Industrial Ecology and Sustainable Engineering

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C H A P T E R 3

Industrial Ecology and Sustainable Engineering Concepts

3.1 FROM CONTEMPORANEOUS THINKING TO FORWARD THINKING

Since the industrial revolution, the activities of firms both large and small have defined much of the interactions between humanity and the environment and significantly shaped social and institutional structure and dynamics. These interactions have, however, traditionally been outside the topics of major significance for corporate decision makers. Technology's influence, and especially the potential magnitude of that influence across the full spectrum of economic activity, has been underappreciated in the business world.

However, no firm exists in a vacuum. Every industrial activity is linked to thousands of other transactions and activities and to their environmental and social impacts. A large firm manufacturing high-technology products will have tens of thousands of suppliers located all around the world, changing on a daily basis. The firm may manufacture and offer for sale hundreds of thousands of individual products to a myriad of customers, each with her or his own needs and cultural preferences. Each customer, in turn, may treat the product very differently and live in areas with very different environmental characteristics; these are considerations of importance when use and maintenance of the product may be a source of potential environmental impact (e.g., used oil from automobiles). The services and cultural patterns that the technology enables will also differ significantly in different communities and societies. When finally disposed of, the product may end up in almost any country, in a high-technology landfill, an incinerator, beside a road, or in a river that supplies drinking water to local populations.

TABLE 3.1 Relating Current Environmental Problems to Industrial Responses to Yesterday's Needs

Yesterday's need	Yesterday's solution	Today's problem
Nontoxic, nonflammable refrigerants	Chlorofluorocarbons	Ozone hole
Automobile engine knock	Tetraethyl lead	Lead in air and soil
Locusts, malaria	DDT	Adverse effects on birds and mammals
Fertilizer to aid food production	Nitrogen and phosphorus fertilizer	Lake and estuary eutrophication

In such complex circumstances, with complicated and intertwined social and environmental impacts at many scales, how has industry approached its relationships with the outside world? Satisfying the needs of its customers has always been pretty well done, at least in market economies. Industry has, however, been less adept at identifying some of the consequences, especially the long-term consequences, of the ways in which it goes about satisfying needs. Since the beginning of the 1970s, when modern environmentalism began to arise, analysis of environmental interactions has increased; examples of a few of these interactions have been collected by Dr. James Wei of Princeton University (adapted and displayed as Table 3.1). The table indicates some of the environmental difficulties created for society in a world in which industrial operations have been perceived as essentially unrelated to the wider world, as suggested in the left side of Figure 3.1.

It is important to note that the relationships in Table 3.1 were not the result of disdain for the external world by industry. Several of the solutions were, in fact, great improvements over the practices they replaced, and their eventual consequences could not have been forecast with any precision. What was missing, however, was any structured attempt to relate the techniques for satisfying customer needs to possible environmental consequences; similar efforts to understand systemic long-term social implications of industrial activity lag behind even the environmental methodologies. For example, we can speak of Design for Environment (or DfE) with some clarity, but development of Design for Sustainability (DfS) is just beginning. While making such attempts does not insure that no deleterious impacts will result from industrial activity, proactive consideration has the potential to avoid the most egregious of the impacts and to contribute toward incremental improvements in impacts that are now occurring or can be well forecast. How are such attempts best made?

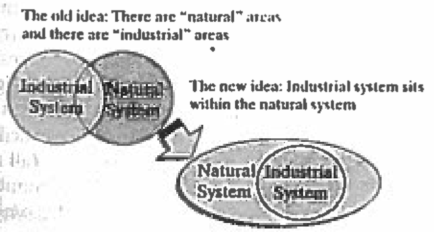

Figure 3.1

The transformation from natural and industrial systems as essentially independent entities to the realization that the industrial system is embedded within the natural system.

The broad approach to industry–environment–sustainability interactions that is described in this book is termed "industrial ecology (IE)." The overall concept is, in part, technological. As applied in manufacturing, it involves the design of industrial processes, products, and services from the perspectives of product competitiveness, environmental concerns, and society. Industrial ecology is also, in part, sociological. In that regard, it recognizes that human culture, individual choice, and societal institutions play major roles in defining the interactions between our technological society and the environment. It recognizes as well that modern technological and societal systems are fully connected with and embedded within the natural world, as indicated at the right side of Figure 3.1.

In a later chapter, we will present an extensive definition of industrial ecology that uses a biological analogy to describe the perspective from which industrial ecology views an industrial system. 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.

In this definition, the emphasis on *deliberate* differentiates the industrial ecology path from unplanned, precipitous, and perhaps quite costly and disruptive alternatives. By the same token, the definition indicates that IE practices have the potential to support a sustainable world with a high quality of life for all.

Practitioners of IE and its companion, sustainable engineering (SE), interpret the word "industry" very broadly: It is intended to represent the sum total of human activity, encompassing mining, manufacturing, agriculture, construction, energy generation and utilization, transportation, product use by customers and service providers, infrastructure systems, service networks, and waste disposal. IE is not limited to the domain within the factory walls, but extends to all the impacts on the planet resulting from the presence and actions of human beings. IE thus encompasses society's use of resources of all kinds.

In considering manufactured products, for example, IE may focus on the study of individual products and their environmental impacts at different stages in their life cycles, but a complementary focus is the study of a facility where products are made. In such a facility, raw materials, processed materials, and perhaps finished components produced by others are the input streams, along with energy. The emergent streams are the product itself; residues to land, water, and air; and transformed energy residues in the form of heat and noise. The IE approach to such a facility treats the budgets and cycles of the input and output streams, and it seeks to devise ways in which smaller portions of the residues are lost and more are retained and recycled into the facility itself or into the facilities of others. Key concepts include conservation of mass (all material must be accounted for), conservation of energy (all energy must be accounted for), and the technological arrow of time—the realization that as society becomes more

technologically advanced, it builds on its past technological base and so cannot sustain or improve itself without strong reliance on technology.

One of the most important concepts of industrial ecology is that, like the biological system, it rejects the concept of waste. Dictionaries define waste as useless or worthless material. In nature, however, nothing is eternally discarded; in various ways all materials are reused, generally with great efficiency. Natural systems have evolved these patterns because acquiring these materials from their reservoirs is costly in terms of energy and resources, and thus something to be avoided whenever possible. In our industrial world, discarding materials wrested from the Earth system at great cost is also generally unwise. Hence, materials and products that are obsolete should be termed "residues," rather than "wastes," and it should be recognized that wastes are merely residues that our economy has not yet learned to use efficiently. We will sometimes use the term "wastes" in this book where the context refers to material that is or has been discarded, but we encourage the use instead of the term "residues," or perhaps the even less pejorative "experienced resources," thereby calling attention to the engineering characteristics and societal value contained in obsolete products of all sizes and types. In doing so, we acknowledge that the law of entropy prohibits complete reuse without loss, but vision is more useful than scientific rigor in establishing this important perspective.

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 ecology in one volume, particularly given the reality that most services, no matter how abstruse, must rely on physical platforms and consume energy. Accordingly, we limit the discussion in most of this book to manufacturing activities, although some of the final chapters explore the subject in more general terms.

3.2 THE GREENING OF ENGINEERING

Engineering has traditionally been regarded as the specialty that employs scientific principles to achieve practical ends. Because engineers are problem solvers in the context of their cultures, at the time when resources and disposal sites were regarded as limitless, their designs made profligate use of resources and unintentionally caused a great deal of environmental damage. Moreover, considerations of the social implications of their professional actions tended to be limited to issues that directly affected the use of their product or design. These approaches are now clearly recognized as outdated, and modern engineers acknowledge the need to do better. But how?

The first step in this increasingly vigorous transformation of the engineering profession is to practice *green engineering*. There are a variety of definitions of this concept, which applies to all the engineering disciplines, but the essence is

> Green engineering is the design, commercialization, and use of engineering solutions, viewed from the perspective of human and environmental health.

The practice centers on minimizing pollution and risk as a consequence of product manufacture and product use, that is, of being more environmentally responsible than had been the case previously.

The second step in this transformation is to move beyond green engineering to *sustainable engineering*. The distinction is that the first step moves in the direction of more responsible technology, but does not ask, "How can social and environmental considerations be fully integrated into the engineering profession?" Nor does green engineering ask, "How far do we need to go?" This latter question is in many ways the province of industrial ecologists, who study the interactions between technology and the wider world. SE draws upon this information to inform itself about limits and goals and then place them within the traditional framework for accomplishing practical ends. Thus, sustainable engineering can legitimately be regarded as the operational arm of industrial ecology, and the essence of IE and SE can be briefly stated:

> Industrial ecology and sustainable engineering provide a template for the environmentally and societally sustainable redesign of the modern world.

A template is particularly useful only if those who use it understand and address the characteristics of the system they are attempting to redesign. It is useful, therefore, to present some of the characteristics of modern technology:

- *Technology is uncertain* (the best solution is never obvious, and experimentation is vital)
- *Technology is progressive* (change occurs by evolution and transformation)
- *Technology is analytical* (measures actions and new ideas)
- *Technology is cumulative* (builds on previous knowledge and existing capabilities)
- *Technology is systemic* (interdependence of technologies is required for progress)
- *Technology is embedded* (technology sits within natural systems)
- *Technology is accelerating* (the waves of technological transitions are ever shorter)

Any attempt to refashion technology must be responsive to these characteristics, and adapt as they change, else the attempt is doomed to failure.

3.3 LINKING INDUSTRIAL ACTIVITY WITH ENVIRONMENTAL AND SOCIAL SCIENCES

The contrast between traditional environmental approaches to industrial activity and those suggested by industrial ecology can be demonstrated by considering several timescales and types of activity, as shown in Table 3.2. The first topic, remediation, deals with such things as removing toxic chemicals from soil. It concerns past mistakes, is very costly, and adds nothing to the productivity of industry. The second topic—treatment,

TABLE 3.2 Aspects of Industry-Environment Interactions

Activity	Time	Focus	Endpoint	Corporate view
Remediation	Past	Local site	Reduce human risk	Overhead
Treatment, disposal	Present	Local site	Reduce human risk	Overhead
Industrial ecology	Future	Global	Sustainability	Strategic

storage, and disposal—deals with the proper handling of residual streams from today's industrial operations. The costs are embedded in the price of doing business, but contribute little or nothing to corporate success except to prevent criminal actions and lawsuits. Neither of these activities is industrial ecology. In contrast, industrial ecology deals with practices that look to the future and seeks to guide industry to cost-effective methods of operation that will render more nearly benign its interactions with the environment and will optimize the entire manufacturing process for the general good (and, we believe, for the financial good of the corporation). Corporate executives are familiar with the liabilities of past and present industry-environment interactions. A challenge to the industrial ecologist is to demonstrate that viewing this interaction from the perspective of the future is a corporate asset, not a liability.

We began Chapter 1 by discussing the "Tragedy of the Commons," in which a large number of individual actions, clearly beneficial over the short term to those making the decisions, eventually overwhelm a common resource and produce tragedy for all. Originally formulated to describe such local commons resources as public grazing lands, the concept was extended to global resources with discoveries such as the Antarctic ozone hole. Industrial processes and products interact with many different commons regimes, and design engineers should interpret the concept of the commons in a very broad way. The concept certainly includes local venues such as city air, local watersheds, and natural habitats. Regional resources are also included, groundwater and precipitation (and their possible chemical alteration) being examples. The global commons calls other regimes to mind: the deep oceans (can oil spills or ocean dumping significantly degrade this resource, or is humanity's influence modest?), the Antarctic continent (50 years of international scientific activity without environmental controls has left a dubious legacy), and, of course, the atmosphere (and its ozone and climate).

In practice, every product and process interacts with at least one commons regime and probably with several, fragile and robust, monitored and ignored, close and distant. Analyses of industrial designs may produce very different results if the same product or process is to be used under the sea, in the Arctic, or on a spacecraft rather than in a factory. Just as industrial ecology extends to all parts of the life cycle, it extends as well to all commons regimes it may affect.

3.4 THE CHALLENGE OF QUANTIFICATION AND RIGOR

Science and engineering are quantitative sciences, drawing much of their value from their exactness. Industrial ecology and sustainable engineering, in contrast, sprang from a few concepts, and rather simplistic ones at that. Here are some examples:

Mimic nature. Nature does many things well, such as minimizing energy use. It also sometimes does things rather badly, such as depositing so many bird droppings on small oceanic islands that the islands become completely hostile environments. Nature's engineering is often a good model to follow, but not always, and only quantification of the consequences can show which path to follow.

The "Circular Economy." The idea of never throwing anything away is a good starting point, but with complex modern technology it is often very expensive in terms of energy and other resources to recover everything. Deciding when to be circular and when not to be is an analytical issue, not a conceptual one.

"Reduce, reuse, recycle." Again, a good general rule, but sometimes reusing an old, inefficient product can result in more harm than good. Is following this rule "committing a little less sin rather than solving the problem," as William McDonough puts it?

The "environmental footprint." It sounds really bad that Amsterdam's footprint is more than 10 times its physical area, but is it? We only know by understanding the assumptions built into the methodology, and the consequences of that footprint, in some detail.

Concepts are important, and they have played a big role in the inauguration of the field described and discussed in this book. As the field moves into its more mature phase, however, it is increasingly quantitative and rigorous. We will present and discuss the important concepts in the chapters that follow, but we will present and discuss even more the ways in which those concepts are now being quantified and made increasingly rigorous.

3.5 KEY QUESTIONS OF INDUSTRIAL ECOLOGY AND SUSTAINABLE ENGINEERING

As in any field, there are key questions in industrial ecology and sustainable engineering. Unlike biological ecology, we are interested not 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. We specifically concentrate on a single species (humans), its relationship with the environment, and the impacts of industrial operations and choices on its social systems. From this broad framework, it is possible to propose a more or less analogous set of key questions to be addressed in this book:

1. How do modern technological cycles operate?
    1.1 How are industrial sectors linked?
    1.2 What are the environmental and social opportunities and threats related to specific technologies or products?
    1.3 How are technological products and processes designed, and how might those approaches be usefully modified?
    1.4 Can cycles from extraction to final disposal be established for the technological materials used by our modern society?
    1.5 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?
    2.1 How do corporations manage their interactions with the environment and society, and how might corporate environmental management evolve?
    2.2 How can the influence of culture/consumption on materials' cycles be modulated?
    2.3 How can engineers appreciate their relationships with environment and society?
    2.4 How might IE systems be better understood?
3. What are the limits to the interactions of technology with the world within which it operates?
    3.1 What limits are imposed by nonrenewable, nonfossil resource availability?
    3.2 What limits are imposed by the availability of energy?
    3.3 What limits are imposed by the availability of water?
    3.4 What limits are imposed by environmental and/or sustainability concerns?
    3.5 What limits are imposed by institutional, social, and cultural systems?
4. What is the future of the technology–environment–society relationship?
    4.1 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?
    4.2 Should systems degraded by technological activity, local to global, be restored, and if so how?

These key questions form the intellectual basis for the discussions throughout the rest of this volume.

3.6 AN OVERVIEW OF THIS BOOK

This book, directed toward codifying and explicating ways in which to transform our technological society from what is largely a nonsustainable system to resemble more and more closely a sustainable system, is divided into sections, as shown in Figure 3.2. Part I, "Introducing the Field," is composed of the information in the first several chapters. The descriptions are intended to set the stage by examining trends and patterns of industrial development and societal and environmental impact, presenting in some detail the biological metaphor upon which industrial ecology is based, discussing the interactions of technology with society and culture, and presenting the concept of sustainability.

Part II introduces and discusses a central concept in industrial ecology, the life cycle of products and how the stresses related to each stage of the life cycle can be assessed. It begins the process of "thinking beyond the factory gate" by considering two simple questions with big implications: "Where did it come from?" and "Where is it going?"

Green and sustainable engineering, which we regard as the operational arms of industrial ecology, are presented in Part III of the book. This is where product design and development, process design and implementation, and industrial ecosystems are described. Part IV addresses the broader topic of technological systems at levels from the individual firm to the planet. It discusses the use, recycling, and loss of resources, country-level material accounts, the implications of energy and water use by technology, analyzing an urban area by treating it by analogy with a biological organism, and the use of models to better understand the interactions that link technology, human systems, and the environment. The fifth and final part of the book is yet more expansive in scope—it deals with corporations and societies as systems; it also tries to understand