implications of doing so.
- Quantifying the environmental effects of zinc ore extraction and refining.

6. It has been proposed that catastrophes related to the environment and sustainability may be likely in the next few decades. They could occur at a variety of levels, for example:

- Personal—$3/liter gasoline
- Corporate-unavailability of a principal raw material
- City/Country—uncertain water supplies
- Planet—ecosystem failures

Prepare a story line for a catastrophic challenge of your own choice at less than planetary level and devise a coherent industrial ecology-oriented set of response options.

Chapter 10 DESIGN FOR ENVIRONMENT

Design for Environment (DfE) is a crucial component of a more responsible society, and this requires detailed consideration of the entire life cycle of each product.

10.1. The life cycle of industrial products

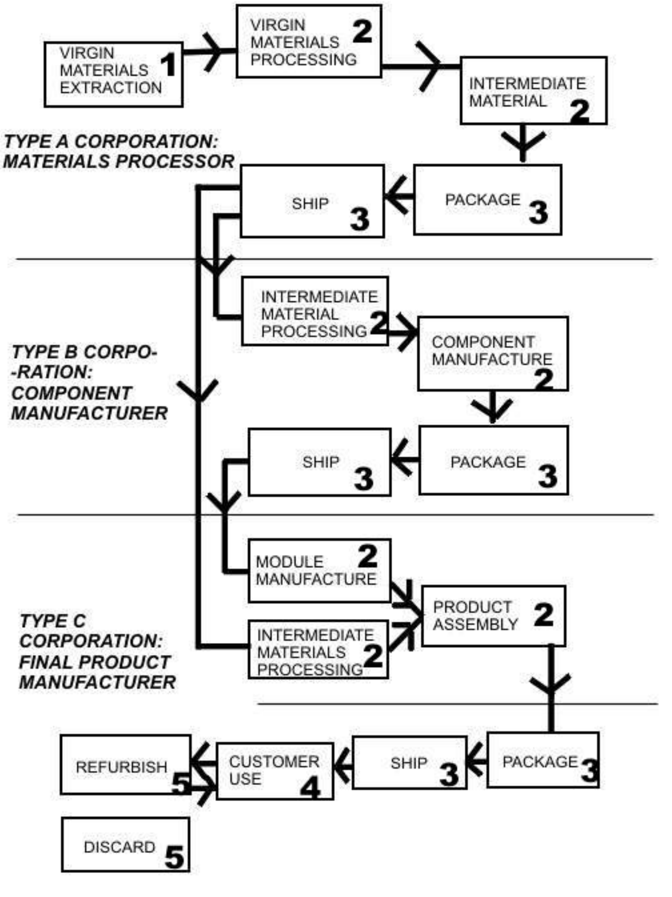

Figure 15. The life cycle of industrial products

There is pictured above the interrelationship of product life stages. Three different types of manufacture are illustrated:

Type A Corporation: the production of intermediate materials from raw materials (e.g., plastic pellets from petroleum feedstock or rolls of paper from bales of recycled mixed paper),

Type B Corporation: the production of components from intermediate materials (e.g. snap fasteners from steel stock or colored fabric from cotton),

Type C Corporation: the processing of intermediate materials (e.g., cotton fabric) or the assembly of processed materials (e.g., plastic housings) into final products (e.g., shirts or tape recorders). In Type C the design and manufacturing team has total control over all product life stages except Stage 1.

Stage 1, Premanufacture: the concept of this life stage is identical for corporations of Types A, B, and C (unless a Type A corporation is the actual materials extractor).

Stage 2, Manufacture: the concept of this life stage is identical for corporations of Types A, B, and C.

Stage 3, Product Delivery: the concept of this life stage is identical for corporations of Types A, B, and C.

Stage 4, Product Use: for Type A corporations, product use is essentially controlled by the Type B or C receiving corporation

For Type B corporations, their products can sometimes have direct influence on the in-use stage of the Type C corporation final product, as with energy use by cooling fans or lubricant requirements for bearings.

Stage 5, Refurbishment, Recycling, or Disposal: the properties of intermediate materials manufactured by Type A corporations can often determine the potential for recyclability of the final product. For example, a number of plastics are now formulated with the goal of optimizing recyclability.

For Type B corporations, the approach depends on the complexity of the component being manufactured (component or module).

Thus, for Type A, B, and C corporations the considerations of the first three life stages are, in principle, completely under their control.

For the last two life stages, the products of Type A and B corporations are influenced by the Type C corporation, with which they deal and, in turn, their products influence the life stages 4 and 5 characteristics of Type C products.

10.2. Guidelines for DfE

1) Minimize or avoid hazardous substances, and utilize closed loops for necessary but hazardous constituents.

2) Minimize materials diversity.

3) Minimize energy and resource consumption in the production phase.

4) Use structural features and high-quality materials to minimize product weight.

5) Employ recycled materials and recycled parts whenever possible.

6) Package products in an environmentally sound manner.

7) Minimize energy requirements and resource consumption and dissipation in the use phase.

8) Choose materials, surface treatments, and structural arrangements to enhance product life.

9) Encourage upgrading, repair, remanufacturing, and recycling through accessibility, labeling, modules, breakage points, and manuals.

10) Design for disassembly by using as few joining elements as possible and emphasizing screws, snap fits, and geometric locking.

11) Avoid material combinations that require time and otherwise unnecessary separation at the recycling stage.

10.3. What are “ecomaterials”?

Materials influence the functioning of a product, its ruggedness, its appearance, and numerous other characteristics. In many cases any of a number of different materials could be chosen for a particular application. The initial considerations of the product designer are obvious and important:

*Does the material have the desired physical properties (strength, conductivity, index of refraction, etc.)?

*Does the material have the desired chemical properties (solubility, photosensitivity, reactivity, etc.)?

*Is the cost reasonable?

However, the designer should also pay attention to a number of additional materials considerations related to sustainable engineering:

10.3.1. Materials choices

They are often limited by toxicity concerns. A designer's objective should be to select materials that have the least significant potential risk. Government environmental agencies generally define those materials that merit concern from a toxicity standpoint, and their lists are a good starting point for the physical designer. Most of these materials have also been restricted by the European Union and other governmental bodies. The list includes both product chemicals and process chemicals: cadmium, chromium, lead, nickel, and their compounds, chlorinated solvents and monoaromatic species, cyanide solutions etc.

The most widespread and important legislative approach to challenges of toxicity is the European Union's REACH (Registration, Evaluation, and Authorisation of Chemicals) program. This action, which came into force on June 1, 2007, requires that chemicals manufactured in quantities greater than 1 metric ton must be registered, those manufactured in quantities greater than 100 metric tons be evaluated for toxicity, and those of high concern (such as carcinogens or mutagens) must be specially authorized for use. Downstream users of the chemicals are involved as well as those who make the chemicals. REACH has made it much more difficult and expensive to utilize previously unauthorized materials and provides a substantial incentive for attempts to meet design criteria without utilizing problematic new materials or new material combinations.

10.4. The prospect of resource scarcity

The modern technology could not exist without renewable and nonrenewable resources. Nonetheless, the availability of these resources has seldom been a matter of much concern, especially for a produce designer. The result is nuclear reactor dependent on the availability of zirconium, catalytic converters dependent on the availability of rhodium, hybrid vehicle batteries dependent on the availability of lanthanum, cellular telephones dependent on the availability of tantalum. Manufacture and use of many other products assume the availability of energy and water in abundance. However, we should be conscious that at least some specific resources may become quite scarce in the years to come.

Designers need to be aware, especially when designing products such as buildings or infrastructure that have very long lifetimes, of the prospect of resource scarcity. A number of materials are available only from a few repositories in nature, are often acquired only as by-products of parent materials, and lack efficient recycling networks. Designers should avoid using any of these "materials of concern"; if they employ them, they should make provision for a suitable recycling system as well.

10.4.1. Mineral resources scarcity

The mineral resources used for millennia have come from rich deposits located near Earth's surface (the crust), and thus potentially mineable. These deposits largely stem from geologic processes that occurred hundreds of millions of years ago. Such deposits are occasionally discovered but most of the likely locations on Earth have now been explored. It is unrealistic to anticipate that major new ore deposits lie hidden and waiting to be found.

Mineral deposits are, of course, of varying degrees of richness. Economic considerations generally require that the richest deposits are mines first, the next-richest second, and so on. As the use of poorer deposits is contemplated, it is useful to know the distribution of occurrence of resources of interest.

10.4.2. Energy resources scarcity

The most common source of energy- fossil fuels- provides a variety of service: heating, illumination, transportation, and so forth. The amount used by individuals varies with their wealth, their geographical location, their culture, and their personal habits.

Oil is the largest current energy source, accounting for about a third of the world's primary energy generation in recent years. Nuclear power and hydropower account for a few percent each. Of the final energy amount, only about 15 percent is used industrially. As a consequence, sectors other than industry will be strong competitors for whatever energy is available.

In the case of oil, coal and natural gas there could well be ultimate supply limitations. In addition, because fossil fuel combination results in the greenhouse gas carbon dioxide, regulatory restrictions on use could be imposed.

Different scenarios of future oil production have been constructed. They suggests that world oil production from conventional sources is likely to peak around 2020. To the extent that the unconventional bitumen and shale oil are employed (they require much more energy to extract and process and generate more carbon dioxide per unit of energy generated), they may provide significant additional amounts.

The outlook for **natural gas** is no more optimistic. Its future is likely to be similar to that of oil, but perhaps slightly later in time.

Coal, the third fossil fuel, is abundant, with a depletion time greater than 200 years. Strip-mining for coal, a common practice, is problematic, however, as are the environmental challenges of coal's combustion. Coal will doubtless continue to be a major component in energy supply, but will need to be developed with care.

Uranium, the fuel for nuclear power, has a depletion time similar to that for oil. Nuclear reactors do not have wide public acceptance in many parts of the world, however, and long-term storage of spent fuel is a continuing concern. As a result, nuclear power use is now beginning to expand after many years of stasis.

Other sources of energy—biomass, hydro, geothermal, solar, wind—appear unlikely to provide as much as 25 percent of energy needs in the next few decades even under the most optimistic scenarios. Broad implementation is limited by supplies (biomass), nature (hydro, geothermal, wind), technology and nature (solar), and environmental concerns (hydro).

As a result of these supply constraints, it is likely that the mid-twenty-first century will see a major shift in the sources of energy. Coal gasification may be a significant contributor, although it is technologically limited at present and the economics are problematic.

A potential alternative is a new generation of fail-safe nuclear reactors. Such a transition would require the development of reliable international approaches to nuclear waste disposal, and considerable public education. It may prove, however, to be the best of the options available within a few decades.

10.4.3.Water resources scarcity

Water is a renewable resource, but a limited one nonetheless. Now labeled "the oil of the twenty-first century," water will increasingly limit industrial processes that utilize it. Unlike wood or other renewable resources, the total average quantity of water available to humans is fixed. Climate change promises to increase these uncertainties in the coming decades.

Water is essential in many parts of industry for cooling, as a solvent, as a transport medium, and sometimes as a constituent of finished products. Actual consumption is generally a small fraction of intake—most cooling water is returned to the source, for example.

Overall, depending on the country and its level of industry, between 5 and 20 percent of global consumptive use is industry related. A much larger amount, 70-85 percent globally, is employed by agriculture. The growing global population will demand additional water in order to increase the food supply. The remaining consumptive water uses, perhaps 5-15 percent, are far domestic purposes, again a use unlikely to diminish in coming years. Industrial acquisitions to water thus need to surmount the growing demand for food and personal needs.

Under various development scenarios, the number of people living under high water stress is anticipated to be between three and five billion (i.e., one-third half the global population) by 2050. This situation will demand a very high level of water in efficiency, recycling, and reuse.

10.5. Use of materials from post-consumer recycled stock

The use of such material avoids the mining and processing of virgin resources, which not only depletes long-term supply but requires more energy, water, and other resources than using recycled stock and generates substantial amounts of "hidden flows" (of waste rock, for example).

"Hidden flows" are materials moved or mobilized in the course of providing commodities, but which do not themselves enter the economy. There are two components to these hidden flows:

(1) ancillary material removed along with the target material and later separated and discarded, such as the rock matrix containing a metal ore, and

(2) excavated and/or disturbed material, such as the soil removed to gain access to an ore body.

The weight of the mining and metal residues that result from the manufacture of a single jet engine are roughly one hundred times the weight of the engine itself, but recycling and advanced casting can minimize this hidden flow of materials.

10.6. Dematerialization or do more with less

Careful attention to product design and manufacturing involving each material in a product not only saves money but inevitably has salutary implications for the environment and sustainability as well.

One reason is that extraction of materials is extremely energy intensive and tends to be destructive of local ecological habitats.

A second reason is that many light-weight products, such as automobiles or aircraft, require less energy when in use than do their normal-weight components.

10.7. Problems of combined materials

It is common for a designer considering how materials are to be combined. However, modern technology often makes it difficult to achieve this intention. For example, today's electronic industry employs roughly half the periodic table of the elements in the manufacture of an integrated circuit. Thus the opportunities for recovery and reuse of any but the most valuable materials are remote.

Of course, materials are generally combined in order to provide improved physical properties of one sort or another. In a number of cases of metal amalgamation (e.g., manganese as a component of steel), almost the entire use of a material is in a combination of this sort. It is usually prohibitive from a financial or technological standpoint to separate the original components. Rather, the alloy or other combination must be reused.

Even in the best situations, separation is seldom perfect, and in some cases impurities can seriously degrade the properties of recycled materials. There are three possible decisions related to the recycling of the individual components of mixed metals:

* *Must separate*. This decision relates to a material combination where valuable resources are lost or seriously degraded if separation is not carried out.

* *Should separate*. The value of the separated resources may or may not justify special attention to recycling.

* *Don't separate*. The resources are under no long-term supply constraints; the value is low at typical concentrations in scrap; they do no harm if retained; and separation will consume large amounts of energy and/or other important resources.

10.8. Problem of waste in product delivery

Some 30 percent of all municipal solid waste has been found to be packaging material. About one-third of all plastics production is for short-term disposable use in packaging.

The use of toxic materials such as heavy metals in packaging inks may be a first-order environmental impact for some products.

10.8.1. Minimization of packaging materials

Improved packaging of products of all sorts thus plays an important role in maintaining environmental sustainability.

There are several possible levels of packaging:

For some products, no packaging at all may be required.

In other cases, only primary packaging (that is in physical contact with the product), is needed.

Less certain is the need in many cases for secondary packaging (a supplementary shipping container) or tertiary packaging (the outer shipping container and associated material).

Product packaging should always aim to use the minimal number of stages. However, different applications impose different packaging requirements. If any packaging stage could be eliminated or simplified, the residue stream will be reduced and shipping and storage expenses for the producer and consumer will be minimized.

Suggested approaches to packaging, in decreasing order of preference, are as follows:

* No packaging

* Minimal packaging

* Consumable, returnable, or refillable/reusable packaging

* Recyclable packaging

The most common causes for overpackaging are as follows:

* Excessive protection of the packaged contents

* Increasing the package size to discourage shoplifting

* Exaggeratedly conservative environmental test specifications

* Requirements of packaging machinery

* Decorative or representational packaging

* Increasing packaging size to provide space for regulatory information, customer information, or bar coding

Many of these causes are easy to eliminate by thoughtful packaging design. For example, the use of electronic theft protection systems is able to mitigate the need for some of the overpackaging that has traditionally been employed.

Does each product require its own package? Not necessarily, say packaging engineers who can often minimize the total number of packages needed. A common example is the sale of window cleaner and liquid soap refills in a size inappropriate for normal use but suitable for replenishing containers in service. The use of refills also eliminates the need to manufacture, use, and discard spray heads for each bottle of product.

10.8.2. Reuse of packaging materials

The next thing to consider is whether the packaging can be reused.

There is a notable innovation such as Ametek Corporation's "couch pouch," a composite of polypropylene sheet foam and polypropylene fabric that can be repeatedly reused for shipping furniture.

Standard packaging system of large breakable items (very effective at protecting the product during shipment) consists of wood, cardboard, steel, two types of foam, and plastic sheeting. The chances of most of this material being recycled are small. It is likely that a packaging engineer could have reduced the materials diversity substantially.

A final rule in packaging is to put package recycling information on (or in) each container and to help provide an infrastructure for the return of packaging for reuse or recycling.

10.9. Problems in the product use phase

The environmental impact produced by products when they are used should be considered. The use and maintenance of a product by the customer is largely constrained only by the product design. This circumstance places special responsibilities on the designer who should foresee aspects of design that minimize impacts during the entire useful life of the product.

There are some suggested instructions:

* Ideally, a product's use will not involve the purchase and eventual disposal of consumable supplies, such as cartridges for laser printers or lubricants for gears. If these seem necessary, the devices should be designed to encourage reuse or efficient recycling. In any case, consumables should have little or no inherently toxic materials within them.

* Products whose use involves such processes as the venting of compressed gas or the combustion of fossil fuels require the industrial ecologist to explore design modifications to minimize or eliminate these emissions. Replacements for the volatile chemical constituents will often be available if the designer looks for them.

* A number of products use energy (electrical, or furnished by fossil fuel) when in operation. Recent redesigns have produced lower energy consumption during use for many products, and legislation in an increasing number of countries will enhance such efforts. Energy-efficient designs may sometimes provide not only lower cost operation but also improved product’s sale, particularly in areas of the world that are energy-poor.

* Longer product lifetimes can sometimes be enhanced by remanufacturing. This involves the reuse of nonfunctional products by retaining serviceable parts, refurbishing usable parts, and introducing replacement components (either identical or upgraded). Such a process is frequently cost-effective and almost always environmentally responsible. It requires close relationships between customer and supplier, frequently on a lease basis; these relationships are often competitive advantages in any case. Remanufacture requires thoughtful design, because the process is often made possible or impossible by the degree to which products can be readily disassembled and readily modified.

10.10. Design for Recycling

One of the important goals of industrial ecology is the design for recycling (DfR). It consists of processes in which the components or constituents of products that have reached the end of their useful life re-enter the industrial flow stream and become incorporated into new products.

The original designer of a product defines the loop options available to the user and potential recycler.

The ideal design permits future renovation and enhancement by changing a small number of subassemblies and recycling those that are replaced.

Next best is a design that requires replacement of the product but permits many or most of the subassemblies to be recovered and recycled into new products.

Usually the least desirable of the alternatives is complete disassembly followed by recovery of the separate materials in a product and the injection of the materials or energy back into the industrial flow stream.

10.10.1. Products and recycling processes

Different products require for recycling diverse approaches. The most important factors in end-of-life strategies are:

* product wear-out life,

* technology cycle (length of time that a product will be on the leading edge of technology),

* number of parts,

* design cycle (how often do companies design new products).

Three groups of products can be identified by this approach, and then their probable end-of-life treatment is specified:

1) Products are long-lasting, but the technology embodied within them changes rapidly (e.g. television sets). This product group should generally be recycled at end of life.

2) Products with lifetimes longer than the technology cycle (e.g. digital copiers and washing machines). For less than 10 years, recycling is appropriate. For over 10 years, individual evaluation should be used to decide if remanufacturing or recycling is appropriate

3) Short-lived products, but with the long technology cycle (e.g. vacuum cleaners and shipping containers). They should generally be remanufactured at end of life.

Two complementary approaches should be considered:

* Horizontal recycling or closed loop. It involves reuse of the materials to make the same product over again (e.g. aluminum cans)

* Cascade recycling or open-loop. This recycling reuses materials to produce different product (e.g. office paper to brown paper bags).

The mode of recycling will depend on the materials and products involved, but closed loop should generally be preferred.

10.10.2. Main goals for DfR

1) Minimization of the number of different materials and the number of individual components (design for simplicity.)

The functional and aesthetic demands of design sometimes make it difficult to limit materials diversity or complexity. However, if you need to locate, sort, clean, and provide efficient recycling for 2 or 3 metals and 2 or 3 plastics, you are far more likely to be successful than if you must deal with 5 metals, 12 alloys, 20 plastics, etc.

2) Consideration about the fate of any hazardous materials at the end of product life.

The goal is equally important in the product recycling arena, where the presence of such materials is a deterrent to detailed disassembly, eventual reuse, or, if necessary, safe incineration and energy recovery. Where hazardous materials must be utilized in a design, they should be easily identifiable, and the components that contain them readily separable.

3) Not to join dissimilar materials in ways that make separation difficult.

Any time a designer uses dissimilar materials together, she or he should picture whether and how they can eventually be easily separated, an important concept because labor costs tend to be a significant barrier to recycling. Simple examples of products not designed for recycling: the glass container for liquids with a metal ring affixed; metal coatings applied to plastic films, plastic molded over metal or over a dissimilar plastic, and the automobile dashboard, which is a complex mixture of metal, wood, and plastic.

EXERCISES:

1. Consider options for packaging of the following consumer products: motor oil, grapefruit juice, toothpaste, magazines, shirts, personal computer.

2. Lead is a material widely used in automotive and stationary batteries. On the basis of whatever information you can locate on lead, evaluate its availability from the standpoint of abundance, co-occurrence, and geographical occurrence. What do you predict for lead as an industrial material in the next few decades?

3. Use information in 10.10.1. and 10.10.2. and draw your recycling approaches for the following products: refrigerator, power lawn mower, bicycle, book of 200 pages, plastic bucket.

Chapter 11 DESIGN FOR ENVIRONMENT IN INFRASTRUCTURE

11.1. The infrastructures

Unlike the individual products—computers, automobiles, and the like—buildings and infrastructure have different attributes:

* The first is their long lives. Thus, if these entities were poorly designed at the start, the consequences of the designs will last over very long periods of time.

* A second feature of buildings and infrastructure is the sheer mass of the resources they require. For example in the United States some 80 percent of all resources (by mass) are employed in the construction, modification, and refurbishment of buildings and infrastructure.

* A third attribute of buildings and infrastructure is that they are built in place, and are generally (but not always) one-time designs. Each project is thus an opportunity for a unique contribution to responsible technology and sustainability.

However, many other features of building and infrastructure design are essentially identical to those of smaller, shorter-lived products.

Four types of infrastructure are commonly identified: electric power provisioning, water supply and treatment, communications, and transport (roads, railroads, airports). Water and transport facilities are generally owned by government entities, and energy and communications by private entities. The key factor is an institution of some kind that constructs, maintains, and administers the infrastructure system.

Partly because of their long lives, and partly because of technological progress, few buildings and few elements of infrastructure live out their lives without change. As a consequence, the evolution of buildings and infrastructure over time and their eventual demise (and recycling) are at least equally important.

11.1.1.The Principles of Green Infrastructure Design and Operation

1) Sites and rights-of-way should be chosen to minimize ecosystem disruption.

2) Material and energy inputs should be renewable.

3) Recycled material should be used, if possible.

4) Material and energy inputs and outputs should be as nonhazardous as possible.

5) Processes and systems should be designed to maximize mass, energy, and space efficiency.

6) Prevent waste formation rather than treat it.

7) Maintenance and refurbishment should be facilitated.

8) Universal design (e.g., "one size fits all") solutions should be avoided.

9) Targeted durability, not immortality, should be a design goal.

10) Designs should be as flexible as possible to facilitate future renovation and expansion.

11) Systems should be designed to enable and encourage recycling at end of life.

11.1.2. Electric power infrastructure

Electric power designers consider three system components: generation (in which power is produced), transmission and distribution (in which power is transferred from generators to users), and use (where power is employed).

Generation can result from a variety of technologies—fossil fuels, hydropower, solar, wind, and so on.

Transmission infrastructure is generally divided into the transmission system, consisting of high-voltage transmission lines and transformers, and the distribution system, which encompasses lower-voltage lines and transformers that form the connections to users. Aluminum is the usual conductor in the transmission system, whereas copper is used in transformers, bus bars, and the distribution system. Portions of either system may be underground. Such installations have much higher installation costs than above-ground systems, but are not subject to outages in storms.

The classic means of energy provisioning is to provide large centralized facilities such as coal, nuclear, or hydropower facilities. These facilities provide (in principle, at least) oversight that encourages good economic, environmental, and safety performance.

A modern alternative to large centralized facilities is distributed generation, in which electricity is generated from many small energy sources. These sources often use clean fuels such as sunlight and wind to generate electricity, or they may adopt combined-cycle natural gas to generate heating or cooling as well. Added benefits are that energy loss in transmission (and construction of extensive transmission facilities) can be minimized in distributed facilities, and the insertion of many small energy sources in a neighborhood grid can often increase reliability and power quality (i.e., avoidance of "brownouts" and power dips and surges).

With the advent of electric cars, planners are now envisioning a grid that charges automobile batteries at night, when electrical demand is low, and draws excess power from those batteries during the day, when demand is higher. So long as the batteries are fully charged when the vehicle is needed, such an approach would allow energy to be stored and utilized much more efficiently than is now possible.

11.1.3. Water infrastructures

Supplying and treating water is a second major element of infrastructure. Some 70 percent of water is used in agriculture. For the other 30 percent and especially where human consumption of water is involved, various degrees and types of purification are employed. Systems of canals and pipes constitute major infrastructure projects.

The complex water infrastructure is comprised of a number of components: acquisition from freshwater, groundwater, or saline sources; transmission; treatment; distribution; use; wastewater treatment; and possible reuse. Where acquisition is from freshwater (rivers, lakes, snowmelt, etc.), the infrastructure generally involves storage behind dams and transport in aqueducts. Groundwater acquisition requires pumping from depth. Saltwater must be acquired through pumping and piping.

Water treatment is designed to remove pathogens and other undesirable trace constituents. If saline water is being used, desalination (the removal of excess salts) is required as well. All of these steps, especially the latter, employ large amounts of energy.

Water quality is an increasingly important topic. The now common detection of low levels of bioactive drug products in water suggests a prospect of a new appropriated design in water treatment.

After use by the customer, the wastewater must be treated again to render it safe for reuse or discharge. If the wastewater is to be restored to drinking water quality, the treatment must be much more extensive.

11.1.4. Transportation infrastructure

It consists of four components: roadways, railways, ports and harbors, and airports. All require dedicated land, initial construction, and ongoing maintenance and renovation. Extensive provisions for public safety are also required.

The construction of streets and highways involves the movement and use of more material than any other human activity except the construction of buildings.

Ports, harbors, and airports require extensive infrastructure to handle freight and people. These facilities are often in environmentally sensitive areas, and their development must be approached with care. **The siting and development considerations discussed below for green buildings are often applicable here.**

11.1.5. Telecommunications infrastructure

It consists of links and nodes. Some networks are private.

As with electrical power, telecommunications infrastructure can be on overhead or underground facilities. It often shares poles and underground passages and access entryways with the electrical power infrastructure. While vital to modern society, the material and energy requirements for telecommunication infrastructures are far less than those for energy, water, or transportation.

11.2. Buildings

Buildings are repositories of materials and embody the energy consumed to prepare those materials for use. On an ongoing basis, buildings are responsible for some 30-40 percent of energy use and some 15 percent of water use worldwide.

11.2.1. The Principles of Green Building Design and Operation

1) Minimize ecosystem disruption.

2) Material and energy inputs should be renewable.

3) Recycled material should be used, if possible.

4) Material and energy inputs and outputs during construction and operation are to be as nonhazardous as possible.

5) Buildings should be designed to maximize energy use efficiency.

6) Buildings should be designed to maximize water use efficiency.

7) Prevent waste formation rather than treat it.

8) Universal design (e.g., "one size fits all") solutions should be avoided.

9) Targeted durability, not immortality, should be a design goal.

10) Designs should be as flexible as possible to facilitate future renovation and expansion.

11) Buildings and building systems should be designed for recycling.

11.2.2. "Green buildings"

Recent years have witnessed a rapid growth of interest in "green building."

This term is defined as "*the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life cycle, from sitting to design, construction, operation, maintenance, renovation, and deconstruction."* The emphasis is on the careful choice and efficient use of materials, energy, and water, and the minimization of environmental effects of all kinds.

New buildings are not the only focus. In many countries, renovation and refurbishment activities are at least as important. There are some characteristics of green building:

* Alternative uses of buildings (e.g. transformation of residences into business offices, industrial buildings into apartments) have created a call for the new design buildings that are easy to alter and renovate.

* Energy use is minimized; water is recycled and reused in various ways; and interior materials are selected to minimize or avoid health problems. The goal is to take advantage of local resources—using natural light instead of artificial light where possible, outside air circulation rather than heating or air conditioning where feasible, solar and geothermal power where practicable, and so forth.

* Buildings should be designed with end of life in mind. Building design for disassembly makes it easier to recover useful elements of the building fabric and interior.

It is not unusual for green building construction costs to be a few percent more than those of a traditional building. This added cost tends to be rapidly recovered in reduced energy and water costs, and in increased productivity of building occupants.

The transparent and widely publicized green building systems around the world have transformed architecture in recent years. Innovations such as energy-efficient elevators, vegetative roofs for storm water management, and the use of low-emission interior materials are increasingly common. Because traditional buildings tend to be profligate uses of materials, energy, and water, green building-design and operation is a vital component of long-term sustainability.

11.3. Recycling of infrastructure and building materials

Infrastructures and buildings share a great commonality in their use of materials:

Concrete: widely used in buildings, arterial highways and expressways, bridge decks, water culverts, and pipes. Usually reinforced with galvanized steel bars (rarely with stainless steel) to avoid corrosion.

Aggregate: the principal constituent of asphalt, used widely on roadways, and the principal constituent of concrete.

Cement: the binding agent in concrete.

Asphalt: the typical surface treatment on local and collector roads.

Steel: widely used throughout all facets of infrastructure and buildings, generally in galvanized form.

Zinc: a relatively inexpensive and largely effective anticorrosion coating applied to most steel used in infrastructures and buildings.

Copper: the principal electrical conductor for electrical power transformers and distribution systems and for much of the telecommunications networks (although gradually being supplanted by fiber optics in the latter use). Commonly used for plumbing throughout infrastructure and buildings, (although gradually being supplanted by plastic).

Aluminum: used extensively for building exterior components such as window frames and siding. Aluminum is the usual conductor in electrical power transmission systems.

11.3.1. Recycling procedures

Infrastructure components can be recycled as can any large industrial product. Among current practices in a number of locations are the reuse of aluminum signs following stripping and cleaning (at one-third to one-fifth the cost of new signs), the reconstruction of metal-beam guardrails, and the reuse at the same or different locations of hardware such as manhole covers and frames, lighting standards, and chain-link fencing.

For the green infrastructure design all infrastructures should be designed to be modular, easy to disassemble, and capable of being reused at the end of rife. However, the economics for this may be difficult given the low cost of much of the virgin material used for roads and highways.

The recycling of infrastructure occurs in several stages:

The infrastructure material recycled in the largest amounts is asphalt pavement. The recycling process involves pavement fragmentation, followed by rotor milling. The resulting milled material is then reheated, mixed with a new bitumen, and reapplied to the base surface material. It is often quicker to recycle pavement on-site.

Concrete undergoes recycling processing by crushing, followed by magnetic separation to separate the steel reinforcing bar and rod fragments from the mineral matrix. These metal fragments are then recycled separately. The mineral–cement matrix has several potential uses: similarly as a granular material from natural sources or as filler for highway construction or modification.

EXERCISES:

1. Your are given two projects by a local city. One involves replacing a mile of old water pipe in the center of a downtown business and residential area. The second involves building a water system for a new town center with closely spaced town homes around it.

(a) What elements of materials selection and design constitute "sustainable" choices for each project, and how do they differ?

(b) You design a very energy efficient water infrastructure for the new build community, only to be told by the city that your initial costs are too high. How do you respond, and what data would you use to support your response?

(d) You propose to the city that it construct an "intelligent water infrastructure" for the new community. What sorts of information systems and functions might such an intelligent water infrastructure include?

2. Identify and review a local infrastructure project. Evaluate it using the principles from 11.1.1.

3. Identify and review a local building project. Evaluate it using the principles from 11.2.1.

Chapter 12 MATERIAL CYCLES IN INDUSTRIAL ECOLOGY

Industrial ecology is a concept with cycles at its very heart, and cycles are analyzed by means of materials and energy budgeting. An approach very similar to that of financial budgeting is used to fashion budgets in industrial ecology.

The process of estimating or measuring the input and output flows and checking the overall balance by measuring the amount present in the reservoir constitutes the budget analysis.

The same concepts occur in budgets devised for various industrial ecology studies. Thus we have sources and sinks, which are rates of input and loss of a specific material within a reservoir per unit time. A system of connected reservoirs that transfer and-conserve a specific material is termed a "cycle."

Examples include the shipping department where completed products are prepared for forwarding to customers, or the atmosphere as a whole, where emissions of industrial vapors collect and react. A second concept is that of flux, which is the amount of a specific material entering or leaving a reservoir per unit time. Examples include the rate of evaporation of water from a power plant cooling tower or the rate of transfer of ozone from the stratosphere to the troposphere.

12.1. Evaluation of material flows

Material flow analyses have many uses, some realized, some proposed:

* Establish and monitor the material and energy requirements for activities related to the maintenance and growth of economies.

* Identify and evaluate trends in discards and the potential for resource conservation and recycling.

* Identify and monitor the losses of substance to the environment and assess the environmental implications.

* Assess the status and trends of mineral and energy systems.

* Track the evolving amounts of material stocks in use, reuse, and disposal.

* Respond to issues related to materials demand and the potential for materials scarcity over the long term.

Industrial ecology plan have the three basic components:

1) determination of the present level (the concentration of a single material or a group of materials),

2) a measurement or estimate of sources,

3) a measurement or estimate of sinks.

A perfect determination of any two of these three components determines the other, as a consequence of the conservation of mass principle: Material can be transformed, but not lost. Because any material of interest in an industrial facility or in the environment may have several sources and sinks, each source and sink must generally be studied individually.

For a system chosen with a boundary surrounding, the entire Earth, and assuming no significant loss to interplanetary space, the overall quantity of material (the content ß) will not change with time:

$\Sigma ß = \text{Constant}$

Similarly, for any geographically limited system in a steady state, the source and sink fluxes into each reservoir exactly balance, so that in each case

$ß_r = \text{Constant}$

that is, the contents of each reservoir will not change with time:

$$\Delta_r = \frac{d(ß_r)}{dt} = 0$$

In a changing system, however, the source and sink fluxes are not equal and Δr is real-valued. Over time, the result for any reservoir will be a change in the content (also termed the "stock') of the element in question, the change being given by

$$\Delta r = \int_{t1}^{t2} (\Sigma F_1 - \Sigma F_0)dt$$

where Fi is an input flux, F_0 is an output flux, and t1-t2 the time interval. Δr can be either positive or negative.

Another useful parameter is the residence time, τr, which is the average time spent in the reservoir by a specific material. The average τ residence time is composed of all forms of the substance, weighted with appropriate probability factors. For example, when one evaluates nitrogen flow into and out of an animal, one finds that some of the nitrogen rapidly flows through the animal whereas other nitrogen flows much more slowly, a reflection of animal lifetimes and foraging and excretion characteristics. We can define the average residence time in a situation with a variety of residence times as

$$\tau_r = \int \tau \psi(\tau) d\tau$$

where $\psi(\tau)$ indicates the fraction of the constituent having a residence time between τ and $\tau + d\tau$. This probability fraction $\psi(\tau)$ is a function of the reservoir processes (the rate of breakdown of nitrogen-containing molecules in food in biological ecology, or the rate of product obsolescence in industrial ecology, for example).

The *age* is the time elapsed since a particle entered a reservoir. The average age of all particles of a specific kind within a reservoir is thus given by

$\tau a = \int \tau\, \Omega (\tau)\, d\tau$

where $\Omega (\tau)$ is the age probability function.

An industrial ecology resource analysis may deal with any spatial scale and with .many reservoirs.

No matter what the cycle, the careful construction of a flow diagram is essential if an n accurate picture is to be obtained. In some cases the flows crossing the boundary may be well known, and the challenge is to quantify them (and the related stocks as well). In others, as in the atmospheric chlorofluorocarbons (CFCs), the importance of some of the sources and sinks may not be realized and must be deduced by quantifying those for which information is available. In all cases, however, the process begins by specifying the metabolic cycle, its metabolites, and its enzymes, in as much detail as possible.

In industrial ecology, the concepts of budgets and cycles are applied to the anthropogenic use of resources such as nickel, or sometimes to the combination of anthropogenic and natural The results help us evaluate present metabolic needs and to estimate those that may be required in the future. Similarly, we can study specific resources as they pass through various technological organisms and thus evaluate resource supply, use, and loss.

12.1.1.Elemental substance analyses

In an elemental analysis, the emphasis is on the atom. This may be because the supply of the atom is highly limited (gold, for instance), or because it is a biotoxicant (cadmium, for instance).

It does not mean that the subject of the analysis is necessarily present in atomic form, but that the chemical form in which the atom exists is not considered in the analysis. The advantage of this approach is that its data are clear— a flow of sulfur is expressed as mass of sulfur.

In-use stocks may be estimated by either a "top-down" or a "bottom-up" method. The bottom-up method begins with inventories of the different service units that contain the resource in question, such as buildings, factories, or vehicles.

The content of the resource per service unit obtained from engineering data is combined with census information on the number of units in a given geographic area to determine the metal stock in use. Mathematically, the computation is expressed as

$S (t) = \Sigma n\ i=1\ Ni (t)\ Mi(t)\ Ni (t)$

where S is the in-use stock, N the number of units of a particular product (automobiles, say) that use the resource to provide services of some sort, and Mi/Ni is the material intensity per unit of product, all summed over the i types of products addressed by the analyst.

The bottom-up method allows determination of the spatial distribution of stocks in particular localities, but yields less useful data on wastes, because we lack extensive information on the, content and extent of landfills.

The top–down method computes the mass balance between the flow of new resources into use and the flow out of use arising from products that reach the end of their service lives. Some of the outflow of end-of-life resources is recycled into new products and so remains in use. The rest enters a steadily increasing stock placed in waste repositories and is found by integrating the balance between the discard rate and the recycling rate. Integration of the mass balance year-by-year determines the cumulative amount of stock that remains in use and the amount accumulated in wastes.

EXERCISES

1. Choose an element from the fifth row of the periodic table and research its substance flow aspects. Describe its principal uses. What information do you need to complete your cycle, and how might you acquire it? (Supplementary material you may find helpful includes the U.S. Geological Survey's annual Mineral Commodity Summaries http://minerals.usgs.gov/minerals/pubs/mcsd and the United Nations Comtrade database http://comtrade.un.orm.)

2. Consider a scenario in which the concentration of Co2 in the atmosphere gradually rises to 400 parts per million by volume (ppmv), about 8% higher than the level in 2000, then stabilizes by the year 2100, as shown in the Figure 15. The bottom graph shows anthropogenic Co2 emissions from 1900-2000, and current net removal of CO2 from the atmospheric by natural processes. Sketch:

(a) Your estimate of likely future net CO2 removal, given the scenario above.

(b) Your estimate of likely future anthropogenic CO2 emissions, given the scenario above.

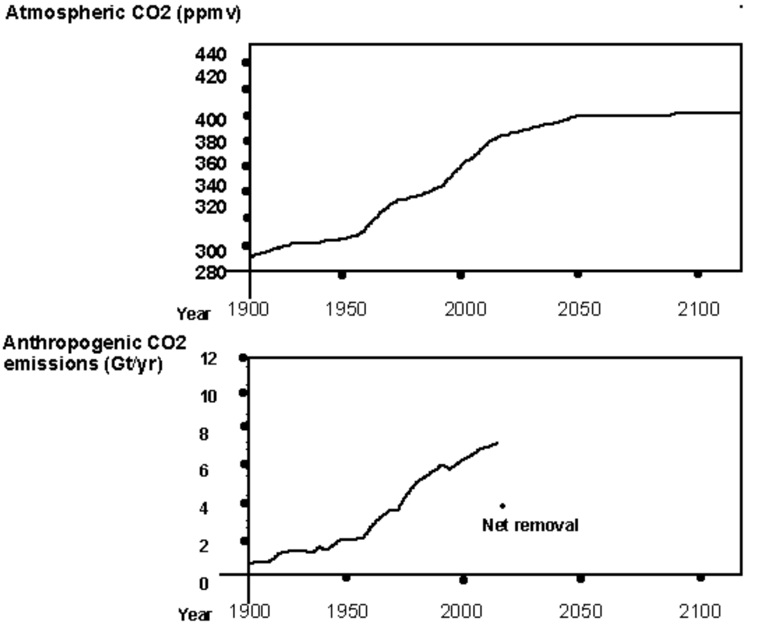

Figure 15. Anthropogenic Co2 emissions from 1900-2000, and current net removal of CO2 from the atmospheric by natural processes.

Chapter 13 ENERGY IN INDUSTRIAL ECOLOGY

Because almost every action of industry involves the use of energy, energy analysis is inherently a part of industrial ecology. Historically, this analysis has been primarily a focus of the most energy-intensive industrial sectors: metal mining and processing, pulp and paper, cement, petrochemicals, and glass manufacture. With energy use becoming a more general concern, energy analysis is now nearly universal and is moving to encompass products as well as manufacturing facilities.

In the case of products, there is now a general realization that energy use occurs at all life stages, is a natural part of life cycle analysis and is one of the principal ways in which designers find their work related to environmental impacts and sustainability. For products that use energy during their service lifetimes—engines; computers, buildings, and so on—there is a particular premium on designs that minimize energy consumption.

Energy intensity differs with industrial sector and with life stage. It is usually the case that the initial extraction of resources is quite energy intensive because of the separation and purification involved.

Paradoxically, the benefits of modern technology often require very pure materials, and manufacturing materials at high purity requires lots of energy.

Another aspect of industrial energy assessment is that the extraction stage for materials often occurs far from the fabrication of the materials into products, perhaps on another continent. This is a "hidden energy flow".

In general, the energy needed to provide materials through recycling is substantially less than that needed for virgin materials, so the use of recycled materials is desirable from both a material and an energy perspective.

13.1. Energy in biological and industrial organisms

The first and second laws of thermodynamics state that all biological and industrial processes require energy conversion and result in entropy production.

13.1.1. Energy flow in biological organisms

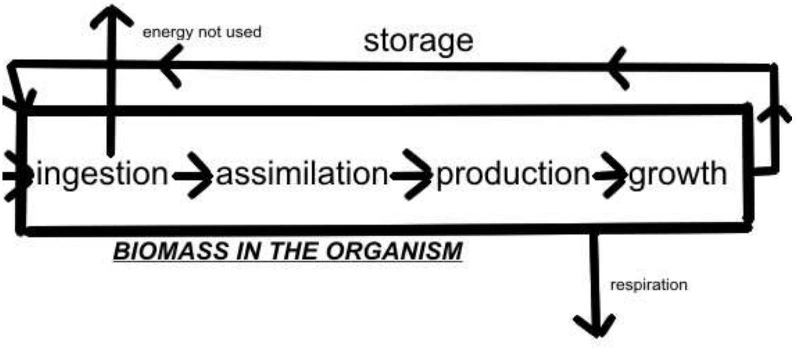

Figure 16. Energy flow in biological organisms.

Biological processes receive their energy from the sun. Industry's energy sources are more varied, but rely heavily on fossil fuels.

Biological organisms expend energy to transform materials into new forms suitable for use (growing muscle or babies, for example). They also release waste heat and material residues. Excess energy is released into the surroundings, as are material residues (feces; urine, expelled breath, etc.).

13.1.2. Energy flow in industrial organisms

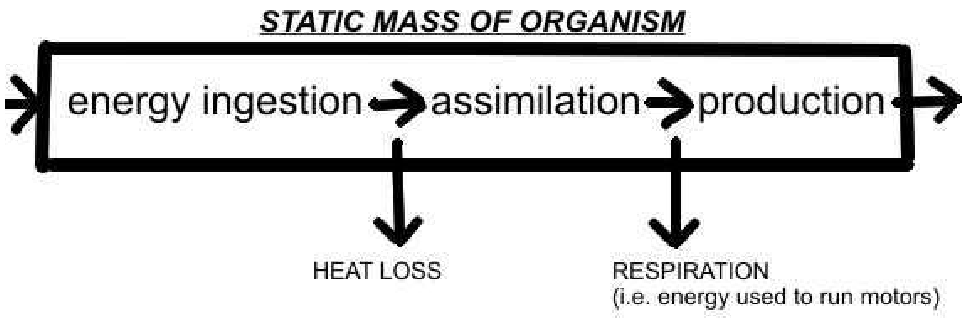

Figure 17. Energy flow in industrial organisms.

In a somewhat similar fashion, industrial organisms expend energy for the purpose of transforming materials of various kinds into their products (their own new forms suitable for use). Energy residues (heat, exhaust gases, etc.) are emitted into the surroundings, as are material residues (solid waste, liquid waste, etc.).

13.1.2.1. The energy audit in industrial processes

Often in industry the amount of energy required to operate a facility is well monitored (because it must be paid for), but the energy required for each individual operation or set of operations within a facility is not known.

In such cases, an energy audit is advisable to show where are the opportunities to improve "green" accounting systems. For a particular process, one wishes to audit the energy use, at each stage of material extraction, processing, and manufacturing.

1) Each processing step is associated with it an energy per unit of throughput. For simplicity, we choose the amount of output material to be 1 kg.

ß is the fraction of throughput that is immediately reused as “prompt scrap” rather than output material: rejected material, sprues, runners, lathe turnings, and so forth.

The energy consumed per kilogram of output material is then given by

$$\Phi = E_p + E_f (1 + ß) + E_m (l + ß)$$

$$= E_p + (E_f + E_m)(1 + ß)$$

It is obvious from this equation that manufacturing operations that produce a smaller fraction of scrap will require less energy per unit of output than those where a large fraction of material must be refabricated.

2) A more relevant case for industrial ecology is a manufacturing sequence that uses both virgin and consumer recycled material.

The latter need undergo only secondary production, which is generally much less energy-intensive than primary production.

There Φ is the fraction of output material from primary production,

Ω is the amount of material entering the process in the ore,

Ψ is the amount of the material entering the process as consumer scrap.

The energy consumed by this system per -kg of output material is given by

$\Psi = E_p(\phi)(1 + \beta) + E_s(1 - \phi)(1 + \beta) + E_f(1 + \beta) + E_m(l + \beta)$

$= (\psi E_p + (1 - \psi)E_s + E_f + E_m)(1+\beta)$

Because $E_p >> E_s$ total energy use is minimized by making ϕ and β as low as possible.

13.1.3. Energy in the product life cycle

The energy use is an important feature of the product life cycle. That property is assessed by calculating energy use and resultant emissions at each life stage.

Attention to energy use in product design can result in some quite startling achievements, as shown by a history of energy use in household refrigerators over more than half a century.

The refrigerators in use in the late 1940s and 1950s in the United States were rather small in volume and used modest amounts of energy. The volume grew to more than twice as large in the 1960s and 1970s, and energy consumption quadrupled.

In the late 1970s the volume stabilized, and attention to energy-efficient design began to rapidly reduce consumption. By 2000, refrigerators with volumes two and one-half times larger than those of 1947 were consuming' only slightly more energy than those early units. Energy was consumed in manufacturing, of course, but life-cycle inventories invariably find that any product that requires energy during its use phase has an energy consumption profile in which all other phases are small to negligible by comparison.

13.1.4. Energy in extraction and processing of mineral resources

These processes require large amounts of energy, the energy needed depending on the material itself and the amount of processing required.

When a target mineral is sufficiently abundant to be above the mineralogical barrier—that is, when the matrix can be called an ore and not a rock—the minerals are freed from the surrounding matrix by crushing and grinding and concentrated by selective processes such as flotation. The resulting concentrate can then be purified to acquire the target metal.

Purification is rather directly related to the melting point of the metal. The energy optimization is much more important for titanium and aluminum than for lead or steel.

The situation for copper presents clearly the relationship between ore grade and energy. Extraction and processing are relatively efficient for copper ore (the rock matrix containing copper sulfide minerals), though considerations of energy are certainly present.

At mineral concentrations below 0.1 percent, however, the copper is thought to be dispersed in solid solution within silicate minerals rather than concentrated into mineral form. To recover the dispersed copper, the silicate minerals themselves must be separated and processed. The energy costs of so doing are very large, because the chemical bonds holding the atoms together in a silicate mineral are much stronger than those holding the atoms of a copper sulfide mineral together.

Metallurgical experience suggests that the overall energy needs will be about 10 times as great per recovered copper atom if recovery from silicate minerals is required. The recovery from ore of grade 0.01 percent will require roughly 100 times the energy needed for ore of grade 0.1 percent.

EXERCISES

1. An office building in your community has 50 offices, each with an average of four desks. Each desk has a desk lamp that can use either a 60-watt incandescent bulb or a 13-watt fluorescent unit. The average use of a lamp is seven hours per day. How much power is required for the building per year for each of the two options? Given your local energy cost, what is the annual cost of each of the two options? If the price of an incandescent bulb is 5 zlotys and that of a fluorescent unit is 18 zlotys, how long will it take to justify the purchase of fluorescent units, assuming everything is newly purchased?

2. Assume a material processing system with $E_p = 31$ GJ/t, $E_f = 5$ GJ/t, $E_m = 5$ GJ/t, and $\beta = 0.1$. Compute Φ.

3. To the system of the previous problem, add a secondary production component to reprocess consumer scrap with $E_p = 9$ GJ/t and $\phi = 0.7$. Find ψ, Ω, and Φ.

4. In the system of the previous exercise, a fraction λ of the material entering the primary production process is irretrievably lost to slag. Reformulate equation from the exercise 1. to take this loss into account. If $\lambda = 0.2$, compute Ψ, Ω, and Φ.

Chapter 14 WATER IN INDUSTRIAL ECOLOGY

Because many actions of industry involve the use of water, water budgets, and responses to what the budgets reveal, are inherently part of industrial ecology.

Water intensity differs greatly with industrial sector and with life stage. It is often the case that the initial, extraction of resources is quite water intensive because of the material separation and purification involved. As a consequence, the nonagricultural sectors that have the highest rates of water use are petroleum and coal processing, primary metals, chemicals, and paper.

Paradoxically, the benefits of modern technology often require very pure materials, and manufacturing those high purity materials often requires lots of water. Another aspect of industrial water assessment is that the extraction and processing stage for materials often occurs far from the fabrication of the materials into products.

In general, the water needed to provide materials through recycling is substantially less than that needed if virgin materials are used, so the use of recycled materials is desirable from both a material and water perspective.

14.1. Water in industry

Water is necessary for life, for industry, for agriculture, and for the continuing function of many coupled natural systems such as the carbon cycle. Yet it is frequently overlooked in lists of sustainability concerns, even though estimations state that by 2025 two-thirds of the human population will experience shortages of water, and almost two billion will experience severe shortages. Agriculture is involved in an estimated 70 percent of all global water use, with industrial use, municipal use, and reservoir losses accounting in roughly equal amounts for the remainder.

From an industrial ecology perspective, the use of water is a classic subject for sustainable engineering. It is a critical material, often regulated and used in a highly politicized environment, and subject to very different laws depending on jurisdiction.

Water is closely coupled to public health, food production, industrial manufacture, national security, and social stability, and water infrastructures are often among the most important elements of a society's built environment.

14.2. Water quality

Water quantity and conservation is not the only concern of the industrial ecologist, who also needs to consider water quality: its acidity, its dissolved oxygen content, its impurity levels, and so on. Does it contain harmful organics? Does it contain reactive chemicals? Do its impurities require extensive treatment before use?

In most cases, regulations limit the discharge of readily measured constituents such as acids, salts, and nutrients. Much less oversight exists for potentially problematic and bioactive constituents that may be present at very low levels: solvents, additives, lubricants, heavy metals, drug metabolites, and so forth. Additionally, regulations are often stricter for "point sources" such as factories than for "nonpoint sources" such as agriculture, meaning that some problematic constituents, such as nutrients in river basins, are essentially unregulated.

14.2.1. Water quality in industry

Industry has three quite different concerns related to water quality:

* the industry's own water cleanliness requirements may necessitate treatment , before use,

* the discharges from its manufacturing facilities themselves are increasingly linked to industrial discharges.

* the discharge of industry's products—pesticides, detergents, and a wide variety of pharmaceutical and personal care products —by its customers.

Many of these constituents are bioactive by design, and so are of particular concern from an ecosystem impact perspective.

The first line of industrial actions related to water quality is the -obvious: discharge as little as possible and render benign what you do discharge. This often requires technologically advanced water treatment.

The second activity is even more difficult—to design products that will cause little harm if discarded by the customer into municipal water supplies or into the environment. This challenge requires the use of the green chemistry techniques. It places a premium on reasonably prompt degradability, as well as ensuring that any transformation products are relatively benign.

This two-pronged requirement raises industrial concerns related to water quality to a much higher level than has historically been the case.

14.3. Water in industrial organisms

Biological organisms are 70-90 percent water. Water is important for most industrial organisms as well, where it plays a central role in such processes as washing, plating, cooling hot machinery, and serving as a chemical reaction medium.

The water flow of an industrial facility consists of the following stages :

* water supplied

* ingestion

* loss of water during production

* wastewater

The start and end of ingestion are linked by:

* recycled water (rarely seen in biological organisms, it helps reducing the amount of water supplied to an industrial facility).

Industry may be aware of the overall amount of water required to operate a facility (because it must be paid for), but often the water required for each individual operation or set of operations within a facility is not known. In such cases, a water audit can show where the opportunities for gains might lie, as well as providing data for "green" accounting systems.

14.3.1. Water in production

It should be possible to construct a life-cycle water analysis for any commercial substance or product of choice. In practice, few such studies have been done, except perhaps for products such as washing machines that require water for everyday use.

A country-level water cycle can be generated and enhanced by computing the "water footprint": the water used within the country and the virtual water supplied by the import of various commercial products, given by

WFP = AWU + IWU + DWU + VW

where WFP = water footprint, AWU = agricultural water use, IWU = industrial water use, DWU = domestic water use, and VW = virtual water in international trade (negative for export, positive for import).

EXERCISES:

1 You currently drive 10,000 km/year in a gasoline-powered car. Given that your car consume 0,8 liters water per 1 km and an electric car consumes 2 liters per 1 km- if you switch to an all-electric car, how much additional water will need to provide your annual needs?

2. All products carry with them embedded energy, water, and solid "hidden flows." Design a label for a new product of your choice that displays its "virtual resource" loads. How could the average customer use your label to make a more informed choice of products?

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