1. Industrial ecology: goals and definitions

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Setting out the goals and boundaries of an emerging field is a hapless task. Set them too conservatively and the potential of the field is thwarted. Set them too expansively and the field loses its distinctive identity. Spend too much time on this task and scarce resources may be diverted from making concrete progress in the field.

But in a field with a name as provocative and oxymoronic as industrial ecology, the description of the goals and definitions is crucial. Hence this introductory chapter describes the field of industrial ecology, identifying its key topics, characteristic approaches and tools. The objective is to provide a map of the endeavors that comprise industrial ecology and how those endeavors relate to each other. In doing so, we seek to provide a common basis of discussion, allowing us then to delve into more conceptual discussions of the nature of the field.

No field has unanimity on goals and boundaries. A field as new and as ambitious as industrial ecology surely has a long way to go to achieve even a measure of consensus on these matters, but, as we hope this chapter shows, there is much that is coalescing in research, analysis and practice.

DEFINING INDUSTRIAL ECOLOGY

The very name *industrial ecology* conveys some of the content of the field. Industrial ecology is *industrial* in that it focuses on product design and manufacturing processes. It views firms as agents for environmental improvement because they possess the technological expertise that is critical to the successful execution of environmentally informed design of products and processes. Industry, as the portion of society that produces most goods and services, is a focus because it is an important but not exclusive source of environmental damage.

Industrial ecology is *ecological* in at least two senses. As argued in the seminal publication by Frosch and Gallopoulos (1989) that did much to coalesce this field, industrial ecology looks to non-human 'natural' ecosystems as models for industrial activity.[1] This is what some researchers have dubbed the 'biological analogy' (Wernick and Ausubel 1997; Allenby and Cooper 1994). Many biological ecosystems are especially effective at recycling resources and thus are held out as exemplars for efficient cycling of materials and energy in industry. The most conspicuous example of industrial re-use and recycling is an increasingly famous industrial district in Kalundborg, Denmark (Ehrenfeld and Gertler 1997; Chapter 27). The district contains a cluster of industrial facilities including an oil refinery, a power plant, a pharmaceutical fermentation plant and a wallboard factory. These facilities exchange by-products and what would otherwise be called wastes. The network of exchanges has been dubbed 'industrial symbiosis' as an explicit analogy to the mutually beneficial relationships found in nature and labeled as symbiotic by biologists.

Second, industrial ecology places human technological activity – industry in the widest sense – in the context of the larger ecosystems that support it, examining the sources of resources used in society and the sinks that may act to absorb or detoxify wastes. This latter sense of 'ecological' links industrial ecology to questions of carrying capacity and ecological resilience, asking whether, how and to what degree technological society is perturbing or undermining the ecosystems that provide critical services to humanity. Put more simply, economic systems are viewed, not in isolation from their surrounding systems, but in concert with them.

Robert White, the former president of the US National Academy of Engineering, summarized these elements by defining industrial ecology as . . . 'the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources' (White 1994).

This broad description of the content of industrial ecology can be made more concrete by examining core elements or foci in the field:

- the biological analogy,
- the use of systems perspectives,
- the role of technological change,
- the role of companies,
- dematerialization and eco-efficiency, and
- forward-looking research and practice.

The Biological Analogy

The biological analogy has been applied principally at the level of facilities, districts and regions, using notions borrowed from ecosystem ecology regarding the flow and especially the cycling of materials, nutrients and energy in ecosystems as a potential model for relationships between facilities and firms. The archetypal example is the industrial symbiosis in Kalundborg, but the search for other such arrangements and even more conspicuously the effort to establish such symbiotic networks is emblematic of industrial ecology – so much so that many with only passing familiarity of the field have mistakenly thought that industrial ecology focused only on efforts to establish eco-industrial parks.

This analogy has been posited more generically as well, not merely with respect to geographically adjacent facilities. Graedel and Allenby (1995) have offered a typology of ecosystems varying according to the degree to which they rely on external inputs (energy and materials) and on release of wastes to an external environment. Expressed another way, the ecosystems vary according to the linearity of their resource flows as shown in Figure 1.1: type I is the most linear and reliant on external resources and sinks; type III stands at the other extreme, having the greatest degree of cycling and least reliance on external resources and sinks. The efficient cycling of resources in a biological system is held out as an ideal for industrial systems at many scales. This framework thus connects the biological analogy to strong emphasis in industrial ecology on the importance of closing materials cycles or 'loop closing'.

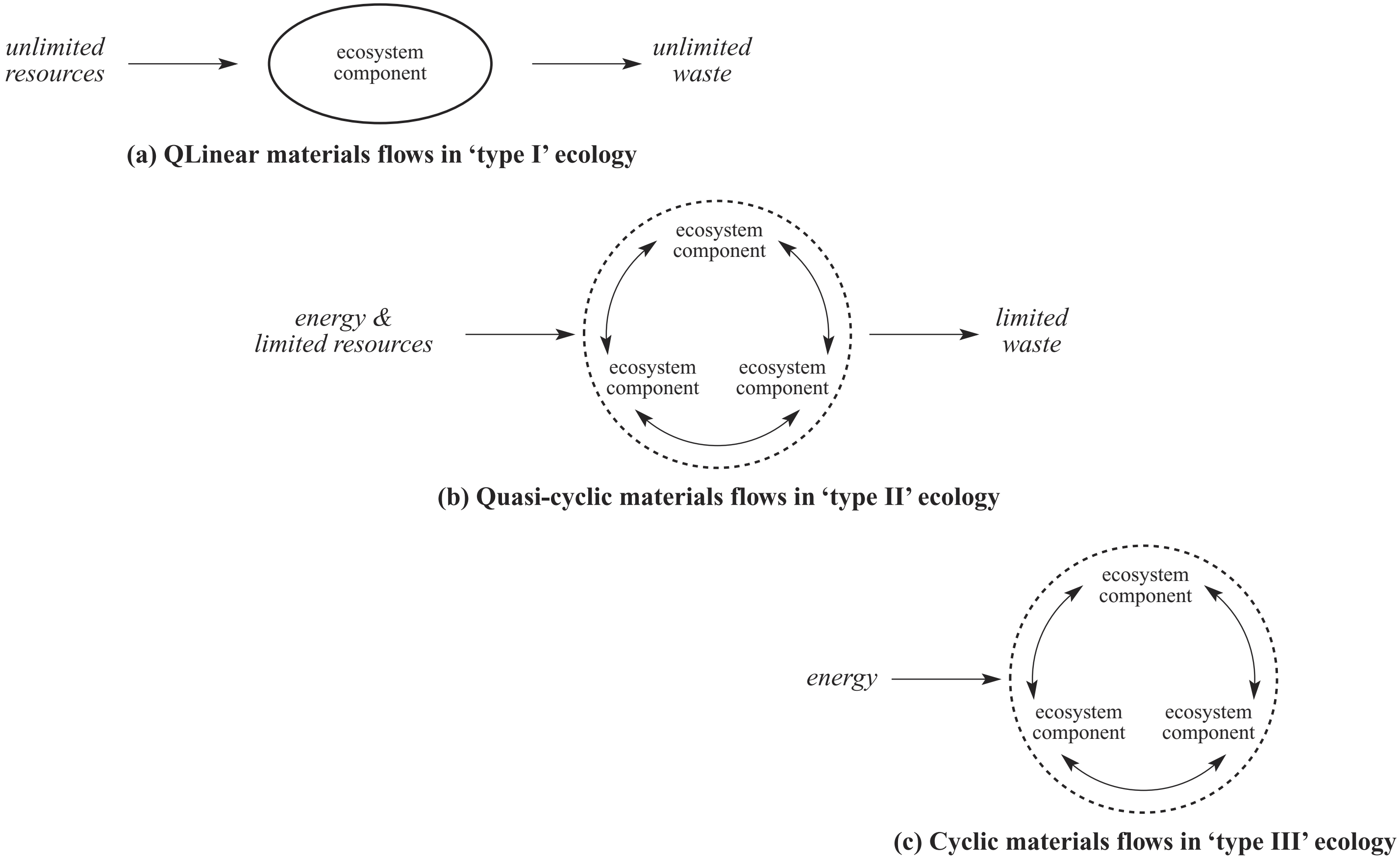

Figure 1.1   Typology of ecosystems

The biological analogy has been explored in other ways. The ecological analogy has, for example, been applied to products as a source of design inspiration (Benyus 1997), as a framework for characterizing product relationships (Levine 1999) and as a model for organizational interactions in technological 'food webs' at the sector or regional levels (Graedel 1996; Frosch *et al.* 1997).

The analogy to ecology is suggestive in other respects (Ehrenfeld 1997). It points to the concepts of community and diversity and its contribution to system resilience and stability as fundamental properties of ecosystems – and as possible models of a different sort for industrial activity. These dimensions of the analogy may point to ways to integrate organizational aspects of environmental management more deeply into the core of industrial ecology, but they have not been as extensively explored as the use of ecosystems ecology with its emphasis on flows and cycling of resources. As Andrews (2000) points out, there are long-standing bodies of scholarship that apply the ecological notions directly to social, as opposed to technological, dimensions of human activity including organizational, human and political ecology. The biological analogy is not confined to ecological similes. A more quantitative embodiment of the biological analogy is the metabolic metaphor that informs materials flow analysis (see below) by analogizing firms, regions, industries or economies with the metabolism of an organism (Ayres and Simonis 1994; Fischer-Kowalski 1998; Fischer-Kowalski and Hüttler 1998). Whether or not there is a significant difference between the ecological and metabolic metaphors is a matter of friendly dispute. For one view, see Erkman (1997).

Systems Perspective

Industrial ecology emphasizes the critical need for a systems perspective in environmental analysis and decision making. The goal is to avoid narrow, partial analyses that can overlook important variables and, more importantly, lead to unintended consequences. The systems orientation is manifested in several different forms:

- use of a life cycle perspective,
- use of materials and energy flow analysis,
- use of systems modeling, and
- sympathy for multidisciplinary and interdisciplinary research and analysis.

The effort to use a life cycle perspective, that is, to examine the environmental impacts of products, processes, facilities or services from resource extraction through manufacture to consumption and finally to waste management, is reflected both in the use of formal methods such as life cycle assessment (LCA) and in attention to approaches that imply this cradle-to-grave perspective and apply it in managerial and policy settings as well as in research contexts. This latter group includes product chain analysis (Wisberg and Clift 1999), integrated product policy (IPP, also known as product-oriented environmental policy) (Jackson 1999), greening of the supply chain (Sarkis 1995) and extended producer responsibility (EPR) (Lifset 1993).

Analysis of industrial or societal metabolism, that is, the tracking of materials and energy flows on a variety of scales is also motivated by a system orientation. Here reliance of research in industrial ecology on mass balances – making sure that inputs and outputs of processes add up in conformance with the first law of thermodynamics – reflects an effort at comprehensiveness. Because of the use of mass balances on these different scales, industrial ecology often involves the mathematics of budgets and cycles, and stocks and flows. By tracking chemical usage in a facility (Reiskin *et al.* 1999), nutrient flows in a city (Björklund *et al.* 1999), flows of heavy metals in river basins (Stigliani *et al.* 1994), or bulk materials in national economies (Adriaanse *et al.* 1997), industrial ecology seeks to avoid overlooking important uses of resources and/or their release to the environment. The tracking of materials and energy is sometimes embedded in the consideration of natural, especially biogeochemical, cycles and of how anthropogenic activities have perturbed those flows. For example, the study of anthropogenic perturbations of the nitrogen cycle is an important contribution of industrial ecology (Ayres, Schlesinger and Socolow 1994).

This same effort to examine human–environment interaction from a holistic perspective is manifested in formal systems modeling including dynamic modeling (Ruth and Harrington 1997), use of process models (Diwekar and Small 1998) and integrated energy, materials and emissions models such as MARKAL MATTER (2000) and integrated models of industrial systems and the biosphere (Alcamo *et al.* 1994). Such systems modeling not only increases the comprehensiveness of environmental analysis; it can also capture some of the interactions among the factors that drive the behavior of the system being studied (for example, Isaacs and Gupta 1997). Conceptual discussions of the nature of industrial ecology and sustainable development have highlighted the importance of non-linear behavior in human and environmental systems and argued that chaos theory and related approaches hold out potential for the field (Ruth 1996; Allenby 1999a), but little such work has been done to date.

Finally, the imperative for systems approaches is also reflected in a sympathy for the use of techniques and insights from multiple disciplines (Lifset 1998a; Graedel 2000). There have been some notable successes (Carnahan and Thurston 1998; van der Voet *et al.* 2000a), but multidisciplinary analysis – where several disciplines participate but not necessarily in an integrative fashion – is difficult and interdisciplinary analysis – where the participating disciplines interact and shape each other's approaches and results – is even more so. Interdisciplinarity remains an important challenge for not only industrial ecology, but all fields.

Technological Change

Technological change is another key theme in industrial ecology. It is a conspicuous path for pursuing the achievement of environmental goals as well as an object of study (Ausubel and Langford 1997; Grübler 1998; Norberg-Bohm 2000; Chertow 2001). In simple, if crude, terms, many in the field look to technological innovation as a central means of solving environmental problems. It should be noted, however, that while that impulse is shared widely within the field, agreement as to the degree to which this kind of innovation will be sufficient to solve technological problems remains a lively matter of debate (Ausubel 1996a; Graedel 2000).

Ecodesign (or design for environment – DFE) is a conspicuous element of industrial ecology (Chapter 36 of this handbook). By incorporating environmental considerations into product and process design *ex ante*, industrial ecologists seek to avoid environmental impacts and/or minimize the cost of doing so. This is technological innovation at the micro level, reflecting technological optimism and the strong involvement of academic and professional engineers. Ecodesign frequently has a product orientation, focusing on the reduction in the use of hazardous substances, minimization of energy consumption, or facilitation of end-of-life management through recycling and re-use. Implicitly, ecodesign relies on the life cycle perspective described earlier by taking a cradle-to-grave approach. Increasingly, it also strives for a systems approach, not only by considering impacts throughout the product life cycle, but also by employing comprehensive measures of environmental impact (Keoleian and Menerey 1994).

Ecodesign is complemented by research that examines when and how technological innovation for environmental purposes is most successful in the market (Preston 1997; Chertow 2000a). The focus on technological change in this field also has a macro version, examining whether technological change is good for the environment or how much change (of a beneficial sort) must be accomplished in order to maintain environmental quality. Here the IPAT equation (*I*mpact = *P*opulation × *A*ffluence × *T*echnology) has provided an analytical basis for parsing the relative contributions of population, economic growth (or, viewed in another way, consumption) and technology on environmental quality (Wernick, Waggoner and Ausubel 1997b; Lifset 2000, Chertow 2001). The equation provides a substantive basis for discussion of questions of carrying capacity implicit in the definition of industrial ecology offered earlier.

Role of Companies

Business plays a special role in industrial ecology in two respects. Because of the potential for environmental improvement that is seen to lie largely with technological innovation, businesses as a locus of technological expertise are an important agent for accomplishing environmental goals. Further, some in the industrial ecology community view command-and-control regulation as importantly inefficient and, at times, as counterproductive. Perhaps more significantly, and in keeping with the systems focus of the field, industrial ecology is seen by many as a means to escape from the reductionist basis of historic command-and-control schemes (Ehrenfeld 2000a). Regardless of the premise, a heightened role for business is an active topic of investigation in industrial ecology and a necessary component of a shift to a less antagonistic, more cooperative and, what is hoped, a more effective approach to environmental policy (Schmidheiny 1992).

This impulse to view business as a 'policy-maker rather than a policy-taker' (Socolow 1994, p.12) is reflected in a diverse set of analyses and initiatives that explore the efficacy of beyond-compliance environmental strategies and behavior. These include product take-back (Davis 1997), microeconomic rationales for beyond-compliance behavior (Reinhardt 1999), corporate environmental innovation pursued to maintain autonomy (Sharfman *et al.* 1998), corporate strategy and sustainable development (Hart and Milstein 1999) and macro-level analyses of the effectiveness of voluntary policy schemes (Harrison 1998).

Dematerialization and Eco-efficiency

Moving from a type I to a type II or III ecosystem entails not only closing loops, but using fewer resources to accomplish tasks at all levels of society. Reducing resource consumption and environmental releases thus translates into a cluster of related concepts: dematerialization, materials intensity of use, decarbonization and eco-efficiency (see Chapters 17 and 18). Dematerialization refers to the reduction in the quantity of materials used to accomplish a task; it offers the possibility of decoupling resource use and environmental impact from economic growth. Dematerialization is usually measured in terms of mass of materials per unit of economic activity or per capita and typically assessed at the level of industrial sectors, regional, national or global economies (Wernick, Herman, Govind and Ausubel 1997; Adriaanse *et al.* 1997). Decarbonization asks the analogous question about the carbon content of fuels (Nakicenovic 1997). Inquiry in this arena ranges from analysis of whether such reductions are occurring (Cleveland and Ruth 1998), whether dematerialization per se (that is, reduction in mass alone) is sufficient to achieve environmental goals (Reijnders 1997) and what strategies would be most effective in bringing about such outcomes (Weizsäcker *et al.* 1997). The intersection between investigation of dematerialization on the one hand, and other elements of industrial ecology such as industrial metabolism with its reliance on the analysis of the flows of materials on the other is clear. There is also overlap with industrial ecology's focus on technological innovation. This is because investigations of dematerialization often lead to questions about whether, at the macro or sectoral level, market activity and technological change autonomously bring about dematerialization (Cleveland and Ruth 1998) and whether dematerialization, expressed in terms of the IPAT equation, is sufficient to meet environmental goals.

At the firm level, an analogous question is increasingly posed as a matter of eco-efficiency, asking how companies might produce a given level of output with reduced use of environmental resources (Fussler 1996; OECD 1998b; DeSimone and Popoff 2000). Here, too, the central concern is expressed in the form of a ratio: output divided by environmental resources (or environmental impact). The connection between this question and industrial ecology's focus on the role of the firm and the opportunities provided through technological innovation is conspicuous as well.

Forward-looking Analysis

One final element of this field is worth noting. Much of research and practice in industrial ecology is intentionally prospective in its orientation. It asks how things might be done differently to avoid the creation of environmental problems in the first place, avoiding irreversible harms and damages that are expensive to remedy. Ecodesign thus plays a key role in its emphasis on anticipating and designing out environmental harms. More subtly, the field is optimistic about the potential of such anticipatory analysis through increased attention to system-level effects, the opportunities arising from technological innovation and from mindfulness of need to plan and analyze in and of itself. This does not mean that history is ignored. Industrial metabolism, for example, pays attention to historical stocks of materials and pollutants and the role that they can play in generating fluxes in the environment (Ayres and Rod 1986). However, industrial ecology does not emphasize remediation as a central topic in the manner of much of conventional environmental engineering.

Putting the Elements Together

There are (at least) two ways in which these themes and frameworks can be integrated into a larger whole. One is to view industrial ecology as operating at a variety of levels (Figure

1.2): at the firm or unit process level, at the inter-firm, district or sector level and finally at the regional, national or global level. While the firm and unit process is important, much of industrial ecology focuses at the inter-firm and inter-facility level, in part, as described above, because a systems perspective emphasizes unexpected outcomes – and possibly environmental gains – to be revealed when a broader scope is used and because pollution prevention, a related endeavor, has already effectively addressed many of the important issues at the firm, facility or unit process level.

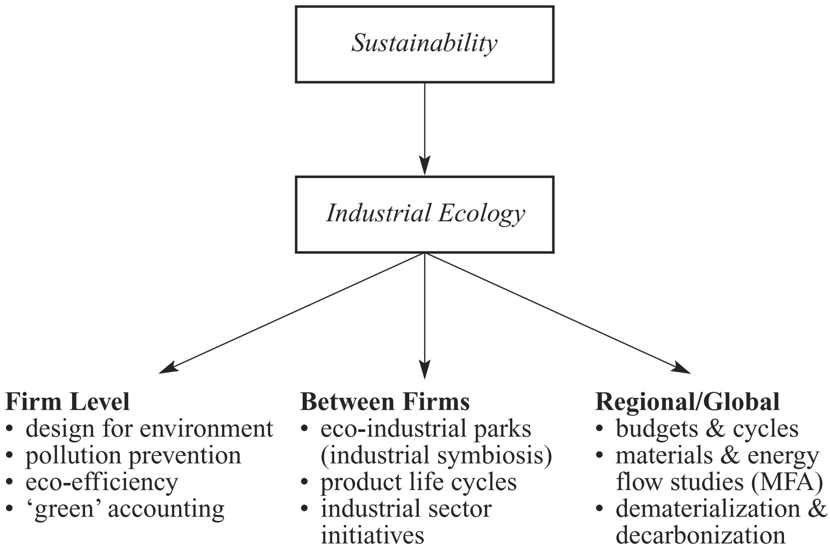

Figure 1.2 The elements of industrial ecology seen as operating at different levels

Another way to tie the elements together is to see them, as in Figure 1.3, as reflecting the conceptual or theoretical aspects of industrial ecology on the one hand and the more concrete, application-oriented tools and activities on the other. In this framework, many of the conceptual and interdisciplinary aspects of the field comprise the left side of the figure, while the more practical and applied aspects appear on the right side.

THE GOALS OF INDUSTRIAL ECOLOGY

Given this overview of the elements of industrial ecology, it is possible to entertain more complicated questions about this field. One set of especially notable and knotty questions revolve around the goals of industrial ecology. Clearly, the field is driven by concerns about human impact on the biophysical environment. Put simplistically, the goal is to improve and maintain environmental quality. Just as clearly, such a statement of goals does not begin to speak to the multiple dimensions of the research or practice in this field.

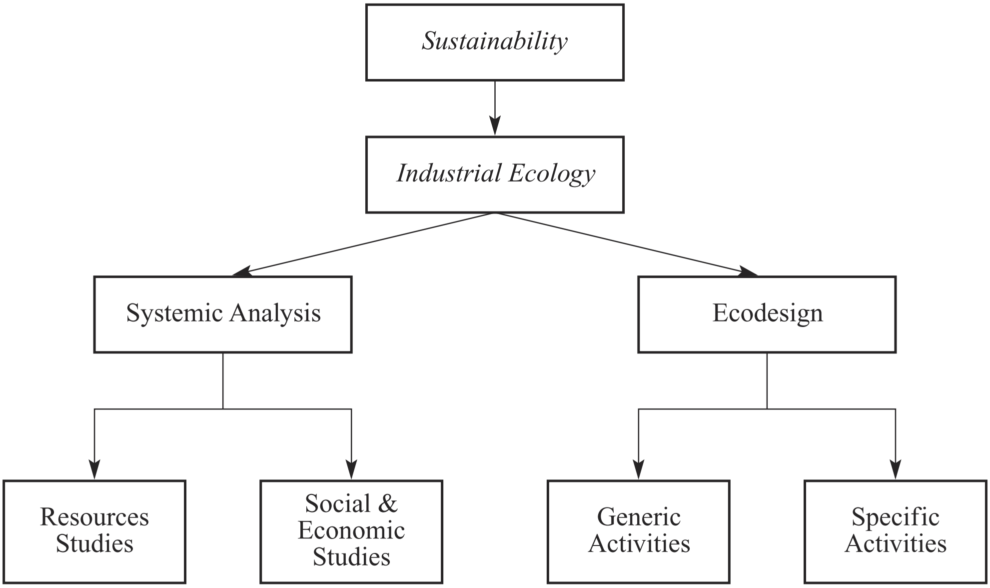

Figure 1.3 Industrial ecology conceptualized in terms of its system-oriented and application-oriented elements

Reducing Risk versus Optimizing Resource Use

Industrial ecology emphasizes the optimization of resource flows where other approaches to environmental science, management and policy sometimes stress the role of risk. For example, pollution prevention (P2) (also known as cleaner production or CP) emphasizes the reduction of risks, primarily, but not exclusively, from toxic substances at the facility or firm level (Allen 1996). Underlying this focus is an argument that only when the use of such substances is eliminated or dramatically reduced can the risks to humans and ecosystems be reliably reduced. In contrast, industrial ecology takes a systems view that typically draws the boundary for analysis more broadly – around groups of firms, regions, sectors and so on – and asks how resource use might be optimized, where resource use includes both materials and energy (as inputs) *and* ecosystems and biogeochemical cycles that provide crucial services to humanity (Ayres 1992a). In concrete terms, this means industrial ecology will sometimes look to recycling where P2 will emphasize prevention (Oldenburg and Geiser 1997). The differences between industrial ecology and P2 are not irreconcilable either conceptually or practically (van Berkel *et al.* 1997). In conceptual terms, P2 can be seen as a firm-level approach that falls under the broader rubric of industrial ecology (as shown in Figure 1.2). In concrete terms, the difference in actual practices by operating entities may not be great, although careful empirical work documenting how these two frameworks have differed in shaping decision making has not been conducted. However, some interesting analysis has been conducted of the risks posed by the recycling of hazardous materials, asking whether it is indeed possible to recycle such substances in an environmentally acceptable manner (Socolow and Thomas 1997; Karlsson 1999).

This is not the only way in which industrial ecology differs from allied fields in its orientation towards risk. The focus of industrial ecology on the flows of anthropogenic materials and energy is not often carried further than the point of release of pollutants into the environment. In contrast, much of traditional environmental science focuses precisely on the stages that follow such release – assessing the transport, fate and impact on human and non-human receptors. Similarly, risk assessment and environmental economics focus on the damages to humans and ecosystems, only sometimes looking upstream to the source of pollutants and the human activities that generate them. In this respect, industrial ecology can be seen as providing a complementary emphasis to these fields by concentrating on detailed and nuanced characterization of the sources of pollution. In a related vein, research in industrial ecology often examines perturbations to natural systems, especially biogeochemical cycles, arising from anthropogenic activities. The impacts of such perturbations can be construed in terms of risks to human health and economic well-being as well as to ecosystems, but the analysis of perturbations differs from the manner in which risk assessment – typically focused on threats to human health – is often conducted. This is not to suggest that industrial ecology ignores questions of risk, fate and transport or environmental endpoints. The intense work on methodologies for life cycle impact assessment (Udo de Haes 1996) is but one example of the field's efforts to systematically incorporate questions of environmental impact. Further, there is work in the field that integrates fate and transport into such analyses (Potting *et al.* 1998; Scheringer *et al.* 1999).

Another aspect of the focus on flows and releases rather than damages and endpoints is that the threats posed by releases – especially of persistent pollutants – endure and the receptors can change in a manner that later causes harms that may not be captured in a typical risk assessment. For example, cadmium deposition to agricultural soils that takes place as a result of naturally occurring cadmium contamination of phosphate fertilizers may not cause significant human health or ecological damage as long as fields are limed and thereby kept alkaline. If the fields are taken out of production, liming is likely to end. Soil pH will thereby increase, and cadmium may become biologically available and environmentally damaging (Stigliani and Anderberg 1994; Chapter 40).

Positive and Normative Analysis

One apparent tension related to the goals of industrial ecology relates to whether the field is positive (descriptive) or normative (prescriptive). If it is positive, then industrial ecology seeks to describe and characterize human–environment interactions, but not necessarily to alter them. On the other hand, if industrial ecology is normative, then some degree of human or environmental betterment is intrinsic to the goals of the field. This tension is reflected in multiple meanings accorded to key terms in the field. For example, the phrase 'industrial ecosystem' refers to facilities or industries that interact in a biophysical sense. Often it is a label for industrial districts like Kalundborg, where residuals are exchanged among co-located businesses. Leaving aside an especially loose usage that denotes any group of facilities, firms or industries, the question arises as to whether an industrial ecosystem necessarily refers to a desirable arrangement – where, for example, the participating firms extensively exchange residuals and thereby minimize releases of pollutants into the environment – or to a neutral description of a network of firms which might constitute complicating this tension are questions of whether these different sorts of inquiry can be construed as modular. That is, can they be pursued independently and *subsequently* melded to generate reliable insights? Or does their intellectual and organizational separation inevitably mean that the modular inquiries will be impoverished, incapable of integration, or even fundamentally misleading (Lifset 1998b)? Put more simply, *must* the questions that industrial ecology seeks to answer be pursued on an interdisciplinary basis to produce reliable answers? Ultimately, it will be the productivity of the various approaches in generating conceptual insights and practical knowledge that will determine their adoption[3].

CONCLUSION

As a new field, industrial ecology is a cluster of concepts, tools, metaphors and exemplary applications and objectives. Some aspects of the field have well-defined relationships, whereas other elements are only loosely grouped together, connected as much by the enthusiasm of the proponents as by a well-articulated intellectual architecture. We do not see this looseness as a fatal flaw in an emerging field, but rather as an opportunity for creativity and constructive discourse, and as a challenge.

NOTES

1. We put 'natural' in quotation marks because there are many ways in which the notion of natural ecosystems is complicated or contested. Many analysts argue that there are no longer any ecosystems unaffected by humankind, although clearly, even in this view, there is wide variation in the degree to which human activity dominates non-human ecosystems. More subtly, the notion of 'natural' is socially constructed and subject to varying interpretations across cultures (Williams 1980; Cronon 1996).
2. Multiple meanings extend to other terms in the field. 'Industrial ecology' is variously used to mean (a) a field of study, (b) a set of environmentally desirable practices and (c) the same practices as in meaning (b), but viewed neutrally. Such plurality of meanings is not unusual, however: 'history' refers both to past events and to the discipline that systematically studies those events.
3. Disagreement about industrial ecology's boundaries are exacerbated by more pedestrian conflation of the ethics and values, the social sciences and public policy analysis. In particular, non-social scientists sometimes do not realize that the social sciences have a primarily positive/analytical focus, characterizing how humans behave, whereas it is the humanities that investigate and debate matters of values. Public policy analysis is often instrumental, asking how effectively certain strategies accomplish a set of public goals. Few industrial ecologists would suggest that the field offers powerful tools for adjudicating disputes over values, even if those disputes are important to the field.