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Human Ecology: Industrial Ecology

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Abstract:

Industrial Ecology aims to inform decision making about the environmental impacts of industrial production processes by tracking and analyzing resource use and flows of industrial products, consumer products and wastes. Quantifying the patterns of use of materials and energy in different societies is one area of research in Industrial Ecology. An extensive literature is devoted in particular to Material Flow Analysis (MFA), the collection of data describing the flows of specific materials from sources to sinks within some portion of the global industrial system. Industrial Ecologists are also concerned with the system-wide environmental impacts associated with products. Design for the Environment involves the design or redesign of specific products so as to reduce their impacts, while Life Cycle Analysis (LCA) quantifies resource use and emissions per unit of product from material extraction to the eventual disposal of the product. The LCA community has created a significant body of best-practice methods and shared data and increasingly incorporates their analyses within input-output models of entire economies to capture that portion of the impact that would otherwise be overlooked. Input-output models, often incorporating both MFA and LCA data, analyze the effects on the environment of alternative consumption and production decisions. Industrial Ecology makes use of this array of top-down and bottom-up approaches, all of which are grounded in its origins in the ecology of the industrial system.

I. Industrial Ecology: Human Activities and Global Ecosystems

The field of Industrial Ecology was created to inform purposive human decision making about industrial production processes, especially as they impact the environment, by taking advantage of knowledge about the functioning of successful ecosystems. More recently the scope of the field has enlarged to include decision-making regarding consumption activities as well. Human decision-making is important because humans, while one species among many, are responsible for dramatic and far-reaching changes to the global environment and thus to the existence of other species.

Industrial Ecology is not the only new, cross-disciplinary field employing the word "ecology." Among others utilizing the ecological metaphor are the Ecology of the Family, Organizational Ecology, and Ecological Economics [see entry in this volume]. In all cases the intention is to suggest that the field in question constitutes a complex system, in some instances with direct relations to biological ecosystems. The Ecology of the Family focuses on how family members are shaped by their interactions, both competitive and mutualistic, with one another. Organizational Ecology applies population dynamics models to the births and deaths of firms and industries and examines how the evolution of organizational structure is shaped by competitive and cooperative interactions. Ecological Economics departs from the observation that natural ecosystems uninfluenced by human activity no longer actually exist: counting both economists and ecologists among its numbers, it attempts to integrate the two professional domains. Industrial Ecology is distinctive in its focus on the industrial system, literally treating it as an ecosystem or, more exactly, the subsystem of principal interest within a more inclusive ecosystem. The flows of energy and material characterize an industrial system and serve as the integrating focus of all description, design and analysis in Industrial Ecology. Not merely analogous to the flows of energy and material in ecosystems, they actually constitute those flows. The production and consumption activities of humans can be described in terms of these flows just like the activities of any other animal. Given this focus on industrially valuable resources, it is not surprising that most of the field's founders were engineers or applied physical scientists with interests in chemical processes and effluents and, more generally, the reduction, reuse, and recycling of industrial wastes.

Industrial Ecology is motivated by its concern for the well being of the environment. As the inclusion of ecology in its name indicates, it puts special emphasis on developing and implementing solutions and policies at the system level, up to and including the global system. Central to the system perspective is the concept that the behavior of individual components cannot be fully understood without reference to the system in which they interact. Industrial Ecology explicitly recognizes that human industrial activities in the modern industrialized world are characterized by the interdependence of many industries, each industry itself often performing many interconnected production processes, all reliant on inputs of energy and materials and discharging wastes.

System scientists have long understood that the basic features of a system of interacting components need to be understood in a top-down fashion, even though many processes operate at the level of component parts. In the case of system design, top-down and bottom-up contributions generally proceed in an iterative fashion. This system perspective influences the direction that Industrial Ecology takes in confronting environmental challenges: improving the environmental compatibility of individual industrial processes is evaluated in the context of improving the overall industrial system. A simple illustration is provided by Figure 1, which combines two waste streams, fly ash from coal-fired power plants and waste plastic from plastic manufacturing, into a useful product, light-weight building blocks. At the same time the waste heat and carbon dioxide from the power plant can be supplied to a large-scale greenhouse, leading to increased production of fruits and vegetables. Reducing any of these waste streams might both increase the unusable waste from the others while also reducing the quantity of useful product. Recognizing the value of waste as a resource is a major theme of Industrial Ecology.

<Figure 1 near here>

The tracking of resources, intermediate products, final products, and wastes can be conducted at the level of business establishments, towns, nations, or in the context of nations interacting in the global economy. And the analysis of these flows, as a basis for action, can also take place at all these levels.

II. Resources and Products in Industrial Systems

The industrial system and the natural system were long seen as separate although overlapping domains. Economists, for example, used to treat resources as “free gifts of nature” and therefore exogenous to their concerns, limiting the designation of so-called factor inputs to built capital and labor. (Many still do, contrasting the ‘built environment’ with the natural environment.) It was a contribution of Industrial Ecology to treat the industrial system as a subsystem of the natural system (see panel a of Figure 2).

As Industrial Ecology now broadens its concerns to include consumption as well as production, this simple diagram is being reconsidered because of the importance of human motives and human agency to the decision-making process. The built environment is part of the biophysical structure of the social-ecological system and subject to the laws of nature (see panel b of Figure 2), but the cultural sphere is better understood using the concepts and methods of the social sciences.

<Figure 2 near here>

In the earliest societies, the built environment was insignificant. Humans in hunter-gatherer societies, like all other species, primarily take what nature makes available. They are not likely to severely overexploit a local ecosystem; when resources become scarce, they move on. However, even before the advent of agriculture, humans began to modify their local environments for the purpose of increasing its productivity (for humans) through the use of fire. With the transition from hunter-gatherer to settled agriculture, farming and herding societies greatly extended the modification and control of the natural system to overcome natural supply constraints and produce more of what humans desired. This control allowed for the possibility of individuals or groups producing more than they required of agricultural and other goods and thus making some of their production available for trade. With the development of trade and of markets, agricultural and other types of output were converted into products: goods (or services) exchanged for something else of value.

A second and related historical transition is the explosive growth of human requirements, the average of what is considered standard in a given society, and the related changes in human consumption patterns. Early human requirements differed little from those of other social mammals, were closely related to physical survival, and were met by the output of nature. In modern times humans are unique among ecosystem species in the volume, variety, and sources of their material requirements. Consumer demand in affluent societies is met by an extensive array of products -- the goods and services output by the industrial system. Humans are not alone in producing products, but no other species even approaches the scale of human production. The modern built environment reflects the prevalence of these human products.

While the flow of mass and energy in ‘natural’ ecosystems is largely dictated by the consumption of resources to supply energy and nutrients to sustain life, many if not most products of modern industry have little to do with directly providing energy and nutrients, and a substantial number have little to do with that function even indirectly. The extent to which industrial systems are dedicated to producing such products contrasts them to the rest of the natural system. Industrial Ecology is concerned with a unique feature of these industrial systems: the unprecedented degree to which the appropriation of resources -- materials and energy -- for the fabrication of products is not bounded by the metabolic constraints of the biological world, both in the quantity of those flows and in the variety of materials involved.

One could say that humans in a modern consumer society have developed extended metabolic needs, where consumer goods and services play a role similar to the need for proteins and carbohydrates in nature. To have toast in the morning requires not only bread but also a toaster and thus electric power as well. This concept of humans having extended needs is hardly new. Rousseau saw industrialization as creating a set of artificial (as opposed to natural) needs, and Marx made the distinction between human and inhuman needs. The material and energy requirements of the modern industrial system serve the extended needs of human consumers. The concept of distinct industrial metabolisms, reflecting the material realities of specific societies, and attempts to quantify them, is an active research area in Industrial Ecology.

Since the majority of industrial products do not satisfy biological metabolic requirements, they need not be composed of organic material. The relaxing of this constraint, coupled with the specialized functions of many products, leads to the development and use of a

wide range of novel, often exotic, materials designed specifically to improve product function. In some cases the development of new products is made possible only by the development of new materials, which in turn often requires the development of new industrial processes. As a result the global ecosystem must cope with stocks and flows of materials that have undesirable properties like toxicity or non-biodegradability.
Most of these complex materials cannot be recycled easily, in contrast to the relatively narrow range of organic materials, which are readily recycled.

Within the realm of personal transportation, for example, the goal of making automobiles lighter in order to reduce fuel consumption has led to the substitution of a variety of high technology materials in the place of steel, itself an exotic material when compared to the wood from which earlier forms of personal transportation such as wagons were constructed. Use of these materials impedes the recycling of automobiles due to the increased difficulty of separation and remanufacture. In many cases the performance of the product is dependent on its containing materials that are non-biodegradable. These products are more likely to be toxic, require large quantities of energy for their production, and have long residence times in the environment, problems that are aggravated by the great quantities in which they are produced.

These materials and products are the output of what is often a multi-stage production process carried out within the industrial system. Just as the diet of a carnivore depends on the consumption of plants by herbivores, the end-product purchased by the consumer requires many indirect as well as direct inputs. Large volumes of consumer products, requiring diverse resources and intermediate inputs as they do, make it necessary to build what are often large-scale production facilities. The material and energy resources required for this part of the built environment, like other private and public buildings and infrastructure, must be counted among the extended metabolic needs of human consumers. Describing and analyzing the total requirements of consumers in a modern industrial economy ultimately rests on accounting for all of the indirect inputs. To do this industrial ecologists often make use of economic models, especially those with a joint focus on material stocks and flows as well as production technologies and consumption patterns.

III. Bottom-Up: Resources and Products

The objective of Industrial Ecology is to provide actionable input to those taking decisions about the industrial system. These decision makers include not only corporate managers, responsible for the extraction of resources and fabrication and distribution of products, and the policy makers who oversee them, but also consumers, acting both individually and as members of households or of the growing number of social institutions that operate in the public interest. The decisions may pertain to an individual resource or product or to an entire industrial system.

Even when studying an individual resource or product, industrial ecologists are concerned with its role in an industrial system. They gather data on system behavior and develop concepts and methods for analysis at the system level. Among Industrial Ecology's most fundamental activities is gathering data for describing the flow of energy and materials throughout an economic system. The scale of the economic system can range from a single factory to a regional economy to the global economy.

Many Industrial Ecologists are engaged in compiling information to describe the flow of a specific material from sources to sinks within the global industrial system or some geographically delimited portion of it. Conventions and procedures have been developed for Material Flow Analysis (MFA, and its variants such as Substance Flow Analysis), which is in certain ways similar to the study of nutrient cycling in ecology. The depiction of the global copper cycle, shown in Figure 3, is reminiscent of illustrations of the carbon cycle in ecological systems, but closer inspection indicates that the copper cycle is nowhere near as efficient as the carbon cycle. A significant fraction of the copper is not recycled but instead ends up being lost to the system. Identifying and quantifying these major flows provides grounding for interventions that aim to modify the existing system to reduce its impact on the environment by making it more efficient in its use of resources. Similar approaches are applied not only to individual elements such as copper but also to compound materials. By pinpointing the presence of wastes that go unnoticed in conventional economic monitoring systems, MFA can direct efforts to improve system performance. MFA has also been applied to the aggregate of all materials (measured in tons per person) in attempts to quantify a society's industrial metabolism.

<Figure 3 near here>

The wide range of MFA studies underscores the increasingly great variety of distinctly different materials in use in the contemporary industrial system, each with unique properties, to support the great number of products required by consumers. The literature includes MFA studies of metals such as copper and zinc, forest products such as pulp and paper, and industrial chemicals such as bisphenol A and nonylphenol. This expansive range of materials contrasts industrial with ecological systems which, relying on the breakdown of complex biochemical compounds by digestion, is typically characterized by a few major cycles – carbon, nitrogen, phosphorous, hydrogen, oxygen – the principal, elemental constituents of biomass. Moreover, since the resources required by industrial systems often are found in specific locations distant from the site of production, which may also be distant from where consumption takes place, considerable amounts of transportation may be required, involving even more energy and material inputs. The material flow analyses of broadest conceptual scope trace simultaneously the physical movements associated with a variety of interrelated human activities. While the objective of most MFA studies is to quantify material flows, such flows can in an additional step provide inputs to a model of the industrial system that explicitly distinguishes their use in specific industrial sectors and modes of transportation to satisfy the product demand of different categories of consumers.

Moving up from resources to products, two additional research areas within Industrial Ecology are concerned with the individual product, situated in the context of its entire life cycle from resource extraction through resource processing and fabrication of the product to its utilization, reuse, recycling, and disposal. These are Design for the Environment (DfE) and Life-cycle Assessment (LCA). Both address the system-wide environmental impacts associated with products.

DfE involves the design of industrial products and processes to minimize their adverse environmental impacts over their lifetimes. Often it is a re-design of an existing product or process that is undertaken. The focus can be on different phases of a product's life-cycle, such as Design for Product Retirement. Actual applications are varied and have included the design of chemical processes, electronic products, mechanical components, and freezer insulation, as well as the increasingly important area of packaging design.

LCA involves the evaluation of the environmental impact of a product during its entire life history on the basis of detailed technical information. Each stage from extraction of resources through disposal of residuals is associated with distinct resource requirements and emissions or other forms of damage, and their impacts, which are experienced at specific times and places. LCA is often used to compare the environmental impacts of alternative products or production processes and has been applied to substances such as chlorine and aluminum, the entire mining industry, industrial materials like PVCs, and to alternative uses of agricultural land.

LCA studies quantify emissions and resource use per unity of output or service delivered. The modeling of the production network, including the quantification of the amounts of inputs required from different production processes, is traditionally based on direct measurement or engineering analysis. This process inventory modeling has generally ignored the contribution of non-physical inputs, such as legal and accounting services or wholesale and retail trade, and left out minor inputs to make the analysis tractable. Empirical studies have established that such an approach overlooks a significant portion of the total impact. As a result, increasing numbers of LCA researchers are integrating their analyses with the use of input-output models of the economy to capture indirect as well as direct requirements associated with a single process or product. The integrated, hybrid approach has made it possible to go beyond examining individual products to examining the impacts of one entire bundle of consumption goods as compared to another.

LCA also includes an impact assessment step, in which different types of emissions are aggregated to a manageable number of indicators reflecting specific problem areas such as global warming or human toxicity. Alternatively, impact assessment can be based on the modeling of damages, for example human health effects measured in years of life lost from both toxicity and climate change. The development of these impact assessment methods build on the knowledge and models of environmental scientists, including eco-toxicologists and ecologists.

IV. Top-Down: Entire Industrial Systems

An early application within Industrial Ecology of ecological concepts to industrial systems is the design and implementation of so-called industrial ecosystems, or eco-industrial parks. Industrial ecosystems are characterized by the prevalence of what has been named industrial symbiosis, a relationship between two or more firms that involves the exchange of materials, energy, or information in a manner that is mutually beneficial. The most famous of these is located in Kalundborg, Denmark; its structure is illustrated in Figure 4. By utilizing what would otherwise be waste products from one firm as input resources for others, the adverse environmental impact of this system of firms can be greatly reduced.

<Figure 4 near here>

Industrial ecologists undertake to design industrial ecosystems either from scratch or around an existing plant. Kalundborg, however, emerged in the absence of advance planning and represents a sequence of accommodations and agreements between pairs of firms. Like any ecosystem, this eco-industrial park is continually evolving. New firms may be introduced. Some existing firms increase in size or modify their product lines and input requirements, while other firms decrease in size or disappear altogether.

Some Industrial Ecologists have turned their attention to larger systems, namely entire economies, using the concepts and methods of input-output economics, a systems approach to describing and analyzing an entire economy in terms of the inputs and outputs of dozens or even hundreds of individual industries, products, and resources. The use of input-output models in Industrial Ecology has grown substantially in recent years as their ability to describe both physical stocks and flows and the associated money costs and prices has been emphasized and expanded. Input-output models require a database, a large portion of which for past years is provided on a periodic basis by national statistical offices around the world. When evaluating scenarios about the future, the framework is reliant on technical data about resources and products, and it increasingly makes use for this purpose of the kinds of information originating in MFA and LCA studies.

Input-output studies have investigated such environmentally significant challenges as water scarcity and water management in different parts of the world including China, Spain, and Southern Africa; emissions of carbon dioxide and other greenhouse gases; and the management of a variety of wastes. Emissions of carbon, sulfur, and nitrogen under alternative scenarios about future technological attributes have been estimated for the world economy described in terms of the production and trade in the outputs of a few dozen industrial sectors in over a dozen geographic regions. As concern builds that the industrialized countries are appropriating disproportionately large shares of the earth's resources via resource-intensive imports from developing countries, input-output models of the world economy that incorporate data from MFA and LCA studies are certain to become more prevalent.

An input-output model can represent the complex interplay of ecological and industrial system concepts. Since being introduced in a modified form into ecology, input-output models have been valued by ecologists for their ability to track the paths of flows, thus accounting for indirect as well as direct interactions and allowing for a more accurate estimate of the total (direct plus indirect) energy and biomass requirements. Input-output techniques have also been the basis for developing measures of ecosystem structure, such as throughput and cycling, which have been applied to the analysis of numerous ecosystems. [cross-reference to input-output analysis of biological ecosystems, this volume] The direct relevance of these ecological system measures to industrial systems is evident, especially when recycling of resources is of major interest. As a result these ecological measures have recently been introduced into Industrial Ecology in, for example, analyzing material flow in the nylon tufted carpet industry.

V. Consumption and Sustainable Development

Since its origins, Industrial Ecology has been mainly concerned with reducing the environmental impact of the use of energy and materials in industrial production by improving the efficiency of production processes. Some industrial ecologists have claimed that material inputs could be reduced by substantial amounts (e.g., a factor of four or even ten) without diminishing economic growth. Such technological prescriptions are mainly addressed to public policy-makers and corporate executives on the implicit assumption that they would not require much change in the motives or behaviors of consumers or negatively impact their well-being.

Recently, however, a new emphasis on consumers and consumption has emerged. Many researchers came to doubt that reliance on changes in the sphere of production alone could achieve the required scale of impact. The inflow of social scientists into Industrial Ecology brought the recognition that households are the major decision makers regarding consumption, and analysis about alternative consumption behaviors should be addressed in the first instance to them. In a consumer society, industrial stocks and flows are demand driven, in contrast to the dynamics governing the availability of traditional materials in ecosystems. In an ecosystem, predators have control over the number of prey they seek to consume, but they have no direct control over the number of prey potentially available for consumption. By contrast human consumers, particularly in the most affluent, industrialized economies, have control over not only how much gets consumed but also over what gets consumed and produced -- and through this connection potentially over how it gets produced.

Life cycle analysts and input-output economists have produced a substantial body of work analyzing the environmental impacts of different types of households and their consumption activities. Most attention has focused on motorized mobility, housing, and intake of food because of the demonstrably intensive use of resources to satisfy consumption requirements in these areas. The objective of this research is to explore alternative ways for satisfying the human need for food, housing, and mobility with less environmental damage. Recent studies have provided a framework for bringing physical measures into the analysis of Social Accounting Matrices, datasets compiled by a number of national statistical offices that describe the consumption patterns of distinct types of households. A special issue in 2005 of the Journal of Industrial Ecology is devoted to the industrial ecology of sustainable consumption.

Such investigations are part of a broader inquiry about the sustainability of systems and, in particular, sustainable development [see entry in this volume] of the global economy. Development of alternate energy systems that can substantially reduce reliance on fossil fuels by making more direct use of solar energy in both production and consumption, thus moving industrial systems back in the direction of ecological systems, promises to be an active area of research. A shift in the diets of the affluent from animal-based toward more plant-based foods could have substantial impacts on resource use in agriculture. Such scenarios about the future will be analyzed using frameworks that integrate material flow data, life-cycle descriptions of products and processes, and input-output models of individual economies and of the world economy. As increasing numbers of researchers with roots in different disciplines turn their attention to the challenges of sustainable global development, the distinctive contributions from Industrial Ecology will reflect its origins in the ecology of the industrial system.

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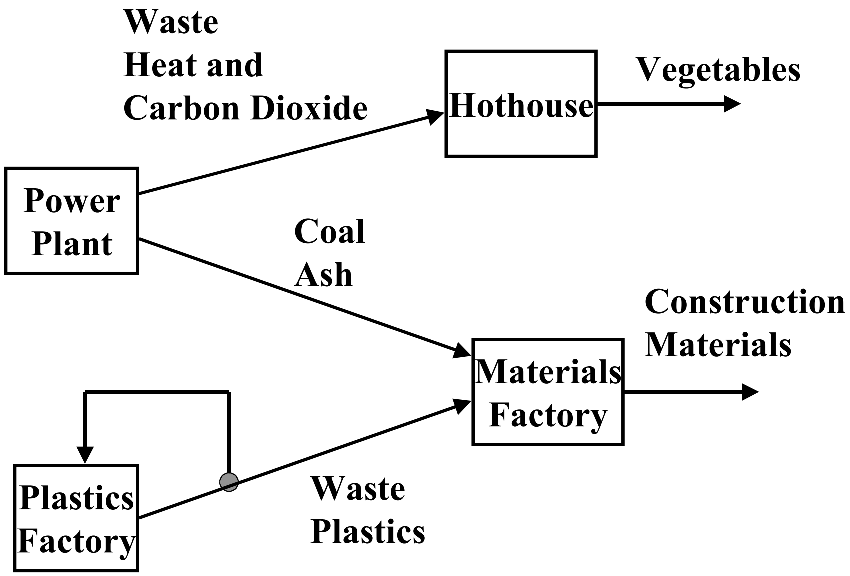

Figure 1. A Hypothetical System for the Reuse and Recycling of Potential Wastes

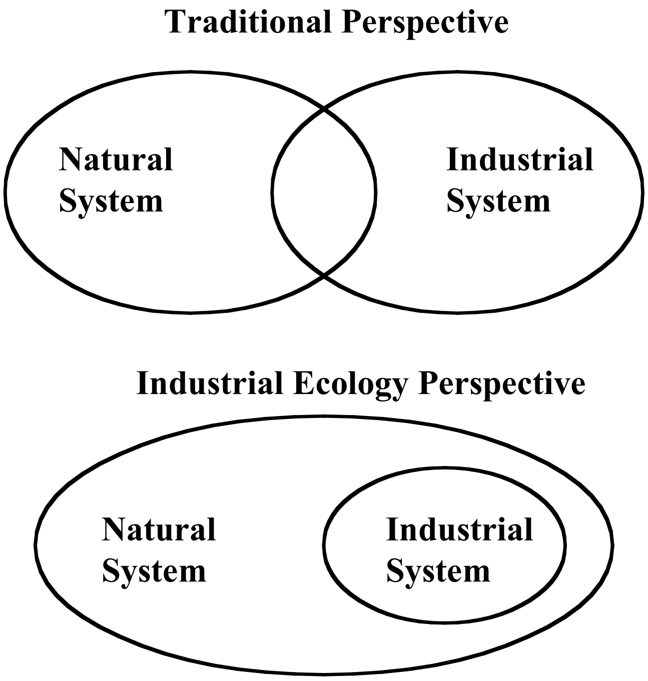

Figure 2a. Conceptual Framework of Industrial Ecology (Source: M. Chertow and M. Portlock, *Developing Industrial Ecosystems: Approaches, Cases, and Tools.* New Haven, CT; Yale University, 2002.)

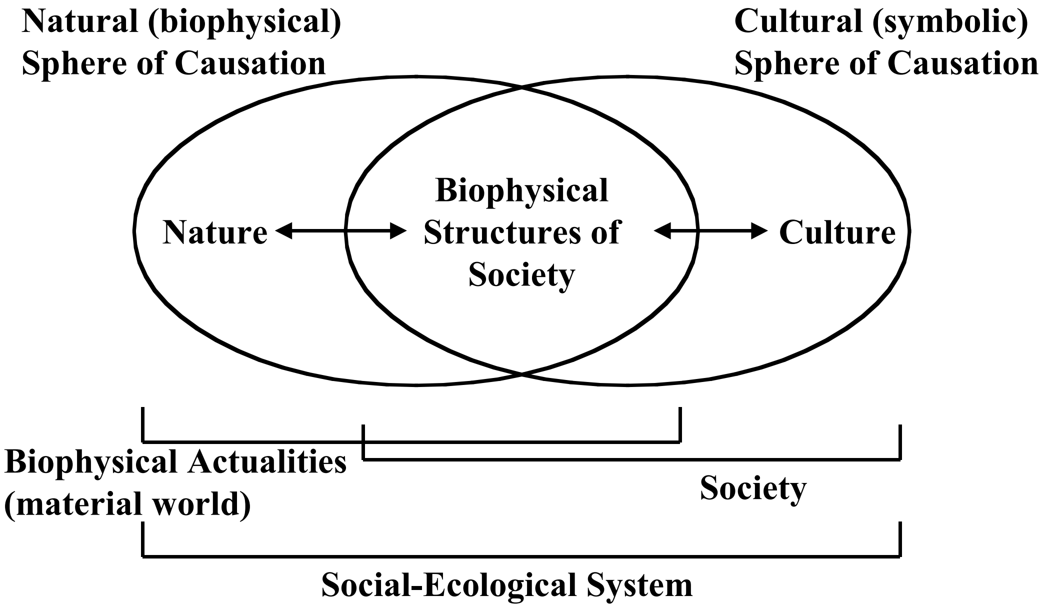

Figure 2b. Social-Ecological Systems as Overlap of a Natural and a Cultural Sphere of Causation **(Source:** Haberl, H., M. Fischer-Kowalski, F. Krausmann, H. Weisz, and V. Winiwarter, 2004. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. *Land Use Policy*. 21:199-213.)

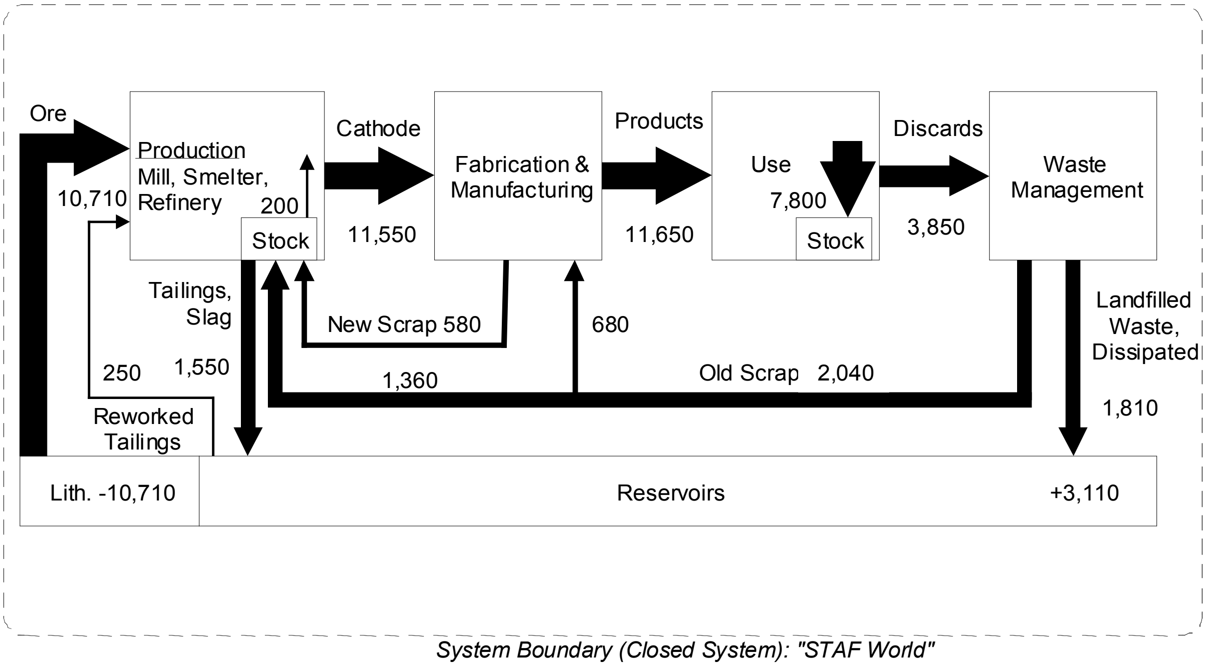

Figure 3. The Global Copper Cycle in the 1990s

The Industrial Ecosystem of Kalundborg Denmark

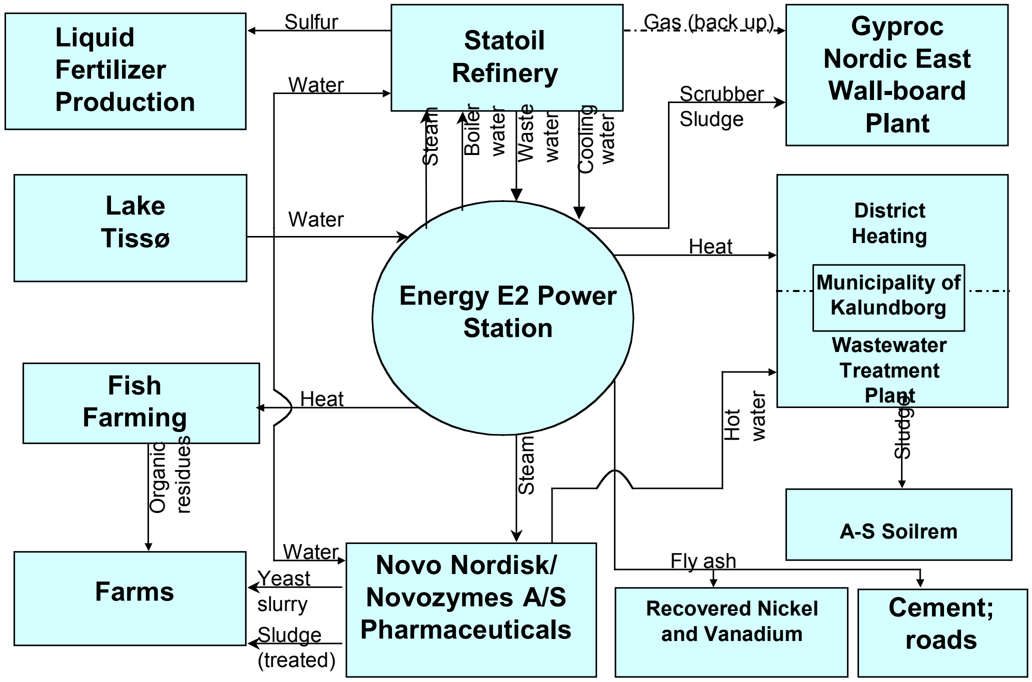

Figure 4. The Industrial Ecosystem of Kalundborg Denmark (Source: M. Chertow and M. Portlock, *Developing Industrial Ecosystems: Approaches, Cases, and Tools.* New Haven, CT; Yale University, 2002.)