Industrial Ecosystems: Developing Sustainable Industrial Structures
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Abstract

Sustainable development, a concept which has gained increasing prominence in recent years, faces a number of challenges from various aspects of human activity and demographics. Significant among them is the extract-and-dump nature of the current industrial system, in which materials and energy are extracted, processed, used, and 'dumped' in a linear flow through, and out of the economy. Simple consideration of the closed material system that is the earth reveals that finite stocks of resources cannot be used indefinitely in such a fashion. The capacity of the earth to assimilate garbage and pollution is similarly limited, such that the traditional model of industrial activity eventually (soon?) runs up against natural limits, with potentially catastrophic results.

This thesis proposes an alternate model for the organization and management of the technological structures that form the industrial economy. This alternative arises from the discipline of industrial ecology, which has emerged over the past several years as a potential guide for that realignment. This new field promises to create opportunities to improve both environmental performance and business performance, while offering a paradigm for restructuring the industrial system in a fashion that is compatible with notions of sustainability. Where traditional approaches to environmental management focus on individual processes and industrial units, industrial ecology takes a more systemic approach, of broader scope and longer time-frame. A key aspect of this view is the analogy it draws between the human economy and natural ecosystems, which exhibit closed-loop materials and energy flows.

This research applies industrial ecology to the development of inter-firm arrangements which mimic the material and energy cycling of natural ecosystems. Industrial symbiosis is presented as a means to greatly increase the systemic efficiency of material and energy use by creating linkages between formerly separate industrial activities. The result is the formation of integrated industrial complexes in which the byproducts of one process are used as feedstocks of another. A community or network of companies in a region who chose to interact by exchanging and making use of byproducts and/or energy in such a way is defined as an industrial ecosystem. This type of technological organization provides five types of tangible benefits:

- reduction in the use of virgin materials as resource inputs;
- reduction in pollution;
- increased systemic energy efficiency leading to reduced systemic energy use;
- reduction in the volume of waste products requiring disposal (with the added benefit of preventing disposal-related pollution); and
- increase in the amount and types of process outputs that have market value.
In addition, the benefits of collaboration can be expected to spill over into other areas.

This thesis endeavors to explain the evolutionary development of industrial ecosystems and to provide a model of the processes and factors that affect their creation. The most advanced implementation of the industrial ecosystem concept can be found in the Danish industrial town of Kalundborg. Accordingly, this thesis contains an extensive case study of its development, based on a study visit by the author. Existing attempts to create the artifacts of industrial symbiosis are identified and evaluated, including the Zero Emissions Research Initiative based in Japan and the Eco-Industrial Park project in the United States. The Resource Conservation and Recovery Act regulates the management of solid waste, and this regulatory structure creates barriers to the reuse of byproducts in the United States. These difficulties are explored and policy and regulatory solutions are offered. The exchange of byproducts as feedstocks takes place within a broader context of cooperation among businesses. The thesis canvases the emergent field of Inter-Firm Collaboration (also known as Flexible Manufacturing Networks), and applies the highly relevant resulting insight to the development of industrial ecosystems.

Finally, the foregoing experience is consolidated to form a holistic model of industrial ecosystem development, drawing on technological, economic, regulatory, and cultural factors.

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This research would not have been possible without the generous cooperation and assistance of many people. Thanks go out to everyone next to whose name in the footnotes the words "personal communication" appear. Valdemar Christensen of Asnæs Power Plant in Kalundborg was the quintessential generous host (see page 140 for details), and his hospitality and helpfulness, coupled with that of others in that town of lore, were of determining importance in getting this research off the ground. Ernie Lowe was a constant source of information and conversation, a genie at the other end of the line who is putting all this and more into practice. The vast majority of the information contained herein was obtained through personal contacts, so all those who were contacted can barely be thanked enough.

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*  *  *

It was the butler in the living room with the rope.
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Industrial Ecosystems: Developing Sustainable Industrial Structures
Industrial ecology and prospects for sustainable development

Sustainable development, a concept which has gained increasing prominence in recent years, faces a number of challenges from various aspects of human activity and demographics. Significant among them is the extract-and-dump nature of the current industrial system, in which materials and energy are extracted, processed, used, and 'dumped' in a linear flow into, through, and out of the economy. Simple consideration of the closed material system that is the earth reveals that finite stocks of resources cannot be used indefinitely in such a fashion. The capacity of the earth to assimilate garbage and pollution is similarly limited, such that the traditional model of industrial activity eventually (soon?) runs up against natural limits, with potentially catastrophic results. While the timing and extent of these disaster scenarios are open to question, there is growing agreement that sustainability requires a realignment of industrial activity in a manner that is more environmentally benign and imposes less of a burden on the limited resources of the earth.1

The discipline of industrial ecology has emerged over the past several years as a potential guide for that realignment. This new field promises to

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1 See, e.g., Allenby and Cooper, Total Quality Environmental Management, Spring, 1994; Lowe, Corporate Environmental Management, Spring, 1994; Frosch, Physics Today, November, 1994; and Allenby, International Environmental Affairs, Winter, 1992.
create opportunities to improve both environmental performance and business performance, while offering a paradigm for restructuring the industrial system in a fashion that is compatible with notions of sustainability. Where traditional approaches to environmental management focus on individual processes and industrial units, industrial ecology takes a more systemic approach, of broader scope and longer time-frame. A key aspect of this view is the analogy it draws between the human economy and natural ecosystems, which exhibit closed-loop materials and energy flows.

The primary input to mature natural ecosystems is sunlight. The material ingredients of ecosystem function are neither added nor lost over time; instead they circulate within the system. Such flows are said to be 'closed-loop' in nature, because substances that are no longer used in one capacity are returned to the resource base to be available for other uses, instead of being discarded and lost. Industrial ecology is an approach to economic activity and development modeled on this cyclic structure of natural ecosystems, in which the flow of materials and energy into and out of the industrial system is greatly reduced. The ecosystem ideal involves complete loop-closing, such that only limited amounts of energy are required as inputs to the industrial system. While such complete closure may be difficult to achieve in practice, industrial ecology guides development in that direction. Even short of complete loop-closing, industrial activity based on such an ecological conception offers tremendous advantages in terms of greatly reduced harms associated with pollution and waste disposal, while easing the drain on finite strategic resources that are the raw materials for economic activity.

Industrial processes convert inputs of energy and materials into desired products which are then sold on the market. These processes also result in outputs whose production is an undesirable side-effect of making the desired products. Traditionally, these 'secondary' outputs, which are in the form of pollution or waste streams, have had no economic value and have imposed a burden on the environment and/or on disposal space. Their material and energy content has been dissipated and lost. However, limits on disposal space, resource stocks, and the environment's assimilative capacity all point out the need to reconsider the fate of these flows. Accordingly, the closed-loop, ecosystem analogy redefines their nature, since in an ecosystem waste products are recycled as inputs to other organisms.
Sustainability thus requires that human activity, which currently is largely dissipative in nature, be altered to more closely resemble the functioning of natural ecosystems. This goal, in turn, requires a redefinition of process byproducts, generally conceptualized in the past as waste. If materials are cycled through the industrial system as they are in mature ecosystems, then the byproducts of one process become the feedstock of another. Thus the concept of waste gives way to a more integrated, systemic view of material flows, where, in the limit, waste as such does not exist. This is an intuitively appealing result, since the notion of 'waste' is more descriptive of what is done with energy and materials then of the energy and materials themselves.

Two lines of action flow from the industrial ecology analogy. One, which may be placed under the aegis of product policy, concerns itself with the life-cycle impacts of products and services as they move through the economy. In this view, the element of continuity that is intrinsic to the industrial ecology paradigm is one in which the focus is on the products. The processes that produce them are of course relevant, but the frame of reference remains the product, with the various stages of extraction, manufacturing, use, and post-consumer fate moving past that frame of reference. This approach to industrial ecology includes product policy, life-cycle assessment (LCA), and design for environment (DFE).

A different approach to the above implementation/interpretation of the industrial ecology analogy is the notion of industrial symbiosis and its resulting industrial ecosystems. Here the goal is to develop integrated industrial complexes in which byproducts of materials and energy (which are results of inefficiencies in producing the desired products) are put to use as feedstocks instead of being wasted. In contrast to the product policy approach, industrial symbiosis focuses on the fixed production structures of the economy. The frame of reference is the manufacturing/production process; products move through the system but their exact nature is transparent. What is relevant under consideration here is the mix of process inputs and outputs in terms of material and energy flows. Products are relevant only to the extent that they determine, or at least strongly delimit, the possible combinations of the material and energy flows of interest. The element of continuity is the production system, and its flows of materials and energy.
From the standpoint of sustainability, there is no readily apparent reason to prefer the product policy approach to the industrial symbiosis approach. More importantly, there is no readily apparent reason to believe that the two approaches compete with one-another. Yet most institutional attention under the aegis of industrial ecology has been paid to the product policy line of inquiry. This may be explained, in whole or in part, by the fact that, since product policy has a focus on products, its deliberations are transferable to any situation/location in which that product is made. That is, once you have a 'product policy' for product $x$, that policy can hold largely independently of the location of production and the mix of other products and processes.

In contrast, while the general concepts of industrial symbiosis and industrial ecosystems can be developed, their implementation depends on the mix and location of processes within some system boundary. Thus, any implementation of industrial symbiosis will in general have to be a unique application of the generic concept, governed by the co-product/by-product availabilities and resource needs of the industries involved, as well as by management structures, institutional linkages, and the regulatory climate. In contrast to LCA and DFE, the development of industrial ecosystems must cross the firm boundary.

This thesis is concerned with the development of industrial structures in which the use of materials and energy are integrated among different firms and processes, such that the material and energy byproducts of one process are put to use as feedstocks of another. The resulting network is defined below as an industrial ecosystem, and the concept of linking industries in such a way as industrial symbiosis. *The Central Question* that this thesis addresses is:

What factors influence, hinder, and/or promote the development of symbiotic arrangements (and resulting industrial ecosystems) between and among industrial production structures and the businesses that operate them?

**Industrial symbiosis**

Industrial symbiosis is an application of industrial ecology which seeks to optimize the efficiency of material and energy flows through large-scale industrial processes. Fundamental to this approach is the cascading use of energy and the use of industrial byproducts as feedstocks for processes other
than the ones that created them. By creating linkages between formerly separate activities, the demand for resource inputs and the output of pollution and waste are both significantly reduced.

Byproduct reuse centers on matching a process producing a given byproduct with another that uses that material as a feedstock. In such a case the virgin feedstock of the latter process is partially or completely supplanted by the byproduct of the former. Feedstock conditioning may be required to render a byproduct usable as a feedstock. Such conditioning may be the result of pollution control technologies, as is the case in the use of gypsum from scrubber sludge as wall-board. Energy cascading involves the use of the residual heat in liquids or steam from one process to provide heating, cooling, or pressure for another process. For example, residual heat from an electric power plant can be used to heat surrounding buildings.

The most advanced instance of industrial symbiosis can be found in the seaside industrial town of Kalundborg, Denmark. According to Valdemar Christensen, one of the main architects of the symbiosis at Kalundborg and originator of the phrase, industrial symbiosis is "a cooperation between different industries by which the presence of each...increases the viability of the other(s), and by which the demands [of] society for resource savings and environmental protection are considered (e.i.o.)". Kalundborg's four main industries, Aasnaes Power Station, a coal-fired power plant, Statoil refinery, Nordsisk, a maker of pharmaceuticals and enzymes, Gyproc, a plasterboard manufacturer, and the municipality trade and make use of waste streams and energy resources, and turn by-products into raw materials. The symbiosis in Kalundborg and the industrial ecosystem it has created have served as the single most significant model of the implementation of the concepts of industrial ecology. Accordingly, the chapter that follows contains a detailed case study of the development of the Kalundborg industrial ecosystem.

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2 Indigo Development, *Fieldbook on the Development of Eco-Industrial Parks*. Draft version, 1995. Energy has quality; electricity is usually the highest quality form. As energy is used, its form degrades towards lower and lower quality. One measure of the quality of energy is the difference between the temperature of an energy carrier and that of the surrounding environment. In the case of a power plant, a high temperature difference drives the turbines generating electricity, while lower temperature difference steam can be used for district heating and other process needs.

3 Quoted in Holger Engberg, "Industrial Symbiosis in Denmark" Stern School of Business, New York University, 1993.
By altering the traditional 'once-through' structure of materials and energy flows through industrial processes, industrial symbiosis reduces the strain on the surrounding environment as well as on resource stocks. In contrast to traditional pollution-control regulation, industrial symbiosis can be directly profitable for business. Despite these advantages, few examples of industrial symbiosis are found in practice. The Kalundborg example highlights a number of factors that impact on symbiosis development, and these are explored in detail in the Kalundborg case study as well as in Chapter 7, "The Development of Industrial Ecosystems."

**Industrial ecosystems**

An industrial ecosystem is what results from the repeated implementation of industrial symbiosis:

An *Industrial ecosystem* is a community or network of companies and other organizations in a region who chose to interact by exchanging and making use of byproducts and/or energy in a way that provides one or more of the following benefits over traditional, non-linked operations:

- reduction in the use of virgin materials as resource inputs;
- reduction in pollution;
- increased systemic energy efficiency leading to reduced systemic energy use;
- reduction in the volume of waste products requiring disposal (with the added benefit of preventing disposal-related pollution); and
- increase in the amount and types of process outputs that have market value.

Participation in the industrial ecosystem requires more extensive informational linkages among companies and may render participants more co-dependent than traditional arrangements. However, the exchange of byproducts and cascades of energy use are not inherently different in most relevant respects from traditional supplier relationships.
Participation in an industrial ecosystem has at least two further significant attributes. The cooperation required among companies that interact in such a fashion can be expected to transcend the exchange of material and energy byproducts to form more robust linkages. In the Kalundborg example, the companies also collaborate in the areas of worker training and workplace safety. Because industrial symbiosis requires interaction and trust among companies that goes well beyond normal business practice, such expanded collaboration is both a component and necessary precursor of industrial ecosystem development. Appropriately, Chapter 6 of this thesis is a survey of the similarly emergent field of Inter-Firm Collaboration and Flexible Networks, with applications to the development of industrial ecosystems. Results from that field indicate that the cooperation of firms in the exchange and reuse of byproducts and feedstocks should be examined through a wider lens of inter-firm collaboration, with significant attention paid to the institutional and social context in which cooperation is to take place.

The other attribute is the notion of place-based development. Traditional approaches to industrial development and to environmental problems have focused on the individual process and firm as the locus of interest. In contrast, the development of industrial ecosystems requires a holistic view of firms as part of their surroundings, both natural and human-built. Place-based development is being advanced through the Eco-Industrial Park project being undertaken by the President's Council on Sustainable Development and through similar projects as a way to make use of local features and conditions and to better integrate industrial activity into both the natural and the man-made environment. This approach requires a heightened awareness and sensitivity to the interactions of a given process with its surroundings and therefore represents a fundamental shift towards ecological design. The Eco-Industrial Park project is discussed in detail in Chapter 4. For further information on place-based development, the reader is referred, e.g., to *Fieldbook on the Development of Eco-Industrial Parks*, forthcoming from Indigo Development, and to *Designing and Operating Industrial Parks as Ecosystems*, a product of Dalhousie University's School for Resource and Environmental Studies.
The benefits of industrial ecosystems

Kalundborg provides the prototype of an industrial ecosystem. There inter-firm linkages have reduced the material and energy through-put of the participating firms without hindering their production and expansion. It is such a systematic increase in the efficiency of materials and energy use which is called for by industrial ecology4. And while the general public benefits from the symbiosis in the form of reduced environmental loading and better use of resource stock, this public benefit does not have a direct advocate among those managers responsible for bringing it about. Several of the symbiotic linkages developed, however, in response to environmental regulation.

Industrial symbiosis, as explained by its architects, results in systemic pollution-reduction effects. Valdemar Christensen, production manager at Asnæs Power Station, describes a two-dimensional representation with environmental impact on one axis and number of firms on the other (see graph above). Normally, an industrial area's total environmental loading, in the form of pollution and waste disposal needs, has been a simple sum of the

environmental loading of each industry. This scenario is represented in the figure by a straight line.

If, however, the industries cooperate by sharing waste products, then some of what used to be pollution is redirected as raw material to another process. Kalundborg has a number of such examples, which are explored in detail in the following chapter. In cases where such symbiotic linkages can be created, each industry's net environmental impact can be brought below that which it would be if it operated in isolation. Environmental impact thus becomes a downward sloping function of the number of cooperating firms\(^5\).

This model is in fact applicable to describing the total materials and energy through-put of the participating industries, since linkages in an industrial ecosystem not only reduce pollution, but raw materials and energy use as well. Viewed incrementally, the addition of each firm that fits into the symbiosis would require less and less energy and virgin material inputs into the system, and would emit less and less pollution as its waste products would be put to use by another industry. This approaches a vision of an industrial ecosystem with limited inputs and limited waste outputs, in which materials and energy cycle to the full extent possible. The difference between linear throughput and industrial symbiosis is shown in figures 1 and 2.

From this vision follows the ideal of an industrial ecosystem: *in the limit, all material inputs go into products, and all energy is used to do work.* Such an arrangement ensures loop-closing at the processing and manufacturing stages of the economy. To achieve complete loop-closing, however, materials need to be recovered for reuse at the post-consumer stage of the economy as well\(^6\). This is the activity that is commonly referred to as recycling. It is the return of materials to the resource stock when the products they embody have exceeded their useful lives. Such a goal is furthered by, among other things, the product policy aspect of industrial ecology.

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\(^6\) Recovery may also be appropriate at the pre-industrial, mining, extraction, and harvesting stages.
No Symbiosis: Linear Throughput
Figure 1.

Symbiosis: Reduced Throughput
Figure 2.
About this document

This thesis represents the culmination of a year and a half of research as part of the M.I.T. Program on Technology, Business, and Environment, under the direction and sponsorship of Dr. John Ehrenfeld. I have endeavored to bring together what relevant information I could find on industrial ecosystems and their development. I have been helped along the way by the good offices of many people. As this is a new field, it is changing rapidly and, hopefully, expanding. I can thus make no claim of completeness. However, the issues identified and discussed in this document all promise to have a significant impact on the direction and extent of future progress in this area. These issues span a number of disciplines and in some cases are only related by their effects on ecosystem development. As a result, the chapters that follow are more akin to separate modules than to a progressively constructed argument. Not to fear; the final chapter applies what comes before to the area of concern.

Chapter 2 contains a detailed case study of the development of the industrial ecosystem in Kalundborg, Denmark. It is based on five days of interviews during a visit by the author in July of 1994. Kalundborg is the birthplace of the study of industrial symbiosis as such, and represents by far the most advanced incarnation of an industrial ecosystem currently to be found. As a result, my visit and the ensuing case study have formed the cornerstone of this research effort.

Chapter 3 introduces the Zero Emissions Research Initiative, an undertaking based at the United Nations University in Tokyo which is seeking to develop zero-emissions industrial clusters. This effort got underway in 1994 and, while not stemming from industrial ecology, represents a promising implementation of the industrial ecosystem concept.

Chapter 4 is a discussion of the President’s Council on Sustainable Development’s Eco-Industrial Park Project, which is the first public-sector effort in the U.S. to promote the inter-firm application of industrial ecology on a large scale.

A substantial body of environmental law regulates industrial activity in the United States, and Chapter 5 offers an examination of the effects of that regulatory structure on prospects for symbiosis development. Specifically, barriers to byproduct reuse caused by regulation under the Resource
Conservation and Recovery Act are discussed, accompanied by proposed solutions.

The exchange of byproducts as feedstocks takes place within a broader context of cooperation among businesses. Chapter 6 addresses the emergent field of Inter-Firm Collaboration (also known as Flexible Manufacturing Networks), which provides highly relevant insight into the development of industrial ecosystems.

The foregoing experience is consolidated in Chapter 7, which endeavors to provide a holistic picture of the development of industrial ecosystems. This chapter is the forward-looking product of the one and one-half years of research upon which this thesis is based. It also offers some parting thoughts on the direction and prospects for future development.

Those who are pressed for time and interest should focus their inattention on Chapters 3 through 6, as the remaining chapters (1, 2, and 7) form the heart of this thesis.
Chapter 2.
The Kalundborg Industrial Ecosystem: Development and Implications

Introduction

Kalundborg, Denmark is home to a system of arrangements by which four large industries and a town share material and energy resources and reuse waste materials. Industrial symbiosis, as this practice has come to be called, has significantly reduced the environmental impact of industry in the area while decreasing its need for energy and raw materials. Although it was not explicitly intended as such, this beneficial arrangement forms the most highly developed implementation of the industrial ecosystem concept to be found anywhere in the world. As a result, Kalundborg has become the prototype for the application of industrial ecology. A number of articles\textsuperscript{7} and at least one extensive case study\textsuperscript{8} have been devoted to describing this system of arrangements. However, the dynamics of their development had not previously been documented. This account picks up where the descriptions left off by taking an in-depth look at how the Kalundborg ecosystem came about. It is based on five days of interviews conducted by the author during July of 1994 which would not have been possible without the generous hospitality of Valdemar Christensen and Asnæs Power Station.


\textsuperscript{8} Holger Engberg, "Industrial Symbiosis in Denmark" New York University, Stern School of Business 1993.
The Concept of Symbiosis

According to Valdemar Christensen⁹, one of the main architects of the symbiosis at Kalundborg and originator of the phrase, industrial symbiosis is "a cooperation between different industries by which the presence of each...increases the viability of the other(s), and by which the demands [of] society for resource savings and environmental protection are considered (e.i.o.) ¹⁰. Kalundborg's four main industries, Asnæs Power Station, a coal-fired power plant, Statoil refinery, Novo Nordisk, a maker of pharmaceuticals and enzymes, Gyproc, a plasterboard manufacturer, and the municipality trade and make use of waste streams and energy resources, and turn by-products into raw materials.

The symbiosis developed gradually and without a grand design over the past twenty-five years, as the firms sought to make economic use of their byproducts and to minimize the cost of compliance with new, ever-stricter environmental regulations. Although industrial symbiosis is presented here as an implementation of industrial ecology, the Kalundborg system was not based on this philosophy, but rather on creative business sense and deep-seated environmental awareness. However, the linkages among the local firms (as well as some more distant ones) through which materials and energy are transferred are the sort of loop-closing measures that are called for by an industrial ecology paradigm.

The power plant significantly increases the overall efficiency of converting coal to useful energy by selling excess heat to the town for district heating and by heating its own fish farm. The plant also sells steam to Statoil and Novo Nordisk, gypsum from its SO₂ scrubber to Gyproc, and fly ash to construction firms. Statoil refinery sells its flare gas as fuel to Asnæs and to Gyproc instead of burning it off, and sends its cooling water to Asnæs thereby reducing the power plant's fresh-water requirements, while selling pure sulfur from its desulfurization plant to a sulfuric acid maker. Novo Nordisk generates a great deal of organic sludge as a process byproduct, which it treats and distributes to local farmers as a fertilizer supplement. At the time of its inception, this scheme was the lowest-cost way of complying with

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⁹ Valdemar Christensen is production manager of Asnæs Power Station in Kalundborg, Denmark.
¹⁰ Quoted in Holger Engberg, "Industrial Symbiosis in Denmark" Stern School of Business, New York University, 1993.
regulations. Gyproc makes plasterboard by using the power plant's scrubber byproduct and fuel gas from the refinery.

Each of these linkages bears an economic advantage for the participating firms, while reducing the pressure on the environment and on resource stocks. While the participating companies herald the environmental benefits of the symbiosis, it is economics which drives or thwarts its development. From the perspective of public policy, however, the environmental and resource benefits should provide the motivation to create incentives which encourage such cooperation. The linkages at Kalundborg have reduced the material and energy through-put of the participating firms without hindering their production and expansion. It is such a systematic increase in the efficiency of materials and energy use which is called for by industrial ecology\textsuperscript{11}. And while the general public benefits from the symbiosis in the form of reduced environmental loading and better use of resource stock, this public benefit does not have a direct advocate among those managers responsible for bringing it about. Several of the symbiotic linkages developed, however, in response to environmental regulation.

As discussed in the previous chapter, industrial symbiosis results in systemic pollution-reduction effects. This result is not lost on the Kalundborg participants, who take pride in the environmental benefits of their efforts. Valdemar Christensen, production manager at Asnæs Power Station, has advanced the notion that environmental impact becomes a downward sloping function of the number of firms cooperating in symbiotic arrangements. This approaches the vision of an industrial ecosystem with limited inputs and limited waste outputs, in which materials and energy are utilized to the full extent possible.

**Symbiosis Results**

Approximately eleven physical linkages comprise much of the tangible part of the industrial symbiosis in Kalundborg. They are the arrangements of materials and energy flows which go beyond the traditional, linear nature of industrial resource use. There are four types of tangible benefits which derive from the symbiotic arrangements:

• reduced reliance on resource inputs - especially water, also coal, oil, gypsum, fertilizer, etc.

• reduction in pollution - lessened thermal and chemical water pollution, reductions in CO₂ and SO₂ air emissions, greatly reduced pollution or potential contamination from land disposal.

• increased efficiency of converting fuel to useful energy - energy cascades have increased the efficiency of coal burning from 40% to over 90% (as an upper bound); refinery flue gas is used instead of burned off.

• beneficial uses of materials formerly treated as waste - several examples. Substantial disposal costs are avoided, and process byproducts are used as inputs elsewhere, foregoing the need for virgin materials.

These results include:

• Inter-firm linkages have reduced the water demand of the four big participants by between 20-25%, depending on whose numbers one uses. The most recent assessment presented by Statoil¹² is a reduction by 1.2 million cubic meters per year, from 4.8 million to 3.6 million. A water treatment facility recently completed by Novo Nordisk should make another 900,000 cubic meters per year of water available for re-use within the symbiotic system, and Gyproc is investigating possibilities for its use. Freshwater is scarce in the area, with industries more and more reliant in Lake Tissø as groundwater is depleted.

• Oil consumption has been reduced by 19,000 tons per year, due to the substitution of power plant heat for municipal heating and of refinery flue gas for oil at Gyproc and Novo Nordisk.

• Coal consumption is reduced by 30,000 tons per year, or about 2% of the power plant’s requirements, by substituting with refinery flue gas.

• CO₂ emissions have been reduced by 130,000 tons per year, or by about 3%. This reduction is due in part to the substitution of refinery flue gas for coal in the power plant’s boilers.

• SO₂ emissions have been reduced by 25,000 tons per year, or 58%.¹³ This reduction is due mostly to scrubbing at the power plant and at Statoil, and

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¹² Slides from Statoil presentation at CONCAWE-MOL Seminar, Siófok, Hungary. Oct. 6-8, 1993

¹³ Numbers differ on this issue as well. 25,000 tons is indicated on the slides cited above. "Facts About Industrial Symbiosis in Denmark", a document written in March of 1992 at Asnæs, credits the symbiosis with a 900 ton SO₂ reduction, prior to scrubbing by the power plant and the substitution of refinery flue gas for some of its coal. It can be inferred that at least 900 ton
in fact could be higher than 58%. These results may not be directly attributable to industrial symbiosis, but scrubbing byproducts are used as feedstocks.

- Conversion of byproducts into raw materials not only reduces pollution and demand for waste disposal space, but also replaces the use of virgin materials. Gyproc, the plasterboard maker, gets about 80,000 tons of gypsum, 2/3 of its yearly requirement, as a byproduct of the power plant’s scrubber. It has also substituted a continuous stream of fuel gas from the refinery for oil to fire its dryers.

- Other waste-to-raw-material conversions involve 135,000 tons per year of fly ash, 2800 tons per year of sulfur, and 800 tons of nitrogen and 400 tons of phosphorus in the form of biosludge fertilizer.

In addition, once managers of the various firms started talking, they realized that the cooperation among their companies had other benefits as well. One such area is worker training. Companies formerly had to send employees to Copenhagen to receive specialized training because their small numbers did not warrant bringing the required instructor to Kalundborg. The increased openness that has accompanied the symbiosis has more recently enabled the firms to find areas of overlap among their worker training needs, making it cost-effective to provide training jointly in Kalundborg. Another area of increased cooperation has been general worker safety, not limited to concerns regarding specific symbiotic linkages.

**Symbiosis Chronology**

1959  Asnæs Power Station commissioned

1961  Statoil Refinery commissioned; water piped from Tissø Lake

1972  Gyproc A/S established; gas is piped from Statoil Refinery

1973  Asnæs Power Station draws water from Tissø Lake through a pipeline after expansion

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reduction can be credited to symbiosis arrangements, while much of the 25,000 ton reduction is attributable directly to pollution-control technologies. However, the two should not be considered in isolation.

14From, Holger Enberg, “Industrial Symbiosis in Denmark”
1976 Novo Nordisk starts delivery of sludge by trucks to farmers

1979 Asnæs Power Station starts to supply fly ash to cement producers, including Aalborg Portland

1981 Asnæs Power Station produces heating for the municipality of Kalundborg

1982 Asnæs delivers process steam to Statoil and Novo Nordisk

1987 Statoil pipes cooling water to the boilers of Asnæs Power Station

1989 Novo Nordisk is hooked up to Tissø Lake for freshwater, replacing groundwater use

1990 Statoil Refinery starts delivery of hot, liquid sulfur to Kemira in Jutland

1991 Statoil delivers treated waste water to Asnæs power plant to meet various water consumption needs (but not for use as boiler feedwater)

1992 Statoil pipes fuel gas to Asnæs Power Station after installing desulfurization plant.

1993 Asnæs supplies gypsum to Gyproc after installing scrubber

Symbiosis Linkages

The tangible linkages are as follows:

- **Link**
  Gas piped from Statoil Refinery to Gyproc A/S

- **Cost of the link / Who paid**
  Gyproc pays for gas

- **Date of Inception**
  1972

- **Participants**
  Statoil to Gyproc

- **Material / Energy Flows**
  Gyproc obtains all of the 900 kg of gas per hour it uses from Statoil. Statoil’s flare gas contains a mixture of ethane and methane, from which impurities are removed. 90-95% of the time Gyproc exclusively uses gas piped continuously from Statoil. Gyproc switches to a butane backup system when fuel gas from the refinery becomes unavailable.
• **Cause / Impetus / Inspiration**  
  Used to fire the furnaces which dry the gypsum; it is cheaper than using oil, and the equipment is easier to maintain. Flue gas replaces oil.

• **Alternatives**  
  Oil-fired furnaces, and burning off the flue gas - a double environmental whammy. In order to hedge itself against disruptions of gas flow from Statoil has installed a butane back-up system.

• **Impacts on Participants**  
  No matter what mix and proportion of petroleum products Statoil makes, it will produce the fuel gas, with minor variations in the ratio of ethane to methane; therefore its flare gas production is very robust with respect to changes in product mix. The gas flow to Gyproc is for the most part continuous, with a temporary reduction in volume when the refinery changes its production mix. In addition, the refinery shuts down for four to five weeks every fourth year. Gyproc is given advance warning of each impending reduction or shutdown.

  Gyproc continuously needs gas to fuel the ovens in which its plasterboard, which starts out as a wet mush, is dried to its solid consistency. The fuel gas from Statoil is very light, and therefore very difficult to liquefy, which makes its storage difficult. Gyproc thus has minimal capacity to store fuel gas from Statoil, but has a butane back-up system. Butane can be liquefied readily, and therefore stored readily, and Gyproc can operate using butane indefinitely. Thus, even though Gyproc needs fuel gas continuously, a breakdown in its gas supply from Statoil will not halt production and therefore is not a concern for management. Switching from one fuel source to another is simple and quick.

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• **Link**  
  Novo (later - Nordisk) delivers treated process sludge (NovoSlam) by trucks and pipelines to farmers as fertilizer supplement

• **Cost of the link / Who paid**  
  Free to farmers, saving about $50,000 per year for the average recipient farmer. Novo has built a network of 40 miles of pipelines, and spends about $3 million a year distributing the stuff. This arrangement is still cheaper than conventional waste disposal under more stringent regulations passed in the 1970's. At the time the regulations were passed, spreading the treated sludge as fertilizer was the least-cost way to meet stricter requirements. Distribution costs are about $7 per cubic meter of sludge by truck, and $3.50 per cubic meter by pipeline.

• **Date of inception**  
  1976

• **Participants**  
  Novo Nordisk, about 1000 regional framers, trucking contractors

• **Material / energy flows**
Novo Nordisk produces approximately 3000 cubic meters of sludge per day, which it must continuously dispose of. Possible alternate disposal mechanisms include drying the sludge and landfiling the remaining solids, and converting the sludge to biogas. However, the infrastructure exists only for distributing the sludge as fertilizer, so this is the only viable disposal option. The firm contracts the spreading responsibilities to others; all the farmers have to do is call and ask for or accept the sludge when it is offered. The sludge is free of heavy metals.

- **Cause / Impetus / Inspiration**
  Nitrogen-rich, watery biomass, or sludge, is a major byproduct of Novo’s fermentation processes by which enzymes and insulin are produced. Until the mid-1970s, the sludge was mixed with waste water and discharged into the sea. Now Novo distributes treated sludge free to farmers, avoiding higher alternate disposal costs. In 1976 regulations placed significant restrictions on the discharge of organics into the sea to reduce biological oxygen demand (BOD). Novo Nordisk therefore needed an alternative way to dispose of its sludge, and at the time treating it and distributing it as fertilizer was the least-cost alternative.

- **Alternatives**
  Novo: conventional, high-cost disposal was the original alternative. Other possibilities to receive more recent consideration are using the sludge as pig feed and using it to produce biogas. Producing biogas may in fact be more economically attractive if not for the large existing infrastructure investment in the sludge distribution network. Novo Nordisk must continuously spread the sludge it produces because it has not developed the infrastructure for any other large-scale disposal alternative; and if it can’t dispose of its sludge it must stop production.

- **Impacts on Participants**
  Farmers get high-quality fertilizer free, reducing their use of chemical fertilizers. Disposal security is Novo Nordisk’s primary concern. The company could charge for its fertilizer but chooses not to in order to assure continued acceptance by the farmers. Novo Nordisk produces about 3000 cubic meters of sludge per day, with no practicable large-scale disposal alternative than spreading it as fertilizer. There is storage space for only three day’s production worth of sludge and the production would have to be shut down at a cost of 10 million Danish Kroner ($1.67 million U.S.) if that storage capacity were exceeded. Accordingly, Novo Nordisk has assigned three employees the full-time task of arranging for deliveries to fields. Such deliveries are highly sought after by farmers during dry weather but much less so when the ground is wet, because then the heavy spreading equipment can damage the soil. Approximately 1000 farmers are intermittently recipients of the sludge. Not every field is so treated every day, so that the scheduling problem is not trivial.

  Novo Nordisk also benefits from the green image that its efforts afford it in the competitive European detergent and enzyme market, where consumers are very eco-conscious in their purchases.
Plans are in place to extend the already impressive pipeline network for sludge distribution, motivated not only by cost savings but also by public irritation regarding noisy, polluting diesel trucks cross-crossing the countryside. The company's environmental report indicates that in the future, at least one-third of the sludge will be moved by pipeline instead of by tanker truck.\textsuperscript{15}

\begin{itemize}
  \item **Link**
  Asnæs Power Station sells fly ash to cement producers, as well as for road building and construction
  \item **Cost of the link / Who paid**
  Asnæs built an ash silo with unloading facilities, sells the stuff to Aalborg Portland A/S
  \item **Date of Inception**
  1979
  \item **Participants**
  Asnæs Power Station, Aalborg Portland, others
  \item **Material / Energy Flows**
  170,000 tons of fly-ash and 30,000 tons of clinker annually, as waste products of coal-fired power generation.
  \item **Cause / Impetus / Inspiration**
  The drive to make economic use of Asnæs' waste products and to avoid disposal costs
  \item **Alternatives**
  Landfilling (?)
  \item **Impacts on Participants**
  fly ash goes to cement manufacture
\end{itemize}

\begin{itemize}
  \item **Link**
  Asnæs Power Station produces district heating for the Kalundborg Municipality. Heat from the power plant's cooling water is distributed throughout the town and carried into homes and other buildings by pipes.
  \item **Cost of the link / Who paid**
  Municipality pays Asnæs at a price indexed to the market price of coal, and charges the people who are thusly heated; their heating costs are lower than for oil heat. The municipality paid for the main capital investment at a time when finance costs were high, and the payoff to the town has so far not been large. Installation of the piping for district heating in homes is expensive, and this cost is born by the home-owners. Initially the Kalundborg Kommune, or town government, only encouraged such investment, but more recently has required that every house have district heating by 2005.
\end{itemize}

\textsuperscript{15}Environmental Report 1993 Novo Nordisk
Residents take out loans to pay for installation, and these loans are guaranteed by the town. This measure was met with some popular opposition, but that has since died down.

- **Date of Inception**
  1981, ongoing

- **Participants**
  Asnæs Power Station, Municipality and residents of Kalundborg

- **Material / Energy Flows**
  Equivalent of 225,000 tons of steam per year, potentially raising the efficiency of energy extraction from coal from 40% to over 90%, although not all of the available waste heat is required to heat the town. A much larger city could be served by the waste heat, and in fact much of Copenhagen is heated in a similar fashion by a power plant located there. Oil heat is replaced, thereby greatly reducing the town's demand for oil.

- **Cause / Impetus / Inspiration**
  Asnæs needs to make economic use of its waste heat to decrease its cost of electricity production in order to be competitive with other power plants. The town was mostly heated by oil before, the availability of which became doubtful during the oil crisis. According to Fleming Malkær of the Kommune, heating security was the main driving force of the switch to district heating. The town also enjoys air quality benefits, as the smoke from the numerous oil furnaces used to foul the air. None-the-less, oil would be cheaper for the foreseeable future.
  Such a shift apparently is not unique to Kalundborg, as the first Danish national energy plan of 1976 has called for and resulted in a "massive change in heat supply from individual oil heaters to district heating and natural gas."

- **Alternatives**
  Oil heat

- **Impacts on Participants**
  Asnæs supplies heat to almost 5,000 houses and buildings, eliminating the use of 3,500 oil-fired house heating systems and contributing to a 19,000 tons per year oil use reduction. Over 90% of the heat demand in the area is met this way and all of it will be by the year 2005. Asnæs does not need to operate all of its five boilers in order to meet the heat demand, and a complete shutdown would be possible during the summer when heating needs are negligible.

- **Link**
  Asnæs delivers process steam to Novo (Nordisk) and Statoil

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16 The Danish Environmental Strategy Danish Ministry of the Environment 1994. p.27
• **Cost of the link / Who paid**
  A two-mile long steam pipe connects the three plants. Novo paid for its share. Statoil pays for the steam.

• **Date of Inception**
  1982

• **Participants**
  Asnæs, Novo Nordisk, Statoil

• **Material / Energy Flows**
  Statoil gets 40% of its steam requirements from Asnæs, about 140,000 tons a year. Novo Nordisk gets all its steam from Asnæs, about 215,000 tons per year. The steam is used to heat pipes and tanks at Statoil, while Novo Nordisk uses it as a source of heat and pressure and to carry its sludge.

• **Cause / Impetus / Inspiration**
  For Novo Nordisk: cheaper to construct a pipeline and buy steam from Asnæs than to renovate and upgrade their boilers. So the need to renovate/upgrade was the impetus. The reason was similar for Statoil. For Asnæs, this arrangement represents another opportunity to make economic use of its waste heat.

• **Alternatives**
  For Novo, upgrade and renovate its old boilers (1982).

• **Selection criteria**
  Novo - save money -- pipeline cheaper than boiler upgrades.

• **Impacts on Participants**
  Reduced discharge of cooling water into Kalundborg Fjord. Novo totally reliant on Asnæs for process steam. J Christensen: we are "vulnerable to any irregularities in Asnæs' steam generation." so this was a major decision, requiring a high degree of cooperation and information exchange between the two firms. Novo Nordisk has so far experienced no problems with the steam from Asnæs, and reports that the pipeline paid for itself in two years. Cost savings were 7 million Kroner (over $1 million U.S.) a year for the first several years, but Asnæs will soon raise the price of steam to reduce Novo’s savings to 2-3 million Kroner per years.
  Asnæs is contractually obligated to supply steam continuously, even if it could meet its power generating requirements by buying cheaper power from Norway and Sweden. The price Asnæs receives for its steam includes a premium for this possibility. The arrangement does not require any extra technical investment or changes on the part of Asnæs, only that it perpetually run enough boilers to produce the steam required.

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• **Link**
  Statoil pipes cooling water to the boilers of Asnæs Power Station

• **Cost of the link / Who paid**
  Investment in pipeline shared equally by Asnæs and Statoil. Asnæs pays for the water, but saves on using lake water.
- **Date of Inception**
  1987
- **Participants**
  Statoil, Asnæs Power Station
- **Material / Energy Flows**
  Water from lake Tissø to Statoil; also to Asnæs but this is substituted for in part by about 700,000 m³ of reused cooling water; this along with wastewater make up nearly 75% of Asnæs’ fresh-water requirements.
- **Cause / Impetus / Inspiration**
  Statoil: community resistance to thermal pollution of fjord. Asnæs: high cost of water from lake Tissø and awareness of water scarcity in general.
- **Alternatives**
  Statoil: discharge into fjord. Asnæs: fresh water piped from lake Tissø.
- **Impacts on Participants**
  Reduced water intake by Asnæs, reduced waste water discharge, and reduced public irritation, by Statoil.

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- **Link**
  Asnæs Power Station fish farm
- **Date of Inception**
  1989
- **Participants**
  Asnæs Power Station, fish
- **Material / Energy Flows**
  Waste heat goes in. 250 tons of fish per year come out.
- **Cause / Impetus / Inspiration**
  Deriving economic value from waste heat
- **Impacts on Participants**
  Asnæs fish farm operates 57 ponds worth 250 tons of fish per year, using heated cooling sea water. The fish like the warmer water and grow faster. Sludge from the fish farm is sold as fertilizer.

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- **Link**
  Statoil refinery delivers hot, liquid sulfur from its desulfurization plant to Kemira
- **Cost of the link / Who paid**
  Liquid sulfur sold to Kemira, transported in special trucks.
- **Date of Inception**
  1990
- **Participants**
  Statoil, Kemira
- **Material / Energy Flows**
  Statoil’s desulfurization plant yields hot, yellow, liquid sulfur.
• **Cause / Impetus / Inspiration**
  Statoil built its desulfurization plant in 1990 under community and regulatory pressures to reduce the amount of SO₂ formed when burning the refinery’s flue gas. The liquid sulfur is recovered by the desulfurization plant and sold, as is the purified gas. Here a pollution control technology recovers waste materials that are then sold as a process inputs and conditions the waste stream - the flare gas - to be used as fuel by Asnæs.

• **Alternatives**
  Desulfurization (removing H₂S) inevitably yields these products, so that the symbiotic potential of the products of pollution control were not relevant to the choice of pollution control technology, if indeed there was a choice.

• **Impacts on Participants**
  By separating its waste stream, Statoil is able to sell its components.

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• **Link**
  Asnæs uses treated waste water from Statoil for cleaning and other purposes (but not as boiler feed water).

• **Cost of the link / Who paid**
  Asnæs paid for the pipeline but gets its water free, also reduces fresh water intake from Tissø.

• **Date of Inception**
  1991

• **Participants**
  Statoil, Asnæs

• **Material / Energy Flows**
  Up to 900,000 m³ (500,000 by a more conservative estimate) of treated wastewater per year is available as a continuous flow, but Asnæs has been using only about 200,000 cubic meters per year. This is less than the amount expected by Statoil, and in fact the water is only used in Asnæs' newer and separate Unit 5 boiler, which accounts for about half of the plant's generating capacity. The treated waste water is led to the sea from Statoil along a drainage ditch, into which Asnæs can tap by way of an adjoining pipeline.

• **Cause / Impetus / Inspiration**
  Community pressure and anticipated regulations led Statoil to invest in a biological treatment plant, which renders the water clean enough for use by Asnæs. Asnæs thus can forego the use of fresh water. Here too, a pollution control technology renders a waste usable as a process input.

• **Alternatives**
  Asnæs: acquire fresh water from lake Tissø via pipeline. Statoil: discharge all treated waste water into the sea.

• **Impacts on Participants**
  Reduced water intake and discharge of waste water
• **Link**
  Flue gas from Statoil to Asnæs

• **Cost of the link / Who paid**
  Asnæs pays for the gas used. Statoil spent about $3.5 million on the gas export system, but expects to recover that within four years. Asnæs saves 30,000 tons of coal per year.

• **Date of Inception**
  1992

• **Participants**
  Statoil, Asnæs

• **Material / Energy Flows**
  The byproduct of petroleum processing contains much sulfur, which is removed by the refinery's desulfurization plant. A gas remains, which is used in-house as fuel, and sold as fuel to Asnæs power station (also to Gyproc beginning in 1972, see above). The sulfur goes to Kemira. Asnæs can forego 30,000 tons of coal per year. This, too, as a result of pollution control technologies.

• **Cause / Impetus / Inspiration**
  Statoil: desulfurization plant built under community and regulatory pressures to reduce emissions of SO₂, which forms as flue gas was burned. Asnæs: less coal burned mean reduced CO₂ emissions. This reduction forms a part of an overall greenhouse emissions reduction program that Asnæs has to present to the county government.

• **Impacts on Participants**
  Drastically reduced discharge of SO₂ and CO₂ by Statoil since scrubbing makes waste products marketable instead of being flared off.

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• **Link**
  Gypsum from Asnæs to Gyproc

• **Cost of the link / Who paid**
  $115 million scrubber for power plant emissions, removes 90% of sulfur content. Though gypsum is sold, the scrubber cost will not be recovered. Selling the gypsum more or less covers the cost of the calcium carbonate required to operate the scrubber.

• **Date of Inception**
  1993

• **Participants**
  Asnæs, Gyproc

• **Material / Energy Flows**
  Scrubbing with calcium hydroxide captures calcium sulfate (industrial gypsum) at a rate of 80-85,000 tons per year, about 2/3 of Gyproc's input requirements. Gyproc also gets gypsum from the scrubber of a German
power plant, and still uses virgin rock gypsum because to mix in varying proportions with the scrubber gypsum (mostly for ceiling tiles).

- **Cause / Impetus / Inspiration**
  Agreement between Danish power stations and the government to reduce overall sulfur air emissions (*a performance standard for the industry*) Where to undertake scrubbing and choice of specific technology were left to the industry. The use of the scrubber's byproduct was a key reason to scrub at Asnæs, even though little of the capital cost is recovered this way. Gyproc obtains the gypsum from Asnæs' scrubber, as well as from that of another power plant, under a long-term contract which locks in a price which is much lower than the price of imported natural gypsum. Once again, a result of pollution control technologies.

- **Alternatives**
  Gyproc: purchasing imported natural gypsum from open-pit mines in Spain at higher prices and/or scrubber gypsum from more distant power plants.

- **Selection criteria**
  Low price, sufficient quality.

- **Impacts on Participants**
  Gypsum is an input to the building industry, and it was important to the scrubber technology choice that Gyproc, the largest Dutch plasterboard manufacturer, was 2 miles down the road. There was extensive prior consultation between the two firms and Asnæs was given material specifications for its gypsum. Gyproc had experimented with gypsum from a German power plant's scrubber before, as well as with other, unsuccessful sources. Gyproc obtains gypsum from Asnæs under a ten year contract and sells that which it does not use to other plasterboard makers. Gyproc's considers its relationship with Asnæs just as it would be with any other supplier.

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**A Potential Link:**

In response to a law passed in the late 1980's requiring tighter controls on the discharge of liquid waste containing nitrogen and phosphorus, Novo Nordisk completed a wastewater treatment plant in the fall of 1992. Gyproc is now considering whether this more thorough treatment is sufficient to render the water usable for plasterboard making. In addition to evaluating the economics of investing in a pipeline between the two firms as opposed to getting its water from elsewhere, Gyproc "must be 150% sure that the water is 110% fine". Such Pete Rose-like effort is necessary to ward off any perception by Gyproc's customers that its plasterboard is made from scrap. As of the summer of 1994, these discussions are on-going.
Symbiosis Requirements

The symbiosis in Kalundborg is worthy of study in and of itself, but even more so as a possible model for such development elsewhere. To this end, it is worth examining some of the conditions which have been necessary or at least helpful in making the symbiosis in Kalundborg possible.

The industries must fit together.

Kalundborg is host to four different process industries. Asnæs and Statoil produce energy in the form of heat, steam, and fuel gas, while all participants consume energy in various forms. Linkages such as those found in Kalundborg do exist elsewhere, but usually one or two at a time. For example, it is not uncommon in cold climates to use the excess heat produced by power plants for district heating. Novo Nordisk operates a similar plant in North Carolina, which also spreads its sludge as fertilizer. It would thus appear that the serendipitous mix of industry outputs and industry needs makes such a highly developed symbiosis possible in Kalundborg while the potential may exist elsewhere as well.

The industries must be geographically close.

This statement, echoed by several architects of the symbiosis, is more true of some of the linkages than of others. Certainly distance is a factor that affects the economic viability of symbiotic arrangements, as the farther something must be transported, the more expensive it is to get it there. This is especially true in the case of heat and steam, in which temperature and pressure are the commodities which must be transported. The construction of pipelines has been a major infrastructure investment for the firms in Kalundborg, and the greater the distance, the longer the pipeline and the greater the cost.

Close geographical proximity is not an absolute requirement even in Kalundborg, however. Gyproc obtains much of its gypsum from the scrubber of nearby Asnæs, but also from the scrubber of a much more distant German power plant. Statoil sells sulfur to Kemira, which is nowhere near Kalundborg. And Asnæs sells fly ash and clinker to industries elsewhere.

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17 The extent to which transportation cost is of determining importance is called into question, however, if one considers that Gyproc's supply of virgin gypsum is shipped from 4000 km (2500 miles) away.
The Kalundborg example indicates that geographical closeness is very important for the sharing of physical energy, such as heat and pressure, and only helpful in the transportation of material resources.

*The mental distance between the participants must be short.*

This requirement is at least as important as the previous one. It is said that a monkey will write the collected works of Shakespeare given enough time with a typewriter. Yet the types of inter-firm arrangements found in Kalundborg did not and cannot arise out of thin air, nor from within traditional corporate boundaries. Openness, communication, and trust are necessary among the firms involved. Kalundborg's small size and relative isolation have been important elements in bringing this about. According to Gyproc's Finn Grobb, Kalundborg is a small society in which managers of the various firms often run into each other, providing opportunities for them to find out what's going on with their neighboring companies. If there were forty large industries instead of four, or if the managers were dispersed throughout the suburbs of Copenhagen, then this sort of communication would be much more difficult. The fact that the four firms are planted in the same interconnected society in which their employees live makes inter-firm cooperation more readily achievable.

*Both cultural and regulatory pressures encourage environmental awareness.*

Although each firm strives for economic gain through each symbiotic arrangement, the symbiotic business linkages are created amid a backdrop of widespread and deep-seated environmental awareness. As managers they are profit-seekers, but as individuals they are environmentalists. Valdemar Christensen the power plant manager looks for ways to increase the economic value of the coal burned by Asnæs Power Station, while Valdemar Christensen the individual takes pride in bringing about a more sustainable future. It is encouraging that these two goals can exist in parallel.

The Danish regulatory framework encourages this sort of evolution. Firms are required to submit plans to the overseeing county government detailing their efforts to continually reduce their environmental impact. A cooperative relationship is fostered between government and the regulated industries, and as a result the firms seem to focus their energies on finding creative ways to become more environmentally benign, instead of fighting the regulators. At the same time, the flexibility afforded the firms for
compliance allows development of the kind of creative arrangements found in Kalundborg.\textsuperscript{18}

**Symbiosis Development**

Although it is presented here as such, industrial symbiosis in Kalundborg did not develop as a case study for the application of industrial ecology. Rather, the symbiotic links can roughly be divided into two categories. The initial links tended to involve the sale of waste products without any significant pretreatment. This pattern includes the initial sale of Statoil's flue gas, Asnæs' sale of fly ash, clinker, waste heat and process steam, as well as the use of cooling water to heat fish farm ponds. These arrangements were based on a re-routing of what used to be waste, without the need to alter the byproducts to any significant extent.

The more recent links, however (most of those over the last seven years or so) have tended to be dependent upon and a direct outgrowth of the application of pollution control technologies. These links, which comprise just over half of the symbiotic arrangements, do not simply move regular process byproducts around, but alter the processes and disposal practices to make them more environmentally benign. The symbiotic relationships that comprise these links are the direct results of and dependent upon these pollution control measures.

It was community and regulatory pressure to eliminate thermal pollution of the fjord (along with general water scarcity) that was a major impetus for the power station's use of the oil refinery's cooling water. Changes in regulations regarding water pollution rendered the treatment and distribution of Novo Nordisk's sludge the least-cost disposal alternative. Scrubbing for SO$_2$ by the power plant and desulfurization at the refinery conditioned the waste stream to turn what used to be pollution into fuel gas, sulfur, and gypsum. And pressure to alleviate water pollution compelled the refinery to invest in a wastewater treatment facility which now renders the water clean enough to be re-used by the power plant.

Valdemar Christensen of Asnæs power station explains this evolution. Existing incentives alone will be sufficient to inspire a certain amount of

\textsuperscript{18} Danish EPA apparently goes even further, by attempting to find uses for all waste streams on a case-by-case basis. This informal program is motivated by a scarcity of disposal space.
symbiosis, that which is economically attractive. This is the low-hanging fruit. Other symbiotic arrangements which would yield environmental benefits are potentially available at this point, but cost more than conventional practices. To go further, political impetus is necessary - to require reductions in pollution and/or to adjust prices to make symbiotic arrangements economically viable. Such external signals are not sufficient, however, since innovative and pioneering cooperation is required among companies for symbiosis to occur. Yet such cooperation is only viable if it makes economic, not just environmental, sense.

The stricter environmental regulations which have in large measure been the driving force for the more recent linkages have been *performance standards*, not *technology standards*. This distinction is significant because it has allowed the local firms to choose pollution control technologies which render their waste streams usable as feedstocks elsewhere, yielding an additional benefit beyond pollution reduction. From among several alternatives, Asnæs Power Station chose a scrubber technology which resulted in the production of gypsum as its byproduct. This gypsum is sold to Gyproc, reducing Asnæs’ cost of pollution control. The distribution of Novo Nordisk’s treated sludge as a fertilizer was motivated by requirements that the firm decrease its emissions into seawater. The method by which such emissions were to be decreased was not specified, leaving Novo Nordisk the flexibility to develop the use of its sludge as a fertilizer. In addition, the firm’s recently completed wastewater treatment facility employs a fermentation process chosen by Novo Nordisk because of the company’s familiarity with fermentation.

The flexibility allowed by performance standards for pollution control as opposed to fixed technology standards was a necessary condition for several of the symbiotic linkages to develop. If one accepts this as a generalizable requirement for industrial symbiosis, then performance standards should be viewed more favorably than technology standards from the point of view of encouraging and allowing such development. The prospect that one type of pollution control technology is preferable to all others in all situations is therefore rendered unlikely, such that the concept of ‘Best Available Control Technology’ loses meaning in an industrial ecology context.

The Kalundborg example points out another interesting relationship between industrial symbiosis and pollution control technologies. The
relevance of waste stream conditioning as feedstock pretreatment should temper the silver bullet view of industrial ecology. A systemic perspective that redefines the concept of waste is indeed necessary, but may not be sufficient in many specific instances in which a waste stream requires some treatment before being usable as a process input elsewhere. In the Kalundborg example, pollution control technologies such as scrubbers play a necessary intermediary role, transforming waste streams into valuable, usable materials. In general, it may be helpful in an industrial ecology system to consider a role for such intermediaries, which condition a waste stream so that it becomes usable as a feedstock of another process.

Salient Issues Regarding Symbiosis in Kalundborg
The following section contains a discussion of a number of issues associated with the development of symbiosis in Kalundborg which are relevant to the development of such arrangements elsewhere.

- Who in the companies supports/makes these decisions/arrangements? Who is opposed and why?

According to Valdemar Christensen at Asnæs Power Station, no one was opposed to linkage decisions because they were earning money, and thus were like any other business decisions. (of course some may be opposed to ordinary business decisions) In general, each company has its own economic interest in mind. Negotiations are reportedly intense and just like those for any other business deals.

Kalundborg city has required that all its residents install the piping necessary for district heating, which uses hot water from the power plant’s excess heat, replacing individual oil furnaces. There was some opposition to this requirement among the locals, but they have since acquiesced.

- What is the role of resource scarcity in these arrangements? Is this scarcity felt by the firms through prices only, and if not then how else?

Freshwater is scarce in Kalundborg. The town and some firms have been using groundwater, but the water table is getting to be low, so they need alternate sources. The town operates a pipeline from nearby lake
Tissø, and charges for the water. The scarcity is thus felt by the symbiosis partners as a direct cost, and this in fact has inspired water reuse schemes.

The oil crisis in the seventies inspired the town government to invest in the infrastructure required for district heating, which uses the power plant's excess heat. In this move away from in-situ oil-fired furnaces, heating security was the town's driving force.

- What is the role of regulation? Do the Kalundborg firms receive special consideration from the regulators due to the symbiosis? How has the government supported / hindered these efforts?

Regulation has played a major role in inspiring linkages and forcing the use of pollution control technologies which made linkages possible. According to Valdemar Christensen, "economics alone will bring you a certain amount of symbiosis - the low lying fruit. To go further, you need political impetus - to require pollution control technologies and / or to adjust prices to make symbiotic arrangements economically viable."

Specifically, Danish power plants were recently required to decrease their aggregate SO2 emissions. The decision as to how to distribute the emission reductions was left to the industry. Not all power plants built scrubbers, but Asnæs did, in large part because it can make use of the scrubber by-product by selling it to Gyproc, the plasterboard manufacturer. This linkage will never pay for the scrubber, however, but does more or less pay for the calcium carbonate, which is the scrubber feed -- this would thus be lower-cost compliance.

Novo Nordisk distributes its treated waste sludge as fertilizer to farmers. This scheme was the least-cost way to meet 1976 regulations restricting the outlet of organics into the sea. Before 1976, there was some mechanical treatment of the sludge prior to discharge. Although the large investment in treatment and distribution infrastructure makes changing to an alternative disposal mechanism unattractive, the conversion of sludge into biogas fuel would be a salient alternative if the initial decision had to be made today.

Statoil, the oil refinery, sells its treated flue gas to others - the treatment was brought about by regulations restricting the amount of SO2 emitted into the air. Also, regulatory pressure forced more complete waste-water
treatment, with the result that the water is now clean enough for miscellaneous uses by Asnæs.

Special consideration from regulators is not granted *per se*. The power plant, and I assume the other industries as well, have to plan and execute programs to reduce their environmental impact, and this process is supervised by county government. Symbiosis linkages thus form part of Asnæs’ overall program, and thus implicitly receives regulatory favor.

- How robust is the system / symbiosis to disruptions? (especially Novo’s steam requirements being fully met by Asnæs) Are there stand-by’s and at what cost?

The system is, in fact, fairly robust. Gyproc receives gypsum from Asnæs’ scrubber and gas from Statoil. The gas is so light that it cannot be easily liquefied, so that Gyproc has very little storage capacity for the gas and instead uses it in a continuous flow from the refinery. To cope with any disruptions in the flow of gas from the refinery, Gyproc has a large butane tank (butane can be liquefied and thereby stored compactly), and the factory can operate continuously on butane, if necessary. The refinery does go down every 4 years for four to five weeks, and Gyproc is given distant early warning of this imminent event. There are also temporary reductions in gas flow when the refinery changes its product mix; Gyproc is similarly informed of these events.

Gyproc also gets gypsum, its main raw material, from the scrubbers of Asnæs and another power plant. This material is easily stock piled. At the same time, it still buys mined gypsum because it uses a mixture of the two. Asnæs is treated as any other supplier, and it could be replaced easily by another source of gypsum; such as virgin/mined, or perhaps another power plant.

Novo Nordisk relies on Asnæs Power Station for all of its steam needs. Asnæs has five boilers, each of which generates a good deal of steam. Asnæs is contractually bound to supply steam to Novo, which generally is not a problem, since not all boilers are required to meet Novo’s (and Statoil’s) steam needs. In case the power plant must go down, it has emergency boilers, which it would have even without the symbiosis, which can kick in to supply the steam. It is conceivable that at some point
in the future Asnæs could buy electricity from hydro power plants in Sweden and Norway cheaper than it could generate it. It would still have to run some boilers to meet its contractual steam supply obligations, and the price of the steam to Novo and Statoil includes a premium as insurance against this possibility.

Statoil supplies gas as fuel for the plasterboard dryers at Gyproc (as well as a fuel supplement to Asnæs). This gas contains methane and ethane, which are mostly what remain after the refinery’s scrubber removes impurities from the flare gas. No matter what petroleum product mix the refinery produces, the ethane / methane mix will be produced as a byproduct, though the ratio of the two components, and therefore the gas’ energy content, may change somewhat. The linkages do not constrain Statoil’s choice of product mix. As the refinery expands its capacity from 3 to 4.8 million tons per year, more gas will become available to be burned by Asnæs in place of coal.

Novo Nordisk only has storage capacity for about 3 days worth of its sludge - therefore, it must continuously find farmers who will accept the sludge as fertilizer, or else stop production, at a cost of 10 million Danish Kroner ($1.66 million) per day. Such a shutdown has never happened. About 1000 farmers participate in this scheme, but each farm does not receive sludge every day. Therefore, Novo Nordisk’s problem is one of finding enough farmers every day to accept that day’s production of sludge.

Novo receives all of its steam from Asnæs, and reports no problems with steam delivery and steam quality over the history of the link.

- How are the scales of the processes interrelated? Are there alternate suppliers and how readily available are they?

Gyproc, recipient of scrubber gypsum and refinery flue gas, considers these symbiosis linkages to be like any other supplier relationships. Alternate suppliers of both gypsum (virgin, mined gypsum, or other power plants) and fuel (butane) are readily available, and changing sources is quick and easy. Conversely, Gyproc sells excess gypsum to other plasterboard manufacturers.

Novo Nordisk must be able to dispose of its sludge by putting it on farmland. It has built a 70km pipeline network (with plans to expand) and
also uses a large number of tanker trucks. It is conceivable that expansion of production could be limited by an inability to dispose of all the sludge, but there is no indication that this will happen.

Statoil is expanding its capacity, and will thereby produce more gas and use more cooling water and process water. The excess gas is expected to be burned by Asnæs in place of coal.

No expansion or contraction of Asnæs Power Station is imminent.

Overall, within a reasonable range of variation, the symbiosis has not limited the participants' ability to alter the scale of their operations.

- How does the symbiosis affect the speed of the firms' response to changing market conditions? Is there any policy protection for this?

From this perspective, the symbiosis participants are fundamentally one-trick ponies. Asnæs generates electricity by burning things. Competitive pressures pushing down the price of electricity are compelling plant management to maximize the economic return on the plant's energy use, but this is an example of reverse causality - changing market conditions are inspiring more symbiosis. A power plant is a power plant, symbiosis or no, and as long as it operates, the symbiosis does not affect its operation.

The same is true of Statoil. The refinery does one thing - process crude oil into a mix of petroleum products. As long as it operates, it produces a gas that varies little along the domain of variation of the product mix.

Fermentation is Novo Nordisk's middle name, and it is this fermentation that produces the fertilizer sludge. If, for some reason, Novo were to alter its processes so that it did not produce the sludge, that would be fine too, since its primary motivation is waste disposal, not agriculture. A different waste stream would require a different form of disposal, however.

Gyproc, as long as it remains in the plasterboard business, is a fairly straight-forward operation. Gypsum goes in, plasterboard comes out, albeit in an impressive variety of shapes, thicknesses, and sizes. Some of its products even have a pattern of holes in them for better acoustics, but Gyproc still only does one thing - make plasterboard.

There is no policy protection to ensure flexibility in the face of symbiotic linkages, and there does not appear to be a great need for it.
• Where have these companies gone? Have they enlarged capacity there or elsewhere?

Statoil is expanding its capacity by 50% in order to sell in the markets recently opened in the Baltic republics and thereabouts. All this expansion means from a symbiosis standpoint is that there will be more gas to be burned, most likely by Asnæs.

In order to get even more out of its heat, Asnæs is contemplating a refrigeration cascade that would involve Novo Nordisk and Statoil, which conveniently have refrigeration needs in different temperature ranges. Another participant is required, however, to make the scheme economically viable. This firm would get to use the refrigerant in the coldest range, from -30°C to -5°C. Food processors and breweries have such cooling needs, and possible candidates are actively being sought. Asnæs is also considering the idea of using its heat energy to operate a desalinization plant to supply drinking water for the town, as the aquifer previously used is being exhausted. This option is not imminent at this point, however.

Novo Nordisk operates in a market where a 'green' image is very important - it manufactures enzymes for detergent and, despite what the ads say, detergent is detergent, so that eco-friendly products tend to get the nod from environmentally conscious European consumers. Novo thus works hard to project an eco-friendly image, and the fertilizer sludge scheme plays a large role in furthering this goal.

Gyproc, on the other hand, operates in a eco-indifferent market, where the focus is on product quality. The firm is considering the use of treated waste-water from Novo Nordisk. In the words of Finn Grob, who handles symbiosis-related affairs for at Gyproc, "We have to be 150% sure that the water is 110% fine." Customer perception that the plasterboard is made form scrap would significantly hurt demand.

• How do the market prices of alternatives and virgin materials compare with the cost of symbiotic arrangements / acquisition?

Each link must be economically viable aside from any environmental considerations, so that the market prices of alternatives and virgin
materials must be consistently higher than the cost of symbiotic arrangements.

- Is every link in and of itself economically beneficial? (i.e. least cost alternative?) What other motivations are there?

Each link has either made economic use of a byproduct or has represented a low- (least?) cost mechanism for compliance with environmental regulations. Thus, each link is economically preferable for the firms to the alternatives available at the time, given the state of the world at the time, including regulatory pressures. Even the elaborate infrastructure by which Novo Nordisk converts its byproducts to fertilizer and distributes it to local farmers was at the time of its inception the least-cost way to comply with regulations.

- What did the participants need to know (technical specifications, etc.) before and in order to make the link arrangements?

   The success of the Kalundborg linkages required the companies involved to treat each other’s operations as more than black boxes. Gyproc, which receives gypsum from Asnæs’ scrubber, initially experimented with a number of gypsum sources, including fertilizer byproducts from Sweden and scrubber ash from a German power plant. Asnæs consulted with and visited Gyproc prior to investing in its scrubber and received material specifications for the gypsum.

   Asnæs needed information on the steam needs of Novo Nordisk and Statoil in order to ensure an adequate and appropriate supply. This information included what the steam was to be used for and the temperature and pressure needed.

- What sort of contractual / enforceable guarantees are there among the participants? Or is it totally voluntary?

   The links are contractual and akin to any other supplier relationship. Prices are agreed upon for set periods, and renegotiated when those periods end.
• Is there a natural progression towards symbiosis?

Yes, if the government response to the environmental impacts of industrial activity sends the right signals. According to Valdemar Christensen of Asnæs Power Plant, increased industrial activity causes increased pollution, which inspires government/policy intervention to increase pollution costs, which makes symbiotic arrangements more attractive.

Of course symbiosis does not necessarily follow from a regulatory push for pollution control; there has to be some propensities. After all, industries in places other than Kalundborg have been forced to decrease pollution, without the effect of inspiring symbiosis. However, it would appear that government involvement is necessary to ‘level the playing field’ in favor of loop-closing arrangements by raising the relative cost of conventional practice (or lowering the cost of symbiosis). It is not, however, sufficient. Symbiosis requires information, cooperation, and creativity, and these requirements are more difficult to supply by fiat.

• Why not elsewhere, either in Denmark or in some other country?

Kalundborg is a sleepy town and there is not much else to do but dream up symbiotic linkages. This claim is not entirely frivolous; people at the various industries know or at least know of each other and tend to live in the same community. According to Finn Grob of Gyproc, managers from the different plants run into one-another and discuss common problems and challenges, from which the realization springs that the different firms should tackle some of them together. None of the symbiosis participants are even remotely competitors with one-another, so there is no cost to cooperation.

The Danes tend to be environmentally conscious, so that there is a common drive to minimize the environmental impacts of their industrial activity. While the linkages must be economically viable, the environmental benefits are by no means lost on the participants, and even less so on the community.

There are a limited number of potential participants within close proximity. Kalundborg is surrounded by rolling farmland and the sea, so that it is very easy to establish the boundaries of the local industrial system.
- what's there is there, and what isn't does not come into play. Of course this is not entirely true, as both the power plant and the oil refinery ship waste products to industries that are not in the immediate vicinity.

The power plant is directly across the fjord from the town, and the two are visible to one-another. The other industries are similarly in plain view. Perhaps this obvious proximity makes it more difficult to think of industry as existing in isolation.
Chapter 3.
The Zero Emissions Research Initiative

The Zero Emissions Research Initiative, or ZERI, is a new program based in Japan which seeks to improve the profitability of manufacturing while reducing its environmental impact by striving for zero waste. ZERI is the brainchild of Belgian economist and entrepreneur Gunter Pauli, who pushed the frontiers of corporate environmentalism and drew world-wide attention as owner, president, and CEO of Ecover, an "eco-factory" producing environmentally benign cleansers. But however green Ecover's operation became, it could only reduce waste, not eliminate it completely. This limitation gave rise to Pauli's Zero Emissions vision: multi-industry clusters of factories, in which emissions from one plant are used as inputs by another. The trick, according to Pauli, is finding the "missing links" to complete the cycles\textsuperscript{19}.

ZERI is based in the United Nations University's Tokyo headquarters, from which Pauli has marshaled a global network of researchers and interested participants. Curiously, the UNU is a university without students; rather it serves as a hub and clearing house for research efforts of international scope. Work on the project began in April of 1994, with the first ZERI Business Roundtable held in July in Tokyo, followed in September by the release of a document outlining ZERI's concept, feasibility, and initial research program. Funding will be secured in part by ZERI Foundation

\textsuperscript{19} Gunter Pauli, personal communication; \textit{GMI Report: Japan}, No. 18 September, 1994.
The ZERI Charter

ZERI Foundation memberships have been offered to 50 companies who, by joining, agree with the following principles of the ZERI charter:

1. The members of the ZERI foundation realize that there is an urgent need to design corporate strategies and industrial policies based on the principle of sustainable social and economic development.

2. The members believe that the creation of value-added benefits for society are best supported through market mechanisms where competitive forces stimulate industry to eliminate all forms of waste.

3. The members accept that industry will only have reached its full potential when all waste has been eliminated. The quest for the elimination of waste (zero emissions) is in line with the corporate drive for total quality (zero defects) and just-in-time (zero inventory).

4. Therefore, the members will target the elimination of all waste. In a case where all inputs are not completely used, consumed or integrated into the product or production process, these residues will become value-added inputs for other industries.

5. The members will search for solutions based on innovative technologies and supported by the appropriate industrial policies. Industry must combine cost reduction schemes with environmental investment.

6. The members undertake joint research, working with the centers of excellence, and are committed to set an example. If research is successful, then pilot projects will be established, followed by the dissemination of the technologies.

7. The members recognize that ZERI will question established ways of manufacturing. The present product formulations, processing systems, engineering and applied technologies will be reassessed with zero emissions as a target.

8. The members support multi-disciplinary research at the pre-competitive level as a methodology.

9. The members are committed to a long-term process. The members will commit for a minimum of five years, combining their corporate strategic interests with a vision on how to secure competitiveness in the future.

10. The members are aware that the public at large needs a broader understanding of the complex issues at stake. A special effort will be undertaken to inform and educate the consumers and the public on the opportunities to TARGET ZERO EMISSIONS.

memberships offered to 50 selected companies, who would benefit from priority access to research results and by participation in ZERI projects. The program will also involve an international array of governments and educational institutions\textsuperscript{20}.

Zero Emissions Manufacturing is being pushed by Pauli as a key aspect of business strategy for the next century, not merely as a way to tweak the system to make it more environmentally benign. Green consumerism in Europe certainly presents ample evidence that being 'eco-friendly' can have significant impact on market share, although this phenomenon has yet to manifest itself in earnest in the United States. ZERI calls for a wholesale reassessment of manufacturing, as indicated by item 7. of its charter: "The members recognize that ZERI will question established ways of manufacturing. The present product formulations, processing systems, engineering and applied technologies will be reassessed with zero emissions as a target (See box)."

In addition, item 3. of ZERI's charter prescribes the ideal or end-state which is to be sought: "The members accept that industry will only have reached its full potential when all waste has been eliminated." The charter draws parallels between zero emissions and zero defects (total quality) and zero inventory (just-in-time manufacturing), placing the zero waste concept squarely in the realm of corporate strategy. According to Pauli, this is clearly not just an environmental issue. Industry "should see this as [a] strategic envisioning for the twenty-first century. I see too many people who say 'very interesting, let's talk with the environmental people.' I say, no, you should talk with the strategic planning people."21

As of the end of 1994, companies and universities from 21 countries had signed on as ZERI participants, with engineering and machinery magnet Ebara Corp. and the software firm ASCII being the first Japanese companies to join.22 Japanese industry may be fertile ground for such an ambitious undertaking as the total elimination of waste, since it is no stranger to the marshaling of concerted effort to achieve difficult goals. Japanese industry was shooting for zero defects while foreign competitors were content with 'acceptable' levels. ZERI's similarly strict goal may be seen as a competitive advantage.23

While advancing a broad philosophy, the ZERI project is currently focused on three research initiatives: recovery of high-value green biomass from logging residue, redesign of paper recycling for zero emissions, and the

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22 GMI News 1995 ibid.
23 GMI News 1994. ibid
clustering of beer brewing and fish farming as complementary industries for the elimination of waste. While the first two projects are clearly important and interesting in their own right, it is the clustering of industries that is of interest to us here.

Consistent with the notion that complementary industries can form zero-emissions clusters, the ZERI project has undertaken to combine beer brewing and fish farming in a scheme that uses the nutrient-rich byproduct of the brewing process as fish food. According to the Outline of ZERI feasibility studies released in September of 1994, the brewing of beer, for which hop, barley, malt, sugar, and rice are the primary raw materials, results in a fermentation residue called 'cake'. This cake has significant protein content, and has traditionally been disposed of as cattle feed. Increasing economies of scale in brewing have forced large breweries to dry, package, and deliver the cake to widely dispersed cattle ranchers. Seasonal fluctuations in beer consumption require similar fluctuations in production, resulting in greatly increased cake production during the summer, for which there is often no useful outlet. Storing or landfilling the extra cake is costly.\textsuperscript{24}

The clustering of brewing and aquaculture is further motivated by the inherent inefficiency of cattle ranching: even when cake is fed to cattle, its protein content is not used to its fullest potential, since it takes seven tons of feed to produce one ton of beef. In contrast, one ton of fish requires only 1.8 tons of feed. Pauli also notes that world prices for selected fish are steadily increasing, while world meat prices are in decline. The nuisance created by the foul odor of brewery cake adds to the impetus for using it on-site.

The ZERI vision is of fish farms operated in immediate proximity to beer breweries. In this way, the byproduct cake could be reused immediately as fish feed, with apparently no need for processing. However, the brewery waste cake is high in fiber, so that it cannot be digested completely by the fish. Unutilized fish excretions would constitute a waste stream, thereby stopping short of the zero emissions ideal. The proposed solution to this snag is the introduction of algae into the fish farms. With over 2000 types of algae to choose from, ZERI researchers are confident that they can identify those that can reprocess fish excrement, and can in turn be fed to the fish. Since algae

need nothing more than sunlight as an energy source, they are an efficient way to proceed.

Fermentation processes also produce heat, comprising another byproduct of beer brewing. Using this excess heat to elevate and regulate the temperature of the fish ponds would permit the more rapid hatching of higher grade fish. Recall that Kalundborg's Asnæs Power Station also makes use of its excess heat in its fish ponds.

While the European, American, Australian and Japanese markets for beer are apparently saturated, Pauli has identified expanding markets throughout the developing world. With growing demand goes increasing production, providing opportunities to introduce brewery/fish farm clusters as new facilities are constructed. Using the world-wide reach of the United Nations University, Pauli has recruited researchers and participants from places as diverse as Nepal, China, Barbados, and South Africa. With additional research support from major engineering firms, the project is likely to net favorable results.

The brewery / fish farm project is a single application of the concept of zero emissions clusters. If successful, it promises to increase the efficiency of beer and fish production, while decreasing their environmental impact. It remains to be seen, however, if other such clusters will be identified and developed. As a feasibility study, the beer/fish connection can be a very poignant demonstration of the ZERI concept. For it to revolutionize manufacturing, as the ZERI charter indicates, the zero-emissions idea will have to take hold in the hearts and minds of member corporations.

It is interesting to note that ZERI proceeds without any reference to industrial ecology or to sustainable development. Eliminating waste is presented primarily as a means by which to obtain maximum economic value from one's resources and maintain or enhance competitiveness, although reduction in environmental impact is also seen as a benefit. Gunter Pauli is more than anything else an entrepreneur, not an environmentalist. His is a strategic vision for industry, and it reaches the same conclusion as industrial ecology, which could just as easily be motivated by purely environmental and sustainability concerns as by business interests. Industrial ecologists have claimed that IE represents a (perhaps more appropriately the) convergence of environmental and business interests. The success of ZERI in developing what are essentially industrial ecosystems by appealing to
traditional business interests would go a long way toward bearing out that claim.

The ZERI charter (see box above) sets forth a transformational vision for manufacturing with the total elimination of waste and pollution as its goal. This is a significant undertaking, and it remains to be seen to what extent this vision is taken to heart by corporate participants (and to what extent corporations choose to participate). It is relevant to speculate as to why they would want to. The first of the ten tenets of the ZERI charter goes as follows:

1. The members of the ZERI foundation realize that there is an urgent need to design corporate strategies and industrial policies based on the principle of sustainable social and economic development (emphasis in original).

This is an altruistic reference that may or may not be a correct assessment of the present state of affairs. Does the manufacturing industry world-wide (or even in Japan) realize that there is a need to redesign their operations based on the notions of sustainable social and economic development? Do they agree on what these notions are? Do they have their own notions? Do they think about these things?

Other tenets of the charter hint at economic gains to be made from the elimination of waste, while the second one subtly implies a role for public policy to 'get the prices right':

2. The members believe that the creation of value-added benefits for society are best supported through market mechanisms where competitive forces stimulate industry to eliminate all forms of waste.

Market mechanisms and competitive forces sound like references to least-cost achievement of environmental performance goals, unless consumers show a marked market preference for products manufactured at zero-waste facilities. If the market forces and competitive pressures rely on getting the prices right, then zero emissions has to be least cost, or at least low enough cost to make it attractive given 'green image' benefits. If zero emissions is indeed least cost, and it may well be in some or many cases, then why isn't industry doing it now? This is not a rhetorical question, since there are many barriers, such as lack of institutional linkages and lack of interest or people may just not have thought about it. But Kalundborg demonstrates that there is a broad class of zero-emissions or symbiotic linkages that are only
economical as a result of public policy intervention in the market, either in the form of regulation or through direct price adjustments (i.e. taxes). So ZERI may well endorse this sort of intervention.

In effect, Pauli is selling an ideology of manufacturing. On the pragmatic level, the charter offers two reasons why industry should be swept up in this transformation: the need for sustainable economic and social development, and economic gain. How compelling the first argument is remains an open question. The second issue, economic reasoning, lends itself more readily to evaluation. Manufacturing can reduce its costs by making more efficient uses of material inputs. But pollution has been the textbook case of an externality, because the generating entity does not bear its full cost. 'Dumping' a waste stream is in most cases less expensive than finding a good use for it. So green consumerism and public attempts at getting the prices right cannot be ignored if we want to bring about a zero emissions revolution.

This discussion has so far focused on the ZERI charter, which is very interesting but comprises only a small part of the persuasive power of the initiative. At the helm of the project is Gunter Pauli, a charismatic man who may well be able to persuade decision makers on less than pragmatic (or other than pragmatic) grounds that zero emissions is the way to go. While most (all?) academic calls for industrial symbiosis, which ZERI is without saying so, proceed from the need for sustainable development, Pauli proceeds in large part from entrepreneurial considerations. According to documentation and personal communication, Pauli sees increasing demands for and decreasing supplies of particular commodities. The implication is that, for certain sectors and in the not-too-distant future, zero-emissions schemes will be economically beneficial without public policy intervention.

The tangible elements of ZERI are three feasibility studies / demonstration projects. While all three offer significant potential, the clustering of beer brewing and aquaculture deserve mention in our context. Some additional comments regarding that undertaking are in order.

The idea of identifying clusters of industries to co-locate and link up falls somewhere between the greenfield and brownfield endpoints. It has characteristics of a greenfield in that it is assumed (or at least implied) that the facilities have not yet been built and therefore can be designed as a unit and to

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25 The greenfield / brownfield distinction and its implications for industrial ecosystems are discussed in detail in Chapter 7.
some extent co-optimized. It has the brownfield element that the specific industries are known. This hybrid approach, proceeding from the analytical identification of symbiotic clusters offers significant advantages over the green/brown endpoints. Because it (seems to) make its intervention before the plants in question are built, it offers the ability to 'design-for-symbiosis' which means that the cluster can be designed, or at least tweaked, from the perspective of the system it forms, not just of individual processes.

The cluster idea also overcomes what appears to be a very significant difficulty of greenfield designs, that being the uncertainty and (likely?) lack of industry participants. At the risk of over-simplification, the greenfield approach stakes a flag in the ground and declares an ecopark, as though lighting the Olympic flame - let the games begin. But there is no guarantee, and indeed very serious reason to doubt, that industry will locate somewhere specifically because it is an ecopark. The eco-industrial park (EIP) idea defines 'the system' as the eco-park itself, which is not much more than a matrix for a symbiotic community. This avenue of development is discussed in detail in the next chapter.

So the cluster idea is another take on defining 'the system' and one that can be very successful on the limited scale of what it is - that is to say, the systems intelligence is resident within a third-party who is 'meta' to the system, and so the scope of ecosystem development is limited by the organizing ability of the 'meta' analyst and change agent. Ultimately, we would like the system to self-organize toward industrial ecosystems.

The cluster idea appears to offer a good chance of success, assuming the 'right' cluster is selected. It is limited in that it is not self-organizing, but it may turn out that the success of a limited number of symbiotic clusters will spur on the indigenous development of others. This is what the ZERI charter calls for, and the clustering of beer brewing and aquaculture is being advanced as a demonstration project. The bottom line is that this approach, the development of specific inter-industry clusters which are brought together by third-party intervention, promises to be the a fruitful way to proceed.
Chapter 4.
Industrial Ecosystems in the U.S.:
The Eco-Industrial Park Project

As part of the President's Environmental Technology Initiative (ETI), the President's Council on Sustainable Development (PCSD) and the U.S. EPA commenced in 1994 an Eco-industrial park project. EPA provided $300,000 "to design and develop an environmentally sound industrial park, which will create jobs and promote innovative technology." This undertaking represents the first national initiative in the United States to develop and foster applications of industrial ecology to industrial parks. As such, it is a major step forward in bringing IE theory and practice into the mainstream and introducing it to a wider audience than was previously exposed. However, as part of the Clinton Administration's Environmental Technology Initiative, the project is highly political, with the result that ribbon-cutting may receive higher priority than substantive results. The PCSD has so far acted as more of an observer than a designer or developer. Perhaps this is the way it should be, but such a posture leaves much of the success or failure of the project up to those involved with four EIP demonstration projects, with little help from the Federal Government. The PCSD is poised to come forth with policy recommendations to further such development, but all else is likely to have to come from the partnerships of state and local governments and private interests that have been brought together at the four demonstration sites.

Project Implementation

The goals of the Eco-Industrial Park Project were set forth by the Project Implementation Plan\(^\text{27}\) as follows:

"To design and develop an environmentally sound industrial park that creates jobs and advances state-of-the-art technology innovation; to provide a forum for piloting flexible, cost-effective approaches to meeting environmental standards mandated by law, while at the same time exploring opportunities to improve environmental, economic, and social outcomes; to demonstrate in practical terms the principles and concepts of sustainable development at the community level; to provide an 'incubator' for new approaches to pollution prevention, training, and new technologies for export to other nations."

These are lofty goals indeed, and rather general. An eco-industrial park is apparently better in all respects than the forms of development that have come before. In the words of one EPA official, "The goal of an eco-industrial park is to advance national goals.\(^\text{28}\) Lacking any formal definition, the eco-industrial park is identified by a set of outcomes, all of which are desirable. The Project Background presents industrial ecology as the necessary and sufficient agent of transformation by which these outcomes are achieved:

"Traditionally, the management of the interface between industry and natural systems has been poorly managed. Poor management has resulted in pollution -- an economically costly and environmentally degrading output. Industrial ecology matches the inputs and outputs of the manmade world to the constraints of the biosphere.

In addition, industrial ecology builds on the important foundation of pollution prevention. Pollution prevention has evolved as a process of gradually backing away from end-of-pipe control, but does not link industrial components into a comprehensive system. Industrial ecology is a systemic framework that fills these gaps. Industrial ecology advances the concept of "product responsibility" so that costs of waste-generation cannot be externalized by sources. Industrial ecology advances the concepts of design for environment by ensuring design of facilities, processes, products, and services with awareness of both ecological and economic costs/benefits across the whole life cycle.\(^\text{29}\)"

\(^{27}\) EPA, Eco-Industrial Park Project Implementation Plan 1994
\(^{28}\) Lea Swanson, Personal communication, 8/11/94
\(^{29}\) EPA, Eco-Industrial Park Project Implementation Plan 1994
All this sounds convenient, but it is semantically tenuous. It is essential to bear in mind that industrial ecology doesn’t do a thing. Industrial ecology is not an agent of action; it is a set of ideas. It is not industrial ecology that is to achieve all of the above but rather people who apply industrial ecology. This is a critical distinction, but one that seems lost in the above passages.

Of course, the body of thought that collectively has developed and come to be known as industrial ecology can offer valuable insight into how such goals can and should be approached. Yet such sweeping statements as the above, which out of nowhere imbue industrial ecology with the ability to apply itself by fiat, gloss over the significant issues of implementation.

If the FIP Project Implementation Plan revealed eco-industrial parks as the unified path to development for the future, a teleconferenced meeting of the eco-industrial park team held in August of 1994 revealed them more as a patchwork expression of stakeholder interests. A representative from the AFL-CIO indicated that the key to an eco-industrial park is high-paying jobs. According to someone from the Department of Commerce, the focus should be on quality of employment. A stalwart from the IE community pointed out the need for self-organization. This author wondered aloud where all this was going. The EPA lead person indicated that whatever an EIP ends up being, there needs to be a ribbon-cutting by June of 1995, less than one year away from the meeting. To a large extent then, an EIP was revealed as what you like.

The President’s Council on Sustainable Development, through the Eco-Industrial Park Project, had $300,000 to spend in 1994 on supporting the development of EIPs, and the main purpose of the meeting in August of 1994 was to select the sites that would be supported. Four sites were in the running: Brownsville, Texas/Matamoros, Mexico; Baltimore and Rochester, New York; Chattanooga, Tennessee; and Port of Cape Charles, Virginia. Each of these areas had a team of local officials complemented by consultants from the outside. Baltimore and Rochester shared a project leader in Ed Cohen-Rosenthal of Cornell University. Brownsville and Matamoros are located on adjacent sides of the U.S./Texas border and are home to an undertaking that involves both cities.

Representatives from each of the four locales made a short presentation as to why their site should be selected, a seemingly competitive process which was followed by an announcement by the EPA lead person that
Phase I: The Eco-Industrial Park Generic Design Study

Phase I of the Eco-Industrial Park Project involves the development of a generic design concept for an EIP which is to form the basis for application and testing in one or more sites in Phase II. Questions to be answered in the research/design phase include:

- what design principles can guide assembling a tenant mix in a park that is optimally resilient in the face of inevitable tenant turnover?

- how can the right mix of companies for a park be recruited to optimize trading wastes as by-products?

- how will the right mix be maintained as companies move, fail, or otherwise leave the park?

- what design principles will ensure optimal materials and energy flows in the park?

- what design frameworks and tools will be needed to integrate economic, socio-political, technological, and environmental planning in the actual development process and in the ongoing management of the park?

- what policy shifts are needed to accommodate development of eco-industrial parks and retrofitting of established parks?

- how can various levels of government best act to catalyze development of parks by the private sector?

- what is the baseline of relatively certain economic and environmental benefits in the park concept that will reduce risks for developers and tenants participating in demonstration projects?

- what criteria will be applied to select eco-industrial park sites?

Results relating to these and other questions are intended to enable the application of the design concept to specific sites of eco-industrial park development and to foster public/private partnerships to create one or more demonstration EIPs. The final step in Phase I was to have been the development of an action plan for Phase II, but funding delays held up the start of the project with the result that Phases I and II were started concurrently.

Sources: EPA "Eco-Industrial Park Project Implementation Plan" 1994; Ernie Lowe, personal communication.

each site would in fact receive PCSD support. Thus began Phase II of the Eco-Industrial Park Project, which, according to EPA documents, "involves applying the design concept to specific sites and to formalize a public/private partnership to create one or more demonstration eco-industrial parks."

The "design concept" referred to above was to have been developed as Phase I prior to the start of Phase II. It was to be a generic design study of the eco-industrial park concept, and would presumably have supplied much of

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30Eco-Industrial Park Project Implementation Plan, 1994 p. 4
the substance and focus that was lacking in the deliberations described above. Unfortunately, funding for the entire project was delayed in getting through Congress, pushing the start-date back, while the ribbon-cutting target of June 1995 was held fixed. As a result, the results of the Phase I study, which were to enlighten the development of the Phase II demonstration projects, were not available at the start of Phase II. Phases I and II got started more or less concurrently. This is a shame, because the Phase I study to be carried out by Research Triangle Institute and Indigo Development, a consulting firm specializing in the application of industrial ecology, was slated to address the core group of key issues in EIP development (see box).

Because Phase II began without the benefit of the results of Phase I, the demonstration projects have had no common knowledge base to work from, as the PCSD did not appear to provide any direction from above beyond the diffuse goals set forth in the Project Implementation Plan. The role of the PCSD to date has been limited largely to that of an observer, with meetings held at the various sites but with little substantive interference or support. The project time table allows one year from the time that demonstration sites were selected, in July 1994, to the official ribbon cutting, scheduled for June of 1995, by which time tangible results are expected. Given the complexities at hand, it is highly unlikely that this project will uniquely produce an eco-industrial park in that sort of time frame. The realistic result of the PCSD EIP project, as will be discussed further below, is to encourage development already underway that is compatible with the EIP concept (however it ends up being defined), to introduce the notion of EIPs to a larger community than would otherwise be exposed to it, and to produce policy recommendations to enable such development. These are significant benefits, although they fall well short of the somewhat hyperbolic project goals.

For the time being, however, the lack of common basis among the demonstration projects extends to issues as fundamental as the very conception of an eco-industrial park. In the words of the leader of a three-day design session held in April 1995 to flesh out the Cape Charles EIP, "We have no clue about what an eco-industrial park is. Nobody does.31"

31 William McDonough, quoted in The Virginian-Pilot & The Ledger-Star April 6, 1995
The Phase I EIP study

The above statement is not entirely correct. At the time of this writing, Indigo Development, under a subcontract with Research Triangle Institute, is in the process of putting together a *Fieldbook on the Development of Eco-Industrial Parks*, which defines them as follows:

An eco-industrial park is a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in management of environmental and energy issues. By working together, the community of businesses seeks a collective benefit that is greater than the sum of individual benefits each company would realize if it optimized its individual performance only.

The goal of an EIP is to improve the economic performance of the participating companies. Components of this approach include new or retrofitted design of park infrastructure and plants; pollution prevention; energy efficiency; and inter-company partnering. Through collaboration, this community of companies becomes an "industrial ecosystem."³²

The *Fieldbook* treats the exchange and reuse of industrial byproducts as feedstocks as a significant EIP attribute flowing from this definition, while incorporating other themes such as a recycling business cluster, a collection of environmental technology companies and companies making 'green' products, the use of renewable energy sources, environmentally friendly infrastructure and construction, and mixed use development. An eco-industrial park transcends any single one of these attributes, but includes some or all of them. The critical element, it is written, is the set of interactions among park members and between them and their natural environment.

While still in draft stage, the *Fieldbook* is a meaningful, comprehensive, and integrated resource bringing the concepts of industrial ecology to bear on the design and operation of industrial parks. As such, it is a primer for aspiring eco-industrial park developers. One of its strengths is the articulation of a specific end-point or ideal of an EIP toward the development of which the rest of the *Fieldbook* is aimed (see box).

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Characteristics of a Fully Developed Eco-Industrial Park

Several basic strategies are fundamental to developing an EIP or industrial ecosystem. Individually, each adds value; together they form a whole greater than the sum of its parts.

Integration into Natural Systems

- design the EIP in terms of the characteristics and constraints of local ecosystems

EIP and Energy Systems

- maximize energy efficiency through facility design or rehabilitation, co-generation, energy cascading, and other means
  - achieve higher efficiency through inter-plant energy flows
  - use renewable sources extensively

Site-Wide Design of Materials Flows and Waste Management

- emphasize pollution prevention, especially with toxics
- ensure maximum re-use and recycling of materials among EIP businesses
- reduce toxic materials risks through integrated site-level waste treatment
- link the EIP to companies in the surrounding region as consumers and generators of usable

Water flows in an EIP are also designed to conserve resources through strategies similar to those described for energy and materials.

Effective EIP Management

In addition to standard park management and maintenance functions, park management

- maintains the right mix of companies needed to best use by-products as companies change;
- supports continuous improvement in environmental performance for individual companies and the park as a whole and
- operates a site-wide information system that supports inter-company communications, informs members of local environmental conditions, and provides feedback on EIP performance.

Construction/Rehabilitation

New construction or rehabilitation of existing buildings follows best environmental practices in materials selection and building technology, including recycling or reuse of materials.

These park characteristics raise a number of conceptual design issues which are addressed in a later chapter of this thesis. Suffice for now that the above elements come together to form a coherent outline of what makes an industrial park an EIP.

Having articulated the goals and attributes of an eco-industrial park, the Fieldbook provides guidance interspersed with case studies and examples to shepherd developers toward the realization of EIPs. In somewhat of a role reversal, experience from the EIP demonstration projects at Chattanooga and Brownsville are providing opportunities to test Fieldbook ideas and document development efforts and progress. While Ernest Lowe, its principal author, claims that the Fieldbook will never be completely finished since experience with EIPs will continually expand and change over time, it promises to serve as the primary work on EIP development once a version is completed.

Phase II Demonstration Projects

The demonstration projects in Chattanooga, Baltimore, Brownsville, and Cape Charles are forging ahead with development which they refer to as eco-industrial parks. These projects represent various conceptions of EIPs and tend to be pre-existing development efforts that have more recently taken on an eco-park dimension.

Chattanooga

Home to one of the PCSD-sanctioned eco-industrial park projects, Chattanooga has plotted a course toward becoming an eco-industrial city. Named in 1968 by the EPA as the major U.S. city with the dirtiest air, Chattanooga has rebounded with a broad-based sustainable community initiative that features ecosystem cleanup, an environmental business economic development plan, and four potential sites for eco-industrial parks. From an environmental nadir in the late sixties, and the flight of manufacturing jobs in the seventies, Chattanooga has emerged as a city that is widely hailed to be well ahead of most in planning for the next century.

33 The bulk of the material presented in this section is based on “Chattanooga, Tennessee: Eco-Industrial Parks in a Larger Context” by Dr. Douglas Holmes, in Fieldbook on the Development of Eco-Industrial Parks Draft January 30, 1995 Appendix
What emerged from the environmental and economic crisis of the late sixties and early seventies was a wide-spread civic consciousness and awareness of common problems requiring common solutions. People began to talk in small groups and with local agendas, a process which fed upon itself and grew. This civic renaissance was galvanized in 1984 when Chattanooga Venture, a non-profit, privately funded group, set out to organize a city-wide planning process to involve all sectors of the community. Meetings run by facilitators were held in virtually every neighborhood. Hundreds of facilitators guided hundreds of meetings, bringing in hundreds of people who had never before been involved with civic issues. What emerged was a development plan called Vision 2000, focused mainly on urban renewal.

Building on the success of Vision 2000, Chattanooga Venture convened in 1993 an Environmental Forum which drew upon expertise from around the country. Inspired by the proceedings, Chattanooga Venture launched Revision 2000 to update its by now ten-year-old forerunner. This undertaking resulted in even more citizen involvement, and was followed by another environmental forum. By now urban renewal was wedded to the concept of environmental quality and preservation. The new Tennessee Aquarium was built, a scenic bridge across the Tennessee river which was slated for demolition was instead converted to a linear park for pedestrians and bicyclists, and over $700 million was committed to new projects, including a stadium and a trade center.

All this activity attracted nationwide attention, including that of the President’s Council on Sustainable Development. Four sites in and around Chattanooga are being groomed to become eco-industrial parks. The one that has been most enthusiastically embraced by civic leaders is a proposed environmental technology complex within the Chattanooga enterprise community zone, also known as the South Central Business District.

This site is 100 acres in size, and is adjacent to the Tennessee Valley Authority’s power headquarters. It includes abandoned foundries, dilapidated industrial structures, and vacant lots. Some of these structures are slated to be reclaimed, and infrastructure improvements will include service by electric buses and the development of pedestrian-oriented greenways. The TVA, city, county, state, the University of Tennessee-Chattanooga, and the Chattanooga State Technical Community College are all active partners. The project has received a $1.2 million planning and design
grant awarded by the city and county, in addition to $700,000 from the state for site planning and reclamation.

Central to the business district’s reincarnation as an EIP is the creation of a Gunter Pauli-style zero-emissions manufacturing complex. According to the South Central Business District Plan, the controlling planning document,

A special site has been designated for “Eco-Industrial” uses. The intent is to create a “zero-emissions” zone where the wastes of one business become the fuel for another. The types of businesses that will be targeted for this area are those that provide well-paying, high-quality manufacturing jobs along with a commitment to environmental quality. Several companies have already expressed an interest in such a site and the marketing approach builds on this demand. An “Ecology Center” is planned in conjunction with the Eco-Industrial zone which would serve a multitude of purposes, including cleaning contaminated soils, wastewater treatment through biological processes, incubator office space, and educational, research, and visitor facilities34.

One of the attractions of zero-emissions manufacturing is the ability to locate downtown which will result in diminished infrastructure needs. The United Nations University’s Zero Emissions Research Initiative has expressed interest in locating a Zero-Emissions Research Institute at this site. The actual mix of companies to locate in this eco-industrial area is yet to be determined, but the carpet maker Collins and Aikman has been claimed to be a shoe-in by William McDonough, whose firm of architects and planners drew up the South Central Business District Plan. Two or three other large businesses are said to be engaged in confidential negotiations and are seriously considering the idea35.

The main difficulty with this line of development is that the 100 acre site is comprised of over 500 separate parcels, the title to which needs to be consolidated before development can begin. There is also a need to assess the contamination of each site due to past industrial activity in order to assess potential environmental remediation liabilities. There is a feeling that under the constraints of current EPA regulations this process could require several years. This hindrance comes much to the chagrin of city leaders, who favor the downtown site because of its visibility and because of the potential to

35 Doug Holmes, personal communication.
bring jobs downtown and adjacent to existing and future housing and to public transportation infrastructure.

The other leading candidate for EIP development is on the site of the former Volunteer Army Ammunition Plan, which is currently mothballed and held in readiness. 4000 acres of the site are under control of the city and county and zoned for industrial use. A key attribute of this site is that the Army and Department of Defense have agreed to assume all responsibility for environmental liabilities that may arise as a result of past contamination. Because the land holding is consolidated, this site avoids the major disadvantages of the downtown location. This potential eco-industrial park has extensive infrastructure including buildings, roads, rail sidings, water, and sewer, and was designed to be self-sufficient for water and electricity. ICI Americas is under contract to operate the site and is charged with generating revenue from the government-owned land. Other partners include the DOD, city, county, Southeast Tennessee Development District, River Valley Partners, the University of Tennessee-Chattanooga, and Chattanooga State Technical Community College. Funding is comprised of a $0.5 million planning grant from DOD, $2.5 million for marketing and development from private sources, and $100,000 for Environmental Network Project, an undertaking organized as a flexible network (see Chapter 6), for developing an integrated waste exchange.

The intended uses of the park include environmental research, recycling industries, and integrated industrial sites. While the South Central Business District's potential EIP is imbued with the spirit of industrial ecology by Gunter Pauli and Bill McDonough, as well as by City Councilman Dave Crockett, who has picked up and run with the torch, it is unclear what, if anything, will create the impetus for an eco-park at the army site. Redevelopment is now planned, and will likely occur given the favorable terms available for occupancy, but there is no force in place at this time to make this an eco-industrial park, so that it may simply end up as traditional development.

The third potential site is a 1000 acre suburban greenfield park to be assembled by the city and county for development by RiverValley Partners. The main innovation planned for this site is the opportunity to demonstrate that people can live where they work.
The final site is an abandoned industrial area in an low-income residential neighborhood and near a federal Superfund site. The opportunities at this location include overcoming barriers to reuse of abandoned industrial sites by limiting the cost of remediation, and job creation and neighborhood revitalization in an economically distressed area. The link to industrial ecology has yet to be made in this case.

Chattanooga is clearly a city on the move, and developments there are worthy of extensive study from the perspective of urban development. From the perspective of industrial ecology and industrial ecosystems, the broad-based support for EIPs and the participation of Gunter Pauli and the Zero-Emissions Research Initiative holds out the prospect of serious development of ecopark attributes in the Downtown Business District. The other three sites present laudable opportunities for development and redevelopment, but it is not clear to what extent such progress would be influenced by industrial ecology or bear its artifacts.

Brownsville

Brownsville, Texas is located on the U.S./Mexican border, an area that is slated for extensive industrial development in the not-too-distant future. The town is directly across the border from the growing industrial city of Matamoros, and accordingly one of the underlying themes of the Brownsville EIP is the international transfer of environmental technology and information.\(^{36}\)

The Texas Natural Resource Conservation Commission (TNRCC) is the lead state agency working on the project, which involves a mixed brownfield/greenfield industrial park, and is the first of the four demonstration sites to have submitted an ecopark development plan to the Environmental Technology Initiative. Other involved parties include the Business Council for Sustainable Development, the U.S. Fish and Wildlife Service, LPA, the local port and airport authorities, private developers, architects, and individual businesses, as well as Indigo Development, which is developing the i-fieldbook. There is broad-based local awareness and support for an EIP, partly in response to severe pollution problems experienced in the past.

According to Joel Youngblood, manager of the environmental technology cooperation program at the TNRCC, the elements that comprise the "eco"-ness of the proposed EIP include:

- Establishing an inventory of the materials flows of existing tenants with a plan to bring them together to look for synergies and to use material availabilities to recruit tenants. This would be to facilitate industrial symbiosis or the exchange of byproducts for use as feedstocks;

- Applying pollution prevention practices to the local industries;

- Building a treatment facility that would allow the reuse of process water. This is a significant issue as water is scarce along the border;

- Establishing improved railway links for the transport of materials in order to reduce truck traffic and concomitant air pollution;

- Energy cogeneration.\(^{37}\)

Local industry includes GM suppliers of car parts, Levi Strauss, a power plant, and a chemical plant on the Mexican side. Said Joel Youngblood, "we’re assessing the waste streams of existing tenants, to see if we can use this as a recruiting mechanism. We also want to look at a variety of cogeneration and pollution prevention strategies that can reduce costs for park tenants. We don’t know if zero emissions is technologically possible, given the EIP’s tenants. We’re trying to take industries that have problems and zero them out if possible.\(^{38}\)"

The Environmental Defense Fund is peripherally involved with the project, in an effort to retrofit an industrial park in Matamoros with processes and technologies that will lower its environmental impact. While it is not the goal of EDF to develop an eco-industrial park, they hope to disseminate the lessons learned from the Brownsville site throughout other manufacturing complexes in Mexico.\(^{39}\) The key to this approach, on both sides of the border, is the ability to demonstrate financial benefit for the businesses involved. Joel Youngblood has identified seven such potential sources stemming from an EIP:

\(^{37}\) Personal communication
\(^{38}\) quoted in BUSINESS AND THE ENVIRONMENT, February 1995. p. 4
\(^{39}\) Ramon Alvarez, Environmental Defense Fund, personal communication; BATE, ibid.
• Cost savings and enhanced revenues owing to industrial symbiosis;
• Cogeneration;
• Recycling and reuse of process water;
• Cost savings accruing from pollution prevention practices;
• Tying the introduction of a residential recycling program to recycling facilities in the EIP, thereby lowering startup costs;
• Waste treatment and disposal costs avoided as a result of the above practices;
• Favorable publicity ('green image') for companies locating in the park\textsuperscript{40}.

At this time, the TNRCC is ready to go forward with an EIP in Brownsville, although obtaining the necessary funding is still a hurdle. Joel Youngblood reports a surprising level of interest in ecoparks throughout the country, a result that holds out the hope of a welcome change in the habits that underlie the manner in which industrial development takes place.

**Baltimore**

The Baltimore EIP project is headed by Ed Cohen-Rosenthal, director of Cornell University's Work and Environment Initiative (WEI). The 20-plus acre Baltimore site is part of an empowerment zone in which the community has begun infrastructure and road repair and demolition of an abandoned housing project\textsuperscript{41}. The proposed EIP is part of an effort to revitalize an economically distressed area that has been contaminated by leaking oil tank farms. The project is currently exploring a post-consumer loop closing option. "One example of the possible connections is the recovery of tires. We could hire local people to collect tires. In turn, Bethlehem Steel could use the recovered steel, detergent makers could use another byproduct, and the tires could be a source of oil to run Baltimore Gas & Electric\textsuperscript{42}." In

\textsuperscript{40} Joel Youngblood, personal communication.
\textsuperscript{41} Elizabeth Kirschner "Eco-industrial parks find growing acceptance" *Chemical and Engineering News* February 20, 1995.
\textsuperscript{42} Cohen-Rosenthal, quoted in *BUSINESS AND THE ENVIRONMENT* Feb. 1995
addition, six companies are reportedly interested in locating in the Baltimore park, but there is a "need to make sure there's a good fit among them."\(^{43}\)

Cohen-Rosenthal and the Work and Environment Initiative are also involved with a site in Rochester, which would be built around an existing resource recovery facility which is currently idle. WEI and partners propose to use the facility as a hub connecting a wealth of companies already located in the area, with a focus on public-private partnerships, labor-management partnerships, and closed-loop systems and resource recovery.\(^{44}\) The Rochester project is currently on hold.\(^{45}\)

The approach taken by Cohen-Rosenthal and colleagues reveals a different philosophy from that embodied by the Zero Emissions Research Initiative. "For both [Baltimore and Rochester], we're talking about continuous improvement and ambitious stretch goals rather than zero emissions. We want to change the way we generally do business in America. If all we do is establish new greenfield sites, then we don't address the underlying challenge, which is how we make the current locations survive and work. Can we reclaim the dirty areas, and do so in conjunction with the community?"\(^{46}\) In this regard, the Baltimore project, with its focus on a brownfield site, is a complement to the new development slated for the zero-emission EIP proposed for the Downtown Business District of Chattanooga.

According to Cohen-Rosenthal, the environmental focus of an ecopark does not alter its fundamental business purpose. "Our objective is to ensure that participating companies have the best return on investment possible."\(^{47}\) In that spirit, he has set an ambitious goal of 50% above industry average return on investment, along with a dual objective of a significantly decreased emissions for the companies involved. These results, which go hand in hand, are to be accomplished through the employment of an integrated set of four strategies.\(^{48}\)

- Loop-closing and industrial ecology - 'closing the loop' is expected to result in improved business performance. This approach is limited, however, by

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\(^{43}\) Cohen-Rosenthal, \textit{ibid}  
\(^{44}\) \textit{BUSINESS AND THE ENVIRONMENT} Feb. 1995  
\(^{45}\) Cohen-Rosenthal, personal communication  
\(^{46}\) Cohen-Rosenthal qtd. in \textit{BATE} Feb. 1995  
\(^{47}\) \textit{BATE} \textit{ibid.}  
\(^{48}\) Cohen-Rosenthal, personal communication
the prevailing composition of industry in Baltimore - mostly chemicals, petroleum, and asphalt - which does not produce much waste.

- Network manufacturing - the organizational analogue of an ecosystem. Firms get together to find out what they can share, with Ed Cohen-Rosenthal acting as the broker. It is his goal to set up a framework for developing interconnections and then to let the community decide who will be allowed to participate. Note that this is Inter-Firm Collaboration (a.k.a. Flexible Networks), a topic whose applicability to industrial ecosystems is the subject of a chapter of this thesis.

- Cooperation with academics and continuous improvement (in lieu of starting with zero emissions49); and

- High-performance work-places and union-management cooperation. These themes fit with industrial ecology in that heightened employee participation is very valuable in decreasing resource use and fostering conservation. A goal is to build incentives for environmental improvement and sustainable jobs - a concept that is attractive to unions (Cohen-Rosenthal, personal communication).

This EIP, like the other three, is in the planning stages. There is a search conference scheduled for late April of 1995, in which stakeholders will come together to investigate the local ecology. It appears that the already established empowerment zone will be designated as the EIP, combining the challenges of ecopark development and urban revitalization.

Cape Charles

The Cape Charles site has already received a $4.6 million bond issue subject to business commitments. Having been designated as a special management area by the Department of Commerce, Northampton County has received support from the Small Business Administration. The community has formed and capitalized the Virginia Eastern Shore Corporation to help create and support 50 locally owned businesses centered around conservation and aquaculture50.

It is therefore surprising that Bill McDonough, Dean of Architecture at the University of Virginia and leader of a Cape Charles design charrette held

49 Each of these is essentially a slogan, or ideal to seek, so that the difference is largely semantic. The manner in which that ideal is approached, however, is significantly different.
50 Kirschner ibid.
in April 1995, was quoted as saying "We have no clue about what an eco-industrial park is. Nobody does." Ecopark or no, the planned Port of Cape Charles Sustainable Technologies Industrial Park is expected to create 395 jobs directly, including 175 in aquaculture and hydroponics, 100 at a wood mill, and 75 in food processing. Environmental goals include keeping paved areas to a minimum to improve water quality, using natural materials whenever possible, and creating wetlands to improve wastewater systems. In addition to areas for light and heavy industry, charrette designs included bike paths, waterfront shops, parks, and art and conference centers. "The most important links will be with the people - creating employee ownership and investment in these enterprises, and supporting entrepreneurs."

EIP Project Results

Although the actual influence of the ETI Eco-Industrial Park Project is difficult to discern, it is clear that positive development is occurring under its aegis. The realistic result of the PCSD EIP project is to encourage development already underway that is compatible with the EIP concept, to introduce the notion of EIPs to a larger community than would otherwise be exposed to it, and to produce policy recommendations to enable such development. A fourth result, which is more difficult to evaluate, is that the interaction with the Eco-Park Project has provided a goal or vision, albeit hazy, to which development projects can aspire. In that regard, the EIP project has given a name to a set of goals and ideas that are shared to varying degrees by development- and environment-minded individuals throughout, without the constraints of clearly delineating those goals and ideas. It may well be that such a common, though hazy, ideal is very valuable in creating interest, dialogue, and support.

The Eco-Industrial Park Project has to date reported the following Priority Policy Areas/Expected Lessons Learned:

- Economic and environmental benefits can be realized by applying the concepts of industrial ecology to current and planned commercial and industrial developments;

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51 The Virginian-Pilot and The Ledger Star April 6, 1995
52 ibid.
53 ibid.
54 Timothy Hayes, director of sustainable development for Northampton County, qtd in BATE February 1995.
• Co-location is an essential component of the application of industrial ecology concepts and practices;

• Place-based approaches to economic development enable the integration of local environmental and social objectives with economic and social objectives;

• Community participation in the earliest design phase of an eco-industrial park development is critical to ensure ownership and to build capacity at the local level to take responsibility for the on-going development and management of the eco-industrial park;

• The role of government (federal, state, and local) in facilitating the development and management of eco-industrial parks is especially important in the areas of permitting, enforcing and working within a flexible regulatory framework, and the provision of common infrastructure;

• In the context of environmental management, multi-media permitting of an eco-industrial park as a single facility may enable the most efficient achievement of environmental objectives;

• Flexibility for park participants to experiment and innovate is the key to determining the environmental technologies (monitoring devices, information networks, process technologies and waste technologies) needed to fully apply industrial ecology principles and concepts;

• Incentives must be provided to park participants to continuously improve their performance in environmental and social terms. In the environmental arena, those incentives can be provided, in part, through regulatory flexibility;

• Incentives must also be provided to the community and regulatory agencies to increase the flexibility of regulatory frameworks. In addition to the promise of better environmental outcomes, park participants must stipulate how they will be held accountable and responsible to the community for achieving environmental objectives.\(^55\)

With the exception of noting disagreement with the notion that "co-location is an essential component of the application of industrial ecology concepts and practices," these issues will be taken up later.

Stemming from somewhat disparate notions of what an EIP is, the four demonstration projects have embarked on development paths which, as a whole, are promising. The different versions of the EIP concept have been influenced by the characteristics of their location, in ways as fundamental as greenfield or brownfield focus as well as by local conditions such as water scarcity. The background and intellectual orientation of the project planners has also been influential, as evidenced by the attention to labor-oriented practices at the Baltimore site (headed by the Cornell Work and Environment Initiative's Ed Cohen-Rosenthal) and the entrepreneurial approach of Chattanooga's drive for Zero-Emissions Manufacturing (championed by Gunter Pauli). These approaches to economic development are therefore not just place-based but personality-based. What all sites do have in common is broad-based local support, an encouraging result.

The four demonstration projects have been the sites of much movement and activity. The bulk of this activity has been preparatory, but that is to be expected given the difference between where they are and where they want to go. These projects present a very valuable opportunity to put industrial ecology principles into action. Whether or not they do so is very much up to the teams assembled at each site. The Republican Congress puts the availability of further federal funding into question, but private-sector interest appears to be significant and on the rise\(^{56}\). If these projects yield tangible results, then they are in a position to give credibility to the new and non-traditional concept and elements of an eco-industrial park. Likewise, a floundering EIP Project can discredit this nascent development approach. Thus those who count themselves as industrial ecologists should hope for and assist successful efforts at these and other EIPs.

A final result of the EIP Project that bears mentioning is the *Fieldbook on the Development of Eco-Industrial Parks*, being compiled by Indigo Development. This document is the first comprehensive primer and sourcebook for those on the ground working to bring about such development, and promises not only to aid in such endeavors, but to focus interest and discussion on a clear though flexible picture of what an EIP is. Program delays have prevented the availability of the *Fieldbook* for the

\(^{56}\) Joel Youngblood, personal communication; et. al.
commencement of the Phase II demonstration projects, but this should not detract from its value in the future.

The one element that is conspicuously missing from this description of EIP Project results is a long list of participating industries. While several companies have been implicated at the various sites, no firm commitments have been reported. This is more of a problem for greenfield sites that need to recruit for the ecopark than for brownfield sites that have a captive group of firms to work with. This issue is absolutely critical, since all the public support in the world cannot substitute for tenant businesses. Developers at the four sites are working on this, and whether or not they will succeed in recruiting viable businesses who are willing to play is the greatest determinant of EIP success. The wedding plans are well underway; all that is missing are the bride and groom.
Chapter 5

Industrial symbiosis is predicated on the realization that 'waste' as such exists only to the extent that something is not used. In a closed-loop system, the outputs or byproducts of one process are the inputs of another. The ideal of an industrial ecosystem calls for complete utilization of all inputs to the system, such that no material flows are ever labeled as "waste." But as industrial ecology redefines waste, the Resource Conservation and Recovery Act (RCRA) defines and regulates it. The problem is that these regulations impede the realization of the industrial ecology vision.

RCRA is an environmental statute that governs the management and disposal of industrial waste. It was enacted in 1976 and amended in 1984 to address significant threats to human health and the environment caused by improper disposal of toxic waste. It is a complement to CERCLA, the Comprehensive Environmental Response, Compensation, and Liability Act of 1980, which created the Superfund. While CERCLA was intended to clean up hazardous waste sites, the 1984 RCRA were intended to prevent them.

To someone imbued with the spirit of RCRA, an industrial byproduct is a menace to be contained, controlled. It is primarily a threat. On the other hand, to someone imbued with the spirit of industrial ecology, an industrial byproduct represents an untapped resource that should not be wasted. It is primarily an opportunity. Neither view is incorrect. Managed improperly, industrial byproducts pose a threat to human health and the environment, as experience shows. However, careful and well-thought-out re-routing of
hyproducts as feedstocks can achieve the same if not greater levels of environmental safety as regulated disposal while obtaining economic value from materials that previously had none. As a result, the need for waste disposal is reduced or eliminated, which brings a finite reduction in environmental risk, while the draw on virgin materials is reduced, also providing an environmental benefit.

As a matter of historical development, RCRA came before industrial ecology. The primary goal of the statute, as implemented, is to prevent improper disposal. Recycling is not specifically addressed in the statute, and when it is addressed by EPA regulation, it is generally envisioned as involving three parties: the generator, the recycler, and the user of the recycled material. The requirements for the management of hazardous waste under RCRA are complex and expensive. Recycling activities are exempt from a substantial portion of these requirements, so that 'recycling' something is considerably less expensive than treating it, which is the other alternative under the statute. In this arrangement, the motive of the recycler is difficult for the regulator to determine: is it to avoid the cost of treatment, or is it to produce a valuable product or commodity?

EPA has enacted complex regulations to avoid the possibility of "sham" recycling - a process that is claimed to be recycling but is primarily motivated by a desire to avoid treatment costs. This has been done through the definition of solid waste, the locus of inquiry that triggers regulation under RCRA. The result has been a very intricate, confusing, and inconsistent set of regulations.

Unlike recycling as envisioned by RCRA, industrial symbiosis involves only two parties\textsuperscript{57}: the generator of the byproduct, and the user of the byproduct as feedstock. In this arrangement, there is little room for intrigue: while in the three-party situation the recycling process may be a sham, in the two-party situation the receiver of the byproduct uses it directly to substitute for a feedstock. There is therefore little to no doubt as to the motive of user; if the byproduct is used as a feedstock, then by definition the activity is not a sham\textsuperscript{58}.

The problem is that regulation under RCRA, in a justified effort to weed out sham recycling, impedes legitimate byproduct re-use as industrial

\textsuperscript{57} In actuality it may involve more, but there are only two types of parties to the relationship.
\textsuperscript{58} One exception to this caveat is 'toxics along for the ride;' this issue is addressed below.
symbiosis. The rest of this chapter introduces the RCRA framework for regulation, discusses implementation issues and RCRA barriers to industrial symbiosis, and offers some solutions.

A rose by any other name: The definition of solid waste

In the United States, the Environmental Protection Agency regulates the management of waste, through a regime of more than 600 pages of complex regulations under the Resource Conservation and Recovery Act. Whether or not a certain stream of byproducts qualifies as a waste under the statute has major implications for the entity generating and handling it. There are three possibilities: a byproduct can avoid being labeled a solid waste, be a solid waste, or it can be a hazardous (solid) waste. EPA jurisdiction under RCRA is limited to the regulation of the management of wastes, so that meeting the regulatory definition of solid waste is both necessary and sufficient to trigger regulation under the statute. That which does not fall under that definition escapes regulation under RCRA. Subtitle C of RCRA governs the management of solid wastes that also meet the definition of hazardous waste. The overriding purpose of Subtitle C is to “protect human health and the environment” from pollution resulting from unsafe handling of hazardous waste products. As a result, the regulations governing hazardous waste management impose onerous burdens and responsibilities on those who generate, handle, treat, and dispose of such materials (see below). The EPA under RCRA also regulates solid wastes which are not hazardous waste, but these requirements are much less stringent than those for hazardous waste.

In the language of RCRA and its attendant regulations, the use of industrial byproducts as feedstock for other processes is referred to as recycling. Since such byproduct re-use is an essential aspect of an industrial ecology, the regulatory treatment of byproduct recycling under RCRA is of great relevance to the development of industrial ecosystems. Unfortunately,

EPA has not promulgated standards for recycling, relying instead on a roundabout manner of differentiating it from waste treatment:

Rather than foster recycling by setting standards to distinguish it from treatment, however, the EPA has attempted to advance recycling efforts through the definition of "solid waste." In this definition, the EPA focuses on describing the circumstances by which a secondary material that would otherwise be a solid and hazardous waste, avoids RCRA regulation if it is recycled in a variety of ways\textsuperscript{62}.

The result is that one must look to the definition of solid waste in order to determine whether a byproduct to be used as a feedstock is regulated as RCRA solid waste, or, worse, as hazardous waste. If the material and activity in question escape the solid/hazardous waste label, then reuse may proceed largely free of RCRA regulation. If meeting the definition(s) triggers RCRA regulation, however, then a number of requirements are imposed upon the generator of the byproduct. Unfortunately, evaluating this question is far from an easy task:

The regulations defining solid waste are the most complex environmental regulations ever written. The core of the definition revolves around whether the material is discarded. The EPA regulations that elaborate on this definition contain a series of special tests and exclusions. Some of the exclusions are required by statute; others are attempts by EPA to address problematic cases involving the reuse or reclamation of materials in industrial processes. In EPA’s recent study of RCRA, the Agency found that the definition of solid waste is "difficult to understand and implement for EPA, the states, and industry. Permitting and enforcement are hampered by the complexity of those definitions." The Agency receives more than 1,000 calls each month on definitional issues\textsuperscript{63}.

RCRA defines "solid waste" as "any garbage, refuse, sludge from a waste treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities\textsuperscript{64}". EPA has encountered difficulty in establishing

\textsuperscript{63} Williams and Cannon, "Rethinking the Resource..." p. 10064 footnotes omitted.
\textsuperscript{64} RCRA §1004(27), 42 U.S.C. §6903(27)
when a material is "discarded" and therefore a solid waste under RCRA's definition. According to a revised definition promulgated by the Agency in 1985, "solid waste" is defined as any discarded material not otherwise excluded by regulation or by variance. Relevant regulations further state that "discarded material" is any material that is "abandoned," "recycled," or "inherently waste-like."

The condition of being "inherently waste-like" is provocative, leading as it does to a circular definition. Solid waste is a discarded material, a discarded material is anything inherently waste-like, such that a solid waste is anything that is inherently waste-like. Perhaps more importantly, it is somewhat perplexing that recycled materials are defined as discarded, since "discard" has the common meaning "to throw away." The reason for all this intrigue is apparently that recycling status exempts a process from the bulk of RCRA regulation, making attaining such a status very attractive to those generating waste. EPA has thus endeavored to separate "sham recycling," which is essentially a show at recycling made by generators of hazardous waste in order to avoid the costs of mandated disposal, from "true recycling."

The resulting regulatory framework has been anything but clear, as explained by Randolph Hill, attorney with the Office of General Counsel of the U.S. Environmental Protection Agency:

The only "recycled" materials that are regulated as solid wastes are those used in a manner that constitutes disposal, burned for energy recovery, reclaimed, or speculatively accumulated. Yet, not all types of waste materials are regulated when reclaimed or speculatively accumulated. By contrast, "inherently waste-like" materials also refers to recycled materials, but since these materials are either predominantly abandoned or contain hazardous constituents (particularly dioxins) not normally found in raw materials for which the wastes substitute, they are always regulated regardless of the type of recycling or the material involved. As a further source of confusion, EPA subjects certain recycled materials and recycling activities to

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65 Hill. "Overview of RCRA: The Mind-Numbing...

66 ibid.

67 Since the three criteria for defining something as a "discarded material" are connected by "or" and not "and," meeting any one of them results in the substance in question being "discarded."

68 The American Heritage Dictionary Second College Edition

limited requirements, rather than to the full subtitle C regulatory system; other recycled materials are subject to all subtitle C requirements.\(^{70}\)

The determination of whether a solid waste is a hazardous waste is a little more straight-forward, but not much. Under EPA regulations, a waste is hazardous either because it exhibits a "characteristic" of a hazardous waste or because it has been specifically listed by the Agency as such.\(^{71}\) "Characteristic" wastes are substances whose inherent properties satisfy one or more tests developed by EPA for evaluating their 'hazardousness'.\(^{72}\) There are four such tests: ignitability, corrosivity, reactivity, and toxicity.\(^{73}\) Further exposition on characteristic wastes is beyond the scope of this undertaking; suffice to say that it is the responsibility of the generator to test his or her byproducts for relevant characteristics.

A solid waste is also a hazardous waste for purposes of regulation if EPA, by formal rulemaking, has placed it on one of four lists of designated hazardous wastes.\(^{74}\) De-listing such a waste once it has been listed is possible as an across-the-board measure, but requires a formal rulemaking. This is a very elaborate process and ensures that a de-listing will virtually never happen.\(^{75}\) At any rate it is an inappropriate tool for obtaining regulatory approval for a byproduct reuse because it would remove the material in question from RCRA Subtitle C regulation in all cases, not just for the specific purpose of re-routing it as a feedstock.

For the purposes of industrial symbiosis, the difference between characteristic and listed wastes is significant, by virtue of the "mixture and derived from" rule:

\(^{70}\) Hill, "A- Overview...  
\(^{71}\) ibid. 
\(^{72}\) Note that 'virgin' materials with similar or identical properties as "characteristic" wastes are not regulated by RCRA, and even if they are regulated under another statute, those requirements are much less stringent than Subtitle C. Thus the "characteristic" label is misleading, because it refers not only to the "inherent properties" of the substance, but also to its history; "virgin" feedstocks with identical "inherent properties" are not regulated. This framework makes very little sense in the case where a byproduct eligible for RCRA regulation is to be reused as a feedstock, because the "inherent properties" are more or less identical, but the byproduct is subject to much more stringent regulation as well as to the stigma of the "hazardous waste" label. This would be the case, for example, if the Kalundborg linkage of Statoil flue gas being piped to Gyproc were to be attempted in the United States (see below).  
\(^{73}\) Hill, "An Overview...  
\(^{74}\) ibid.  
\(^{75}\) VanAcker, U.S. EPA, Personal communication
The key difference between characteristic and listed wastes is the effect of the so-called mixture and derived-from rules. A waste that is not listed is hazardous only as long as it exhibits the characteristic. If a characteristic waste is mixed with another solid waste or treated in a way that the mixture or treatment residual is noncharacteristic, the waste may then be managed (i.e. transported, further treated, stored, or disposed of) as a nonhazardous solid waste. By contrast, EPA's basic rule for listed wastes is: once hazardous, always hazardous. In other words, a listed waste, once generated, retains its classification as a RCRA hazardous waste regardless of what is done to it, including mixing it with nonhazardous wastes or treating it...In addition, residuals derived from treatment of a listed hazardous waste remain listed hazardous wastes. Most importantly, the mixture and derived-from rules operate regardless of whether the mixing or treatment eliminates the properties...that originally caused EPA to list the waste76.

This policy raises a number of concerns. Note first that one of the triggers for listing a waste as hazardous is that the waste exhibits one of the four characteristics77. Thus, any characteristic waste can be a listed waste, and therefore subject to the mixture and derived from rule. It would seem that the intent of this approach to regulation is to prevent "solution through dilution." That goal would explain the 'mixture' part of the rule. The 'derived from' part of the rule may also serve some desirable purpose, but has the chilling consequence of placing a major roadblock in the way of the use of residues of pollution-control technologies as feedstocks. Recall that in Kalundborg, the desulfurization plant of Statoil refinery yields liquid sulfur, which is sold to a sulfuric acid producer. Under the RCRA regulatory scheme, this practice would invoke the mixture and derived from rule and quite likely result in the liquid sulfur being classified as a hazardous waste78. This would surely discourage such a sale, with the result that the sulfuric acid from Statoil would have to be disposed of by some sort of hazardous waste treatment, storage, and disposal facility, producing no economic value and imposing a finite risk to human health and the environment, while the sulfuric acid producer would have to obtain its sulfur from some other source, assured!,; with some adverse environmental impact. It is possible in this type of situation to obtain from EPA a variance from the definition of

76 Hill, "An Overview..." p. 10259. emphasis added. footnotes omitted.
77 ibid
solid waste if the interested party can prove that the material in question is commodity-like and has economic value\textsuperscript{79}. Such a variance would allow the sale of the byproduct as a feedstock; however the administrative process required can be long and arduous\textsuperscript{80}. Liquid sulfur exhibits the characteristic of corrosivity, so that even as a direct byproduct it would be considered a hazardous waste. The Kalundborg example, however, demonstrates the viability of its safe reuse.

The resolution of the definition issue is very important for the generator of a byproduct stream. If the material is classified as hazardous waste, then the generator must follow a very rigorous set of regulations which prescribe its management. RCRA requires cradle-to-grave tracking of hazardous waste once it leaves the generator's site, using a manifest system that creates a paper trail of the waste which follows it to its final resting place and beyond\textsuperscript{81}. CERCLA, the Comprehensive Environmental Response, Compensation, and Liability Act, assigns joint and several liability for hazardous waste contamination at a site to any and all generators who have contributed hazardous waste to that site. The specter of future liability creates a powerful incentive for generators of hazardous waste to ensure that their byproducts are disposed of safely\textsuperscript{82}. It also creates a disincentive to send hazardous waste to be recycled off-site, as chance of future liability cannot be ruled out; liability is maintained by the generator\textsuperscript{83}.

If, however, a byproduct stream can evade the hazardous waste label, then its recycling is virtually unregulated under RCRA. What one does with a byproduct is either recycling or treatment. Treatment processes are required to have a pre-construction and an operating permit, which under RCRA require three to twelve years to obtain, while a recycling process requires neither\textsuperscript{84}. There is therefore a significant financial incentive for generators of waste to avoid RCRA Subtitle C regulation by gaining "recycler" status. This

\textsuperscript{79} Ibid.
\textsuperscript{80} Hill, "An Overview..."
\textsuperscript{81} Comella, "Understanding a sham..."
\textsuperscript{82} Mel Vyvial, Chevron, Personal communication; John Stansbury, Fermenta ASC Corporation, Personal Communication.
\textsuperscript{83} According to Robert Frosch, "General Motors is sometimes reluctant or refuses to transfer regulated waste to brokers, waste exchanges, or potential users because it cannot get rid of the legal responsibility for the material and is not sure it can trust the downstream users." Source: "Industrial ecology: A philosophical introduction" Proc. Nat. Acad. Sci. USA Vol. 89, P. 800-3, February 1992.
\textsuperscript{84} Comella, "Understanding a sham..."
has given rise to "sham recycling," an undertaking which endeavors to make something out of a waste stream (to "recycle" it) with the principal motivation of avoiding disposal costs\(^85\). Park benches made from glassified toxic waste are a prime example\(^86\). It has been EPA policy to root out sham recycling, and RCRA regulations are accordingly artifacts of deep suspicions about the true purpose behind claimed recycling activities\(^87\). It is stated EPA policy, however, to encourage recycling hazardous waste which yields a product that itself has economic value\(^88\).

**Implementing RCRA**

RCRA implementation has been criticized for a lack of clarity, consistency, and coherence. It has become an environmental statute that people who deal with it love to hate. One significant reason for this disgruntlement is that, despite the name, EPA regulations under Resource Conservation and Recovery Act are intended to prevent unsafe handling of hazardous waste, not to encourage recycling. In theory at least, EPA likes the idea of recycling,\(^89\) but has long perceived that lenience toward recyclers allows sham recycling to occur. Bad recycling has been seen as worse than good treatment and disposal, so that regulations and their implementation have leaned toward channeling potentially harmful materials into theSubtitle C system. At the same time, the lack of regulation of recyclers has allowed those operations that manage to qualify for such designation to be largely unregulated, with some significant resulting abuses\(^90\). RCRA is philosophically a mirco-management, command-and-control sort of law,\(^91\) with the result that the task of separating the legitimate from sham recycling has been hard-wired into regulations. At the same time, Congress wrote much of the regulations for managing hazardous waste under the 1984 Hazardous and Solid Waste Amendments directly into the statute because it did not trust the EPA under Gorsuch and Reagan\(^92\). What was left up to

\(^85\) Secunda and Papetti, Personal communication.
\(^86\) Van Ackron, Personal Communication.
\(^87\) Secunda and Papetti, Personal communication.
\(^88\) Van Ackron, Personal Communication.
\(^89\) Camella "Understanding a Sham..."
\(^90\) ibid.
\(^91\) Robert Frosch, Director, Project on Public Policy for Industrial Ecology, Harvard Kennedy School of Government, Personal Communication.
\(^92\) Secunda and Papetti, Personal communication.
Agency discretion was implementing the definition of solid waste, which explains why so much controversy has been focused there.

RCRA has been implemented in what has been poignantly described as "an administrative haze\(^{93}\)." In the words of Joshua Secunda, Assistant Regional Counsel, EPA New England, "it is not clear to the regulators or the regulated: a) who or what materials are regulated, and when; b) whether EPA has a consistent philosophy for regulating wastes and recycling, and; c) why regulatory recycling exemptions for hazardous waste can't all appear in one RCRA regulatory section\(^{94}\)."

In essence, the implementation of RCRA is shrouded in great mystery. According to Robert Frosch, Director of the Project on Public Policy for Industrial Ecology, "it is not clear to anyone what it all means - businesses cannot get a clear answer to specific questions\(^{95}\)." RCRA gives EPA considerable latitude to define what is solid waste and what should be managed as hazardous waste, which has allowed the Agency to shape the RCRA program through the regulatory process\(^{96}\). This freedom has had the undesirable consequences of making the overall purpose of RCRA difficult to identify\(^{97}\), and of focusing intense pressure on EPA from competing interests on the basic definitional elements of the statute\(^{98}\). These factors, along with the inherent difficulty in establishing regulatory heuristics by which to separate "sham" from legitimate recycling have resulted in an "extremely (if not unworkably) complex management system, the internal logic of which can lead to irrational results\(^{99}\)."

To add to the confusion, EPA RCRA regulations are enforced by the states, not surprisingly with great variation among them\(^{100}\). Each EPA regional headquarters has oversight over state implementation within its region, and can challenge in court permits granted to generators\(^{101}\). States are therefore forced to gaze into a kaleidoscope of nebulous requirements:

\(^{93}\) Robert Frosch, Personal communication.
\(^{94}\) Secunda "The Resource Conservation..." p. 3.
\(^{95}\) Frosch, Personal communication.
\(^{96}\) Williams and Cannon, "Rethinking the Resource..."
\(^{97}\) Frosch, Personal communication.
\(^{98}\) Williams and Cannon, "Rethinking the Resource..."
\(^{99}\) ibid. p. 10065.
\(^{100}\) Frosch, Personal communication
\(^{101}\) Secunda "The Resource Conservation..."
States are united in their perception that guidance from EPA on how to interpret hazardous waste regulations is confused and inconsistent. States are thus reluctant to approve permits for (or exempt) recycling; they believe that EPA will inevitably "second guess" their determinations. Further, EPA's inconsistency in interpreting (as illustrated by the innumerable memo "wars" between the ten regions and headquarters) its own regulations makes states unable or unwilling to definitively advise the regulated community on what procedures would avoid an enforcement action for treatment of hazardous waste or "speculative accumulation" of wastes otherwise exempt as "recyclable.\textsuperscript{102}"

This uncertainty is passed along to industry, which is leery of entering a regulatory tangle for which it cannot get explanations\textsuperscript{103}. The lack of regulatory consensus creates legal risks for a company that engages in recycling operations,\textsuperscript{104} due to uncertainty about whether EPA will view its efforts as "sham" or legitimate recycling\textsuperscript{105}, and possibly to regulatory volatility over time. The prospect of permitting as a Treatment, Storage, and Disposal Facility is enough to drive companies away\textsuperscript{106}. In sum, the several levels of uncertainty with regard to what passes as legitimate recycling that is exempt from stringent RCRA regulations creates a significant disincentive to recycling efforts.

This litany of criticism is in large measure an artifact of the era from which the statute originates. At the time of passage of RCRA's Hazardous and Solid Waste Amendments in 1984, in the wake of Love Canal, the issue of concern was a much more acute need to ensure safe handling and disposal of hazardous waste. With some exceptions, that goal has been achieved. The reuse of industrial byproducts as feedstocks has only received attention outside a small group of industrial ecologists within the last few years. Viewed through an industrial ecology lens, RCRA regulations leave much to be desired in the way of promoting byproduct reuse. The task now is to examine the barriers and find ways to eliminate them, without compromising RCRA's charge of protecting human health and the environment from improper management of hazardous waste.

\textsuperscript{102} ibid. p. 3.
\textsuperscript{103} Frosh, Personal communication.
\textsuperscript{104} Secunda "The Resource Conservation..."
\textsuperscript{105} Van Ackron, Personal communication.
\textsuperscript{106} Secunda and Papetti, Personal communication.
RCRA Barriers to Industrial Symbiosis

In addition to the general implementation problems discussed above, RCRA poses a number of regulatory barriers to industrial symbiosis. These include:

*The 90 day rule* Under RCRA regulations, a generator of hazardous waste may store that material in RCRA-approved containers for up to 90 days on-site without having to obtain a permit as a Treatment, Storage, and Disposal Facility (TSD)\(^{107}\). To store for longer, a TSD permit is required. Given the cost, complexity, time, and stigma required to obtain such a permit, *it is a foregone conclusion that no firm will seek licensing as a TSD facility solely for the purpose of participating in a symbiotic byproduct-to-feedstock linkage*. The ninety day rule has been pointed out as a great impediment to recycling because in many cases it does not allow the accumulation of byproducts in sufficient quantity to make transportation to the site of reuse economically viable\(^ {108}\). This limitation is a problem in cases where byproducts are to be moved off-site in discrete batches. In Kalundborg, such examples are the movement of sulfur from Statoil to Kemira, and the movement of scrubber ash gypsum from Asnæs Power Plant to the wallboard maker Gyproc.

The storage limitation has been overcome by some small generators of similar byproducts by coordinating and jointly financing their transport to recycling/reuse facilities\(^ {109}\). In the model of industrial symbiosis developed in this thesis, the number of participants is likely to be small, so that this approach is not appropriate. In general, the ninety day rule is a significant hindrance to recycling, but mostly for small quantity generators.

*Permitting requirements for storage prior to recycling* While the generator of a hazardous waste may store on-site for up to ninety days, *any* storage by the facility which is to recycle or reuse that waste requires a RCRA permit. The regulatory scheme is such that the recycling process does not require a

\(^{107}\) Camella "Understanding a Sham..."

\(^{108}\) Secunda, "The Resource Conservation..."; Frosch, Personal communication.

\(^{109}\) Audrey Webber, "Harvard Kennedy School of Government, Personal Communication."
permit, but storage of byproducts deemed 'hazardous waste' does\textsuperscript{110}. As a result,

what a legitimate recycling facility gains by avoiding RCRA permitting for the recycling process, it partially loses by being required to obtain such a permit for the storage of hazardous waste. The lack of on-site storage forces a facility either to transfer directly hazardous waste from a truck to the recycling process, or to not recycle...Without a storage permit, any temporary holding of hazardous waste prior to recycling is illegal\textsuperscript{111}.

To the extent that byproducts replace feedstocks in a symbiotic linkage, this requirement is tantamount to a prohibition against maintaining any inventory without a RCRA permit. The problem here is that permitting under RCRA is very time, money, and resource-intensive, as well as carrying with it the stigma associated with hazardous waste. In this regard, RCRA constitutes a major barrier to industrial symbiosis involving byproducts that fall under the definition of hazardous waste. Overly stringent permitting requirements decisively detract from the attractiveness of byproduct reuse, a result that is in contradiction with the overall goals of RCRA and of environmental laws in general. The use of an industrial byproduct as a feedstock eliminates the need for disposal and also reduces the need for virgin materials of the same kind. The regulatory conception of hazardous waste is inappropriate for this situation; a hazardous waste is hazardous strictly because it is to be disposed of. The virgin feedstock that these byproducts replace are just as hazardous as the byproducts themselves - they are the same thing;\textsuperscript{112} otherwise they would not and could not be used as feedstocks.

While concern over the management of potentially hazardous materials is legitimate, byproducts should not be subjected to substantially more stringent standards than the feedstocks they directly replace. If EPA is to make possible the use as feedstocks of byproducts that fall under the hazardous waste definition, then the permitting process for storage as inventory must be made palatable for legitimate recycling/reuse operations.

\textsuperscript{110} Camella "Understanding a Sham..."
\textsuperscript{111} \textit{ibid}. p. 450.
\textsuperscript{112} The one exception to this claim is 'toxics along for the ride,' whose presence either renders the byproduct unusable as a feedstock, thereby eliminating the problem, or can be tested for with thresholds which can be used to disallow the exchange if exceeded.
A model for expedited permitting procedures is already in place\textsuperscript{113} and should be applied.

Restrictions on shipping waste off-site A generator may store a hazardous waste on-site for up to ninety days. After storage on-site, the generator must prepare the waste for shipment by first packaging it according to Department of Transportation guidelines, properly labeling the containers, obtaining an EPA identification number, completing a hazardous waste manifest, and handing off the package to a licensed transporter of hazardous waste\textsuperscript{114}. This system is highly effective for ensuring that hazardous waste is disposed of in accordance with regulations, but is inappropriate to facilitate or allow the reuse of such byproducts as feedstocks. To use the Kalundborg example, piping Statoil flue gas to Asnæs and Gyproc would be illegal under this system, at least at first glance. Consultation with EPA could result in the granting of a variance to allow such a transfer\textsuperscript{115}, but, in general, flare gas is construed as hazardous waste.

Mixture and derived from rule This rule establishes that once a substance is tagged as a listed waste, any substance derived from treating it is also a hazardous waste. This stipulation makes difficult or impossible the use of residues of pollution control technologies as feedstocks. In Kalundborg, the sulfur from Statoil and the gypsum from scrubber sludge both fall into this category. The mixture and derived-from rule threatens to eliminate a portion of the industrial waste-stream from potential re-use.

Liability The fact that liability stays forever with the generator herds generators toward disposal rather than reuse. The ability to transfer liability would solve this problem, but would likely require a statutory change in CERCLA. A possible solution to this problem lies with the definition of solid waste, in the intuitively attractive idea of not labeling as waste materials that are to be used as feedstocks.

\textsuperscript{113} Commella "Undertanding...."
\textsuperscript{114} ibid.
\textsuperscript{115} Statoil flue gas is an ethane/methane mixture which replaces the burning of 'virgin' fuels at the other facilities - clearly an environmental gain.
Uncertainty / Lack of regulatory flexibility  This set of problems is addressed in the above section. Suffice to add that the prospect of TSD permitting pushes companies away from recycling/reuse\textsuperscript{116}.

Proposed solutions

Although the above presents a grim picture, all is not lost. RCRA as written allows EPA the flexibility to remove most if not all barriers to byproduct reuse cited here. Suggestions for how to go about that follow, but first an observation: RCRA Subtitle C regulations only apply to hazardous wastes, not all solid waste. A sizable portion of the industrial waste stream is available for reuse, sans RCRA regulation\textsuperscript{117}. That is good, but all of it should be available.

The extreme vagueness of the definition of solid waste, the locus of inquiry that triggers RCRA regulation, is a major part of the problem. It can and should also be a major part of the solution. EPA is not statutorily wedded to any particular policy toward the reuse of industrial byproducts as feedstocks. Therefore, EPA can remove barriers as a matter of regulation, or even as a matter of policy.

First and foremost, EPA headquarters needs to issue a statement of policy indicating support for the legitimate reuse of industrial byproducts as feedstocks. Such a statement can and should be tied in with the Environmental Technology Initiative's Eco-Industrial Park Project, one of whose products is to be a set of policy recommendations. EPA should back away from the micro-management of waste handling that has characterized the RCRA program and instead issue guidelines for what should be considered legitimate recycling. EPA regions and the states should then be allowed discretion in allowing, on a case-by-case basis, recycling/reuse activities. This approach can take two forms.

The definition of solid waste can be used as a regulatory vehicle for exempting processes that involve legitimate reuse of byproducts as feedstocks from the 'solid waste' label. What is required is a stipulation that materials that are to be used as feedstocks to replace virgin materials do not fall under

\textsuperscript{116} Secunda and Papetti, Personal communication.

the aegis of solid waste. This is, after all, intuitive. Standards can be set for comparing the byproduct with the virgin material it is to replace. The presence of 'toxics along for the ride' in significant amounts should disallow this exemption. At the same time, however, the treatment of byproducts to render them fit for reuse should not inexorably tag them with the 'hazardous waste' label. This stipulation refers to the 'derived from' part of the 'mixture and derived from' rule. That rule should be modified so that a substance that comes out of a waste treatment operation should not be construed as a hazardous waste, if, aside from its history, it qualifies for an exemption as a feedstock.

The potential problem with this approach is that something that is not a 'solid waste' escapes RCRA regulation, with the result that there may be no safeguards against improper management. A solution is to treat byproducts slated for reuse as virgin feedstocks, subjecting them to Department of Transportation guidelines (and/or EPA guidelines under TSCA and other applicable laws) for shipping and storage. Another solution, which should be implemented regardless, is to streamline and simplify the permitting process for storage of hazardous waste prior to reuse as a feedstock and apply simplified management standards.

EPA is currently reassessing the definition of solid waste, and the definition's effect on byproduct reuse should weigh heavily in that reassessment. The other manner in which EPA can remove barriers to byproduct reuse and thereby to industrial symbiosis is to affirm the authority of states and regions to grant variances from the definition of solid waste and from various regulatory requirements. Less stringent, though still meaningful, requirements should be available as substitutes to ensure safety. The definition of solid waste and the accompanying maze of regulations are intended to hard-wire the process of differentiating between legitimate and sham recycling. Such intrigue should not be necessary in the case of industrial symbiosis.

It should not take a panel of experts to establish whether the material exchanges in an industrial ecosystem comprise legitimate recycling. As the Kalundborg case study illustrates, such linkages are very clear and unequivocal. If a byproduct is used to replace a virgin feedstock, then that activity should be encouraged, not hindered, given that the material is handled in a manner that is no less safe than the handling of the virgin
feedstock. The only other stipulation that is needed is to ensure that the byproduct does not contain 'toxics along for the ride' in significant quantities.

EPA headquarters should therefore make it a policy to allow states and regions to grant necessary variances on a case-by-case basis to allow industrial symbiosis. Common sense on the part of regulators should be all that is needed to establish what constitutes byproduct reuse as feedstock. This approach would not require a change in regulations, and therefore could be implemented very quickly and easily.

State and local EPA should therefore be prepared to enter a dialogue with industry to jointly explore opportunities for byproduct reuse. EPA headquarters should establish a coherent approach to the regulation of recycling, while allowing states and regions to make regulatory decisions without the threat of being second-guessed. Such an approach would go a long way to disentangling regulation under RCRA and putting it on a course that is consistent with its broader goals and with those of other environmental laws.
Chapter 6
Flexible Networks and Inter-Firm Collaboration: Applications to Industrial Ecosystem Development

Introduction
This chapter introduces the field of flexible networks and inter-firm collaboration, which offers a body of experience that is in many ways applicable to efforts to develop industrial ecosystems. The two areas of endeavor confront many of the same issues and barriers, although they have yet to be treated in the literature as meaningfully related. What follows is an attempt to bring the two fields together and to identify implications to IE.

The concept
A flexible manufacturing network (FMN), or the resulting Inter-firm Collaboration, as it is more recently being called, is an organizational phenomenon by which distinct firms interact in collaborative ways in order to solve problems or achieve results they could not do so acting individually. According to "A Short Guide To Inter-Firm Collaboration", a pamphlet from Regional Technology Associates, Inc, which has also compiled more lengthy guides on the subject,

"Inter-firm collaboration (IFC) is the new frontier of competition -- a way for firms to develop joint solutions to common problems. IFC allows firms to combine resources to gain knowledge, achieve economies of scale, acquire technologies and resources, take advantage of their mutual capabilities and enter markets otherwise beyond their reach."

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This is a fairly open-ended definition, but it is narrower in its implementation. The focus of networking efforts has been small- and medium-sized business enterprises -- generally manufacturers. Based on the success of similar arrangements in some industrial areas (see below), several economic development-minded government agencies, as well as some NGOs in the US and elsewhere, have taken it upon themselves to cultivate such networks. The motivation is as follows. The globalization of markets has altered competitive conditions such that innovative strategies are needed if small to medium-sized manufacturers are to survive and prosper. Demanding customers are apparently scouring the globe for highly specialized products. Firms must specialize to be competitive, but to do so for a small firm means sacrificing flexibility and putting too many eggs in too few baskets. The answer seems to be that firms must specialize to some extent and learn to combine their core competencies with others. There is too much to do and learn to do so alone. By collaborating, firms can achieve synergies in which the whole is greater than the sum of its parts.

Inter-firm collaboration is a loosely delineated phenomenon, and exists over a broad range of levels of trust and interdependence. Four broad categories can be identified:

- informal and unorganized cooperation among two or more firms around a very specific problem;

- formal and organized cooperation among several firms within a membership-based organization, with very limited inter-dependence, and where the primary unifying factor may be geography, sector, or end markets;

- formal and organized cooperation (but not necessarily 'legally defined') among a smaller set of firms, with some significant degree of interdependence, and with quite specific shared interests; and

- value-adding partnerships between customers and groups of suppliers working on better meeting customer needs.

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119 Bosworth, Brian "Thinking About Inter-Firm Cooperation: Where are the points of intervention?" Non-published, document from Regional Technology Strategies Inc. 1995.
The third category, interdependent networks of firms, is worth further consideration. This category involves a discrete group of firms "who are willing to depend significantly on each other in order to achieve some benefit not available to them independently." Within this grouping, four more categories of interaction avail themselves:

- co-production networks of where firms cooperate in manufacturing components, assemblies, or finished goods;
- co-marketing networks of firms that jointly market their products in ways that give them access to and power in high value markets;
- learning networks of firms who collectively seek to learn about and manage complex issues related to competitiveness;
- resource networks of firms who pool or share resources in developing a joint solution to a common problem, such as waste management.

**Why this is relevant**

There are three reasons:

- As it turns out, there exists in Chattanooga, TN (home of a budding Eco-Industrial Park) something called the Environmental Network Project, which has a focus on environmental issues and innovative ways to utilize firms' waste products.
- Industrial ecosystems, or rather industrial symbiosis, is a specific form of inter-firm cooperation, and as such forms a subset of that field of inquiry; albeit the motivation for IFC is competitiveness. The philosophical underpinnings of IE are different, but if the same end can be approached as a realization of disparate goals, all the better.
- Efforts to create networks by way of third-party intervention offer somewhat of a parallel with efforts to establish industrial ecosystems. As detailed below, several public sector bodies have taken a number of different approaches world-wide to fostering inter-firm cooperation, based on the perceived success of such collaboration in a region of Italy. Lessons learned in bringing about manufacturing networks may well be relevant to efforts aimed at creating industrial ecosystems.

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120 *ibid.*
121 *ibid.* p.2.
The origins of inter-firm collaboration

Small and medium-sized manufacturers have received more and more attention over the past five to ten years, both in the United States and abroad. These firms have traditionally been very independent, but mounting pressures from globalizing markets and competition from newly industrializing nations have put many of them at risk. The search by experts and public sector agencies for ways to make these firms more competitive has come to rest in large part on the concept of firms working together to accomplish more than they could individually.

This conceptually new economic development strategy originated in the Italian region of Emilia-Romagna. The success of its small artisan-based industrial economy in the 1970's garnered international attention and gave credence to the idea of flexible specialization, cooperation, and networks. This form of organization was celebrated and revealed to the world at large in Michael Piore and Charles Sabel's *The Second Industrial Divide*. Similar collaboration among firms proved successful in Japan and southern Germany.

Intrigued by this success, those concerned with development policy have begun to examine ways to transplant and emulate this organizational phenomenon to their own regions. An increasing number of jurisdictions in the United States and Europe have begun to experiment with policy interventions to encourage collaboration, ranging from an extensive national program in Denmark to foundation grants in some U.S. communities. State and regional efforts to develop networks within the U.S. have taken a variety of approaches, offering the opportunity for comparing their effectiveness.

The parallel between manufacturing networks and industrial ecosystems

The history of efforts to develop and foster inter-firm collaboration in the U.S. and abroad is only relevant to the development of industrial ecosystems if the two are indeed similar in meaningful respects. There is reason to believe that they are. The U.S. public-sector effort toward flexible manufacturing networks is an attempt by a third party to change the behavior

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of small and medium-sized firms in a manner that enhances both the good of the firms involved and the common good. It involves the application from the outside of a model of firm behavior and interaction. It involves a change in the way firms see themselves vis a vis other firms in their general vicinity. And it involves an attempt to overcome institutional and cultural barriers to such changes. The pathway of development is at issue, as is the manner of third-party intervention. All of these statements are applicable to attempts to develop industrial ecosystems, with the exception that these attempts tend to focus on larger firms, which is a meaningful difference. Both schools have a Mecca; of flexible manufacturing it is the Emilia-Romagna region of Italy, of industrial symbiosis, it is Kalundborg.

**Emilia-Romagna: The Kalundborg of manufacturing networks**

According to Bosworth and Rosenfeld\(^1\)\(^2\)\(^3\), the United States lacks a history of industrial policy toward small and medium-sized firms. Those interested have looked to Europe, where Northern Italy, as revealed to America by *The Second Industrial Divide*, has become the prototype for inter-firm industrial collaboration. Highly competitive small manufacturers can be found in other countries, but nowhere is inter-firm collaboration as advanced and dynamic as in the Emilia-Romagna region of Northern Italy. Visiting the region has become a pilgrimage for students of manufacturing networks just as visiting Kalundborg has for industrial ecologists.

The interactions among the hundreds of very small, technologically advanced manufacturers in the region are hybrid results of evolution based on economic, cultural and historical conditions, and government intervention to catalyze collaboration. The institutional matrix in which collaboration takes place is comprised of the services of independent trade associations and government assisted, sector-specific service centers. The trade associations are self-sufficient, funded by membership fees, and provide services such as accounting, financing, and training. The 12 service centers, which were established in the late 1970's by regional governments, provide 'competitiveness' services, and presumably catalyze inter-firm collaboration.

Emilia-Romagna has experienced a sharp loss of mass-production jobs since 1970, which has been paralleled by tremendous growth of small

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businesses. As of 1991, there were 325,000 registered firms in a region of 4 million people\textsuperscript{124}. According to Hatch,

The key to this success in rebuilding the base economy on the limited capabilities of individual small firms has been the spread of manufacturing networks. Regional government, labor unions, and trade associations have learned how to foster cooperating systems of small and medium-sized firms, bringing them together around shared services (for example, quality assurance, market forecasting, or materials purchasing) until strong commercial ties can give these networks a life of their own. Today, large numbers of small firms in north-central Italy participate in various forms of network activity, not out of public spirit, but because networking contributes visibly and immediately to the bottom line, to profits\textsuperscript{125}.

While Emilia-Romagna is widely held to be the ideal to which U.S. efforts aspire, there is some doubt as to whether the results of an evolutionary process that has its roots in specific regional conditions can serve as a valid model for such development elsewhere. \textit{This clearly parallels the Kalundborg / EIP question.} Calling into question the direct applicability of the Italian model in the United States is a host of factors, including "the presence [in Emilia-Romagna] of very active trade associations, along with high concentrations of very small, locally owned artisan firms in the same or related sectors and tight family and community relationships\textsuperscript{126}". Others have stressed the importance of shared values and face-to-face contacts among firm owners and workers, pointing out the importance of personal interaction in achieving the information flow that is essential for collaboration. \textit{This, too, is just like in Kalundborg.}

\textbf{The Danish Network Experience}

In 1988, Denmark faced a growing trade deficit, high unemployment, and low corporate investment. In May of that year, a study for the Danish Ministry of Trade and Industry by McKinsey & Company concluded that the fundamental problem was that Danish companies were too small. The study indicated that changes in the business climate over the previous decade had favored the large-scale operations of multi-national corporations and that

\textsuperscript{124} Richard Hatch, "The Ties That Bind" \textit{Entrepreneurial Economy Review} Spring 1991
\textsuperscript{125} \textit{ibid.} p 14
\textsuperscript{126} Bosworth and Rosenfeld "SIGNIFICANT..."
Danish firms lacked the 'critical mass' to take advantage of these trends\textsuperscript{127}. The study recommended that Danish firms merge to achieve critical mass in key areas. But despite support from the government, the recommended mergers were not forth-coming, due in part to populist fears of concentrated power along with a long tradition of independent businesses. As a result, a different approach proved necessary.

The coming of the European Common Market in 1992 added to the impetus for change. C. Richard Hatch, director of Manufacturing Network Projects of the Center for Manufacturing Systems at the New Jersey Institute of Technology, placed the focus on competence, not size, as he recounted in *The Entrepreneurial Economy Review*:

At a seminar on "1992 and the Single Market," I made the case that if Denmark wished to be competitive after 1992, she would have to either build big firms - and do it quickly, before 1992 put the cost of gaining initial shares of new markets beyond reach, or make existing, mostly small, firms perform like the best big ones...Economic forces favored Denmark's existing smaller, flexible production units. To link them in a viable flexible network would require leadership, but networks held the country's greatest hope\textsuperscript{128}.

In the ensuing period, Hatch and colleagues lobbied the Danish Ministry of Trade and Industry, putting forth a general, multi-step plan for building networks in large numbers: providing information to firms about network concepts, offering limited financial assistance to support network experiments, and training network brokers to catalyze cooperative projects\textsuperscript{129}. The idea caught on, garnering support from both government and industry, such that in March of 1989 the Danish Ministry of Trade and Industry announced a plan for establishing network collaboration among small and medium-sized enterprises. The program, presented as "Strategy '92," was presented by the ministry as a means to mobilize the country's small and medium-sized enterprises to strengthen its competitive power\textsuperscript{130}.

\textsuperscript{127} Hatch, "The Ties..."
\textsuperscript{128} *ibid.* p.14-15.
\textsuperscript{129} *ibid.*
\textsuperscript{130} *ibid.*
Denmark’s "Strategy '92"

Denmark's Ministry of Trade and Industry announced "Strategy '92" in March of 1989. Within 18 months, more than 3000 of Denmark's 7300 manufacturing companies were actively involved in networks. The program was intended to provide a workable context for inter-firm collaboration in areas such as marketing, joint use of advanced technology, organizational learning, studies of markets and rival industries, research and development, and quality control. Strategy '92 was based on a three-step approach to building networks in large numbers: providing information to firms about network models, offering grants to support network experiments, and training network brokers to catalyze collaboration. Provisions of the program included:

- Participation in networks by companies on equal terms with firms of their choosing, assuming responsibility for all working relationships
- Government financing of 100% of the cost of determining network feasibility, up to 75,000 kroner ($10,000)
- Subsidies of up to 50% for network development
- A national training program for network brokers

The governmental body charged with administering the program used a variety of means to reach firms in every industry and every city in Denmark, including press releases, newspaper stories, television talk shows, presentations to trade associations, and direct mail advertising. The campaign was highly effective, and the network concept gained salience in Denmark within a few months. Results followed shortly thereafter.


The undertaking proved highly successful. Eighteen months after the announcement of Strategy '92, more than 3000 of the nation's 7,300 manufacturing companies were actively involved in networks\(^{131}\). Denmark followed the Italian example but did so by way of a very different path. The development of flexible networks in Emilia-Romagna was the result of a long, evolutionary process which was aided by government involvement at the regional level. In contrast, Denmark has become the most successful model of a purposefully created inter-woven economy\(^{132}\). Two keys to the Danish approach are the training of network brokers and the provision of challenge grants. According to Brian Bosworth of Regional Technology Strategies, Inc., the Danish flexible manufacturing model is very much a brokered system\(^{133}\). The typical broker is a private consultant who

\(^{131}\) *ibid.*
\(^{132}\) Bosworth and Rosenfeld "SIGNIFICANT..."
\(^{133}\) Personal communication, 2/16/95
recognizes networks as a device for organizing small firms into larger groups that can afford to engage his or her consulting services. It is thus in the self-interest of brokers to organize networks, since while their training (for which they had to pay a fee) was organized as part of a government program, they do not appear to receive direct funding from the government.

Government support was provided in the form of challenge grants available directly to groups of firms who submitted satisfactory proposals for network development. This source of funding had a significant positive effect on the level of network activity, according to a Danish government report.

While Strategy '92 was a very successful rapid intervention by the Danish government to foster cooperation among its manufacturing firms, the effort to link firms did not have to start from scratch. Denmark built its network program upon a solid technology assistance infrastructure, including the Danish Technological Institute, 15 county-level Technology Information Centers, five research universities and intermediate applied research centers, numerous local technology centers, strong trade associations and unions, and industry consultants. In addition, the initial export orientation of Danish firms may have rendered them more amenable to cooperation in the interest of global competitiveness.

The picture that emerges is that the Danish network program took advantage of the existing institutional linkages among its firms and the widespread acceptance of the need for coordinated effort to enhance the competitiveness of the nation's industries. The rapid and extensive development of networks proves that Strategy '92 encompassed an approach that was appropriate for Denmark. The distinction has been made in the literature between the evolutionary development of networks in Italy and their rapidly crafted appearance in Denmark, but this distinction may be overstated. It is clear that Danish industry was primed for such development, so that, while the network strategy was not without some opposition, it was not necessary to alter significantly the cultural underpinnings of business practice: "The Danish manufacturing economy has long been populated almost exclusively by small, export-oriented firms with a long history of associative

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134 Bosworth and Rosenfeld "SIGNIFICANT..." P.35.
135 Hatch, "The Ties..."
136 Bosworth and Rosenfeld "SIGNIFICANT..." P.26.
organization through trade and industry groups." Strategy '92, with its challenge grants and network brokers, appears to have crystallized the latent collaborative potential of small and medium-sized Danish manufacturing firms.

The application of this analysis to the field of industrial ecology is to place the rapid, seemingly externally-imposed system of inter-firm collaboration in Denmark into perspective. While the change was fast and wide-spread, its cultural and institutional underpinnings were already in place; it was a rapid change following and extending an evolutionary process. This should serve to dampen somewhat the apparent potency of external intervention, but the role of network brokers is intriguing in the Danish experience, and deserves serious consideration in the context of network development elsewhere, and more specifically in the context of the development of industrial ecosystems.

Network development in the United States

The concept of flexible networks was introduced in the United States in the mid-1980's, amid significant doubt as to its viability for transplantation from Europe. "It will never work here," was the response of the head of one the largest U.S. development associations: Firms were too independent and fear of antitrust prosecution too great. Networking was fundamentally at odds with the way firms did business here. That prediction proved to be incorrect, as by 1991, at least 50 nascent networks had been spurred into existence by public-sector initiatives, and by 1992 their numbers had swollen to almost 80. The latter survey, by the National Institute of Standards and Technology, found wide diversity and complexity among emerging networks.

Merely introducing the network concept as a business strategy has been sufficient in some instances to motivate the formation of networks, while some came into being without reference to any outside model or ideal. In addition, a substantial number of networks have sprung from state initiatives which have taken a variety of forms. Despite initial fears to the contrary,

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137 ibid. p.25.
139 ibid; Bosworth and Rosenfeld "SIGNIFICANT..."
Networks at a glance

The following are a few examples of the networks that have taken shape in the United States over the past five years.

The Environmental Network Project in Chattanooga, Tennessee, focuses on environmental issues, with particular emphasis on finding innovative ways to utilize firms' waste products. The network has also been involved in joint marketing, including participation in a number of international trade shows. While there is no formal membership, 15 to 20 firms are estimated to be active. The project is funded by a $100,000 grant from Regional Technology Strategies Inc. through the Siaoan Foundation. Specific results of the project are at this time unknown.

ACEnet is based in Athens, Ohio, serving eleven counties in the southeastern part of the state. ACEnet's focus is on joint production, worker training, telecommunications, access to capital, and improving community relations. There is no formal membership, but ACEnet coordinates a number of projects, including twelve firms which cooperate to build housing components for people with disabilities, and forty firms which work together to produce agricultural products and specialty items. ACEnet receives financial support from state and federal sources, as well as from fees charged to participants.

Located in Portland, Oregon, the Alltech Manufacturing Network is comprised of three metalworking firms, an engineering firm, and a marketing/consulting firm. The network's focus is subcontracting metal parts and components, joint marketing, shared technologies, and capital investment, and shifting from job shop orders to production orientation. The network received a $10,000 start-up ('challenge') grant from the state of Oregon's Flexible Network Initiative as well as a $10,000 grant from General Electric.

The Oregon Publishers Expanded Network counts as its members 167 small book publishers and printers in Northwestern Oregon. Participants share equipment, technology, training, information, and cost-cutting procedures, as well as a publishing center geared specifically to the needs of the small publisher. Initial funding was in the form of a $10,000 challenge grant from the state of Oregon.

The Technology Coast Manufacturing and Engineering Network (TeCMEN) is an Okaloosa County, Florida agglomeration of 31 firms which have been brought together through the efforts of a local economic development council. Founded in large part to help defense contractors shift to other markets, TeCMEN's focus is on joint marketing, joint purchasing, sub-contracting, and new product development in the electronics, metal-working, electro-mechanical, information services, chemical, civil, industrial and metal engineering industries. Funding comes from a variety of state, local, and foundation sources, as well as from member firms.

Sources: Networks at a Glance, a publication of USNet; Firm Connections, Vol. 2 No. 4 1994.

there is evidence that small U.S. firms are not averse to cooperation, although they often lack the means and venues\textsuperscript{140} The motivation, not surprisingly, is increased profitability and competitiveness. According to NIST's Gail Morse, individual firms will pursue a network only if they are

\textsuperscript{140} Friedman, Entrepreneurial Economy ...; Bosworth, Personal communication.
able to see its potential to render a "tangible and fairly short-term impact on that bottom line\textsuperscript{141}."

The 50+ networks identified in 1991 operated in at least 14 states and involved more than 1500 small firms. According to Robert Friedman, chair of the board of the Center For Enterprise Development, these networks demonstrate some consistent patterns in their development:

\textit{Thoughtful policy} - Network initiatives have taken root in states with high concentrations of troubled manufacturing firms and innovative and thoughtful development policy makers. Some of the first experiments appeared in Massachusetts after the recession of the early 1980's, while the industrial Midwest also generated a great deal of early activity. The Southeast, with heavy reliance on mass production, followed soon after. More recently, the Northwest, facing serious challenges to its wood products industry and extensive competition from nations of the Pacific Rim, has taken up the cause of networks.

\textit{Crisis as incentive} - Certain sectors dominated by small vulnerable firms seem to embrace the network concept most readily: wood products, metalworking, forging, and suppliers to large original equipment manufacturers that are demanding higher quality standards.

\textit{Brokers and grants} - Most network activity has been generated in the presence of public-sector support for brokers and challenge grants to business.

\textit{Higher education partners} - Network initiatives often ally with universities and build on established technology and modernization efforts.

\textit{Quick payback} - Networking often begins with marketing or subcontracting activities that produce quick, tangible results and build trust and commitment among participants first.

\textit{The road to failure} - Networks usually fail when the project's leadership is less than fully committed or less than credible with the affected firms. Lack of steady public or private support has also contributed to failures\textsuperscript{142}.

The vast majority of public-sector interventions aimed at fostering network cooperation have taken place at the state level, while some are being carried out regionally. States have served as laboratories of cooperation, trying different approaches toward the same ends. Michigan drew on the resources of existing state programs to promote network development

\textsuperscript{141} qtd. in Bosworth and Rosenfeld \textit{"SIGNIFICANT..."}  
\textsuperscript{142} \textit{Entrepreneurial Economy Review} Spring 1991 p.6
through its Manufacturing Modernization Service. The program combines research expertise to map business linkages and regional concentrations of firms with challenge grants of up to $20,000 per network initiative, and up to $70,000 to interested trade associations. Pennsylvania's Manufacturing Innovation Networks Program focused funds and efforts on a few sectors which expressed significant interest in networks. State assistance is predicated on the establishment of a private labor-industry steering committee, the completion of a strategic audit of industry firms, the implementation of specific collaborative projects, and on the availability of private-sector matching funds.

The North Carolina Network Demonstration Program awards grants of up to $10,000 to assist network brokers in putting together collaborative efforts. The Southern Technology Council has sponsored broker training in Arkansas, raised $100,000 in challenge grants, and involved existing development groups in network initiatives. As of 1991, both Washington and Minnesota have commissioned studies of the potential of networks in key industries and developed statewide network strategies. And in Oregon in 1991, the state legislature passed the most comprehensive networking program in the United States (see box).

Methods of public-sector intervention

In a 1993 article in Firm Connections, network guru Stuart Rosenfeld identifies four strategies that typify state efforts at fostering collaboration: offering financial incentives, recruiting and training network brokers, altering the 'institutional platform' used to help launch networks, and building on existing network entrepreneurship. Each state networking program incorporates one or more of these approaches.

Offering financial incentives is the most common mechanism, generally in the form of state grants to support the formation of cooperative inter-firm activities that are likely to enhance market opportunities and competitiveness. According to Janet Jones, manager of the public-sector department overseeing Oregon's flexible networks program, such inducements reduce the risk of trying a new and perhaps foreign way of doing

143 Friedman, Entrepreneurial Economy ...
144 Stuart Rosenfeld, Firm Connections, Vol. 1 No. 3 p.1
Oregon's Flexible Network Program

Oregon's Flexible Network Initiative was introduced in April 1992 in an effort to shore up the competitiveness and long-term viability of sectors designated by the state as 'key industries.' This focus arises from the belief that the well-being of Oregon's economy in the global marketplace is directly related to the competitiveness of the state's key industries. Helping those industries achieve a global competitive edge is the role of the Oregon Economic Development Department, purveyor of the flexible network program.

The network concept was championed in Oregon by a state legislator who led a study tour to the cradle of networking in Northern Italy and to the emergent networks of Denmark. Upon his return, he made policies to encourage flexible networks a part of key industries legislation. The Oregon Flexible Network Initiative has two principal elements:

**Challenge Grants** - Phase I. challenge grants are awarded to industry groups and associations to encourage broad industry-wide discussion of flexible networks. Phase II. challenge grants of up to $10,000 are available to groups of at least three companies for the purpose of planning and implementing flexible networks. In the words of Janet Jones, manager of Key Industries Development for Oregon, these grants serve to reduce the risk of trying something new and bring people to the table to look at a new way of doing business.

**Broker training and availability** - The other cornerstone of Oregon's Flexible Network Initiative is the training and cultivation of network brokers. Brokers are selected by the Key Industries Development program based on their established business reputations in one or more key industries. Oregon provides eight hours of free broker time to firms who are evaluating prospects for forming a network, after which brokers are paid by the firms if the network effort proceeds. Jones ascribes many roles to network brokers, including shepherd, organizer, CEO, psychiatrist, coach, cheerleader, and facilitator.

The long-term goal of the Oregon program is to build a culture of cooperation among the state's industries. Pre-existing trade associations have laid the foundation for such collaboration, but little networking activity took place before government intervention. The Key Industries Program is seen as a catalyst, bringing firms together who, despite their best interest, would not normally meet.

The results are encouraging: in little over a year, 31 flexible networks have been formed, comprised of over 250 companies. Virtually all of them were aided by a broker and assisted by challenge grants. Evidence of qualitative success is anecdotal, so it is difficult to evaluate the benefits of such networking. It is apparent, however, that the spirit of cooperation is catching on in Oregon.

Source: Oregon Economic Development Department, Key Industries Development

business, and appeal to the direct financial interest of would-be collaborators. Of the eleven networks described as part of USNet, a fifteen state consortium administered by Regional Technology Strategies, nine have received public-sector funding, while the remaining two are supported through membership fees and commissions.

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145 Janet Jones, Personal communication.
The recruitment and training of network brokers is the other cornerstone of network development efforts. According to Rosenfeld, "brokers are the often indispensable individuals who catalyze and facilitate networks by providing ongoing liaison, trouble-shooting and strategic planning services to the participating firms." Denmark's program established the model for broker-catalyzed networking, having selected and trained forty brokers who carried the torch of networking throughout the country. To complement the brokers, the Danish program also identified "scouts" such as bankers, accountants, and engineering extension agents, all of whom had a financial interest in fostering networks, to help identify opportunities for collaboration. Brokers play an important role in the programs of a number of states, including Oregon, where they are seen as "an invaluable asset" and "crucial to the success of this initiative."

The third approach to fostering networks is finding the best institutional platform, or charging an economic development agency with encouraging and promoting networks. Such efforts have also been undertaken by a few trade associations, including the Chemical Coaters' International, the Tri-State Manufacturers' Association in Minnesota, the Oregon Software Association, and National Tooling and Machining Association, which use their contacts with firms to encourage networks.

Lastly, states are piggybacking on network entrepreneurship by building on existing collaborative efforts and attempting to create multipliers. In states such as Florida and Kentucky, the success of a few locally grown networks is being publicized and serves as an inspiration and testimonial to the network concept.

A number of states are moving beyond the above strategies to integrating networks into their economic development and modernization programs. These initiatives are ultimately aimed at changing businesses culture to produce more collaboration. Experience with state networking programs indicates that widespread implementation of a new practice requires a critical mass of resources before it becomes part of business culture. Patient and methodical state programs are gradually assembling critical mass, although these undertakings are still in or near their nascency. Given the

146 Rosenfeld, ibid. p. 4.
147 Rosenfeld, Stuart "Jump-Starting Networks" Firm Connections Vol 1. No. 3. July/August 1993.
relatively low level of inter-firm collaboration in the U.S. and the absence of strong trade and industry associations, a group of networking professionals meeting at the Aspen Institute in the summer of 1992 concluded that financial incentives and network brokers will play a key role for the foreseeable future\(^\text{148}\).

**Factors influencing network development and an alternate view**

Network initiatives are interventions into the environment in which small and medium-sized enterprises operate. Several elements of this environment affect the success or failure of these efforts. The group of Aspen participants reflected on the U.S. networking experience to identify conditions that appear to generate or influence inter-firm collaboration.

- **Common crisis** - A perceived crisis often precedes action. In the U.S. where the business culture is relatively unfamiliar with collaborative behavior, the recognition of a serious threat will tend to encourage a group response.

- **Common benefit** - Firms also frequently need to perceive a clear and immediate common benefit. Managers are reluctant to invest the time required to investigate inter-firm cooperation without clear potential for rapid payoff.

- **Personal contact** - Opportunities for face-to-face contact among firm owners and managers seem very important, especially among small firms. *Many are convinced that trust and communication are the essential starting points for effective inter-firm collaboration. Personal relationships can facilitate problem solving and accelerate the information flows that lead to higher levels of innovation.*\(^\text{149}\)

- **Geographic concentration** - Geographic concentration is a prevailing but not essential characteristic of most successful inter-firm cooperation\(^\text{150}\).

Yet barriers exist to collaboration, and Brian Bosworth and Stuart Rosenfeld of Regional Technology Strategies, Inc. have identified a number of them:

- **Lack of familiarity with the concept of inter-firm collaboration** While network ideas are spreading, many small firms are inexperienced with this

\(^{148}\) Bosworth and Rosenfeld "SIGNIFICANT..."

\(^{149}\) ibid.

\(^{150}\) ibid.
sort of collaboration. Introducing this new concept takes time and requires careful explanation and lots of examples.

- **Lack of adequate knowledge about other firms** - Small firms tend to work in isolation from each other. Networking requires an understanding of the capabilities and whereabouts of potential collaborators.

- **Lack of institutional linkages** - The development of collaborative arrangements requires a venue for social interaction among the potential participants. Yet, "small firms lack well-developed institutional mechanisms for getting to know other firms in their region and their sector, or institutions that promote collective learning. They seldom collaborate with other firms outside of the context of very specific and, usually, very immediate problems. They lack an adequate vocabulary to talk about collaboration as a business strategy"\(^{151}\).

- **Lack of recognition of the opportunities and need for inter-firm collaboration** - Most small firms look to see what they can do with what they have without looking for or realizing opportunities that require cooperation with others in joining core competencies.

- **Lack of trust** - Owners and managers who don't know and trust each other are usually unwilling to put their business at risk by depending on each other or by sharing knowledge or resources they may regard as proprietary. The culture of manufacturing is individualistic; developing trust is difficult.

- **Lack of time and resources** - Inter-firm collaboration requires both, while firms may have them in short supply.

Networking is not without its (potential) disadvantages, since participants must cede some control of their operation to an outsider in the case of a brokered network, and in general inter-link their success with the success or failure of others. To this extent, cooperation creates interdependence. Thus it should not be a foregone conclusion that networking is preferable to a lone-star existence.

The conclusion of RTS's Brian Bosworth is therefore not surprising:

"We have learned that it is usually very hard, time-consuming and costly for 'outsiders' to broker...networks of co-production and co-marketing relationships among firms. Especially if they have not previously developed trust relationships through cooperation in

\(^{151}\) Bosworth and Rosenfeld "SIGNIFICANT..." p. 23.
'softer' networks of membership-based associations, these firms are understandably resistant to putting their business strategies at mutual risk. In fact, we suspect that many of the hard co-production and co-marketing networks we have identified had their origins in less ambitious mutual help collaboratives where they developed mutual trust\textsuperscript{152}.

By now the story should be starting to sound familiar, as the conclusion reached above parallels the development of networks in Emilia-Romagna in Northern Italy, as well as the development of industrial symbiosis in Kalundborg. Janet Jones of Oregon's Key Industries Development program echoes the sentiment that trust is key among all participants\textsuperscript{153}.

But what of the success of the near-spontaneous, brokered Danish network initiative? There is reason to believe that brokers can bring firms together successfully \textit{if they are credible within their industry segment}. The predominant conceptual model of networks in the U.S. does assign the catalysis role to a broker. Yet there is a body of experience supported by observations such as the above that delineates a different model of network development.

According to an apparently authorless article in (yet another) issue of \textit{Firm Connections}, many networks in the United States

"emerge as a consequence or byproduct of a membership organization coalesced to foster or create relationships among firms...what often appears at first glance to be a local trade association or business center is a de facto network that offers members collective services, supports their pursuit of common goals, and encourages, much as a broker, increasingly specific forms of inter-firm collaboration...The concept of a network hub, [as such organizations may be viewed] is rapidly gaining credence because it simultaneously affords a locus of activity and convenient meeting place for small- and medium-sized manufacturing enterprises...and enables service providers to achieve economies of scale...The network hub thus serves social as well as economic purposes\textsuperscript{154}."

At the risk of being redundant, it is such a social fabric that augments the economic functioning of firms in Emilia-Romagna and Kalundborg.

\textsuperscript{152} Bosworth, "Thinking About..." p. 3-4.
\textsuperscript{153} Personal communication
\textsuperscript{154} Vol. 2 No. 2 p. 1.
The cultivation of network hubs is an idea that represents a different ordering of the cart and the horse from the more common incentive/broker approach. In the latter, the focus of intervention is on creating the artifacts of a network culture. Three or more firms are brought together by a broker or challenge grant to form a network as a sort of demonstration project whose success, it is hoped, will result in an incremental legitimation of networking and thereby nudge business culture toward collaboration. In contrast, the focus of a hub-based policy is on creating a network culture (not its artifact networks) by providing a venue for gaining familiarity, building trust, and exploring opportunities for collaboration. It represents a more evolutionary approach, where the focus of intervention is not the end-point of interest, but the set of conditions which are conducive to achieving that end-point. "Brokers and incentives attempt to establish a practice that becomes part of a culture; hubs attempt to establish a culture that will generate inter-firm networking practices."

The celebrated Northern Italian region of Emilia-Romagna boasts several hubs of collective activity, namely the National Confederation of Artisans (a trade association), sector-based centers organized to provide services to industries under ERVET, the region’s economic development agency, and numerous civic and business associations. Direct financial incentives are apparently unnecessary in this environment. Brokers are de facto providers of needed services. The Prato impannatori, the entrepreneurs who find markets for textiles and then organize networks for production, are an example.

In the United States, hubs can arise from the top down, in the form of institutions such as community colleges or manufacturing technology centers, which delivers services to build relationships among firms rather than addressing their needs individually. The bottom-up approach has manufacturers coming together to shape an organization that serves their

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155 Firm Connections Vol.2 No.2 p.1 e.i.o.
156 There is, however, a fly in the ointment, as most of the ERVET centers were closed in the latter half of 1992 when government support was withdrawn and industrial support was too low - this according to SIGNIFICANT OTHERS p. 38. The extent to which these developments affect the above line of discourse is unknown.
157 Firm Connections Vol.2 No.2 p.4.
needs. Trade and industry associations at large are potential hubs in the sense that they represent latent relationships among firms. In conclusion, the article acknowledges a need for both the hub-based and the incentive/broker approaches to network development. "For inter-firm collaboration to become accepted business practice, a locus of interaction is needed; hubs can fill that gap. But to nudge firms ahead into uncharted territory of best practice will require, at least for a time, brokers and incentives in some form." But ultimately, the success of networking as a self-sufficient phenomenon seems very much dependent on the establishment of a social fabric through which firms can interact. In addition to their expertise in and attention to networking issues, brokers represent a surrogate for that fabric, creating linkages and piercing the veil of corporate isolation.

Implications for the development of industrial ecosystems

The study, encouragement, and creation of networks embodying inter-firm collaboration as detailed above offers a body of experience which is informative to efforts to develop industrial ecosystems. Industrial ecology is a new and emerging field, with an as-of-yet limited body of scholarship. While there is currently a good deal of interest in the kinds of integrated manufacturing complexes entailed by the concept of an industrial ecosystem, very little practical experience in the field is available for reference, and the bulk of that which is available, namely Kalundborg, describes a different path of development from what is currently being attempted.

Attempts by third parties to introduce and encourage inter-firm collaboration are institutional interventions aimed at altering the way firms do business and see themselves vis a vis other firms. They are attempts to induce firms to interact in new ways that expand the scope of their relationships and, ultimately, changes business culture toward one of greater collaboration. All this is also true of on-going initiatives to develop industrial ecosystems, so that lessons learned from networking programs are at least somewhat transferable.

Like the pursuit of industrial ecosystems, inter-firm collaboration has a model, in the Emilia-Romagna of Northern Italy. Here a mix of economic, cultural, and historical conditions has combined with government

158 *ibid.* p. 4.
159 *ibid.* p. 4
intervention to bring about the most celebrated networking culture in the world. Students of networking liked the results, and have attempted to transplant the process to their own regions. It should be heartening to industrial ecologists that these attempts have met with a reasonable amount of success, since what has been transplanted has been the end result, not the cultural evolution that has brought about that result. Inter-firm collaboration has been replicated elsewhere in a manner that has essentially by-passed the slow, evolutionary development of the model. The prime example of this pathway is in Denmark, where networking became wide-spread in a few years as a result of a governmental initiative. The results are less impressive in the United States, but are none-the-less noteworthy. This experience points to the prospect of being able to induce artifacts of a business culture in the absence of, or at least preceding the establishment of, the culture itself. Still, a cat that barks is not a dog, and there is some question whether networking initiatives in the U.S. are sufficiently ingrained as to continue beyond the initial period of public-sector support.

The network experience echoes the lessons of Kalundborg in pointing out the importance of the institutional context and social fabric within which cooperation takes place. In Emilia-Romagna, independent trade associations and government-assisted, sector specific service centers are augmented by face-to-face contact, shared values, and even family connections among firm owners. It is such an environment that has fostered the culture of cooperation, as it has in Kalundborg. The Danish network initiative, on the other hand, has created the artifacts of networking without the full cultural underpinnings of its Italian model (although a solid technology assistance infrastructure was already in place). Network brokers are one of the two key aspects of the Danish program for overcoming the reticence of potential network participants, and they may well have a significant role to play in the development of industrial ecosystems.

Where normal business practice does not foster interpersonal relationships among owners and managers of various firms, network brokers have been effective in many cases in bridging the gap. Brokers can fill the institutional void between firms and create linkages by championing a result that can only be obtained by collaboration among firms. As such, the broker is *meta* to the system, a quality which creates a conceptual niche for him in optimizing (or at least improving) the overall performance of a set of
enterprises in which other decision-makers operate at the level of system components. More immediately, the broker can overcome the barrier caused by the lack institutional linkages that has been reported in the U.S. and elsewhere. As implicit in Oregon’s flexible network program, it is critical for the broker to have credibility in the eyes of potential participants in order to be trusted and for the undertaking to be viable. Thus brokers do not bypass the need for trust and personal contact among participants to any sort of collaboration; instead they act as catalysts around whom such personal interaction can crystallize. Their credibility is necessary for the legitimacy of the undertaking, and acts as a seed for building trust relationships.

There is nothing in the role of the broker with regard to inter-firm collaboration that could not or should not be transplanted to efforts toward the development of industrial ecosystems, and this conceptual and practical niche for brokers in the development of industrial ecosystems is addressed in a later section.

In the United States, network brokers and challenge grants have been the two key elements of state networking initiatives. Linking up with partners in higher education has also been a successful ingredient, and the involvement of Cornell University with the Baltimore Eco-Industrial Park Project is an application of the concept in the realm of industrial ecology. Financial incentives in the form of challenge grants have been widely used, but there is some doubt as to their necessity in developing industrial ecosystems. The justifications given for challenge grants to encourage networking are that they reduce the risk to small businesses of ‘trying something new’ and woo SMEs with the prospect of free money. Since participants in industrial ecosystems can be assumed to be larger firms, and since the benefits of the exchange and reuse of energy and industrial byproducts are reasonably predictable, such financial incentives do not seem necessary nor appropriate in the realm of industrial ecology.

Charging an economic development agency with encouraging and promoting networks is another strategy for network development and this approach could find ready application to industrial symbiosis. The IE analogue is an agency, likely at the state level, that encourages and assists byproduct reuse and other IE practices. The TNRC, Texas’ state EPA, is doing just that by operating a waste exchange and by participating in the Brownsville-Matamoros Eco-Industrial Park project. Some trade associations
have also played successful roles in catalyzing network development, and
trade associations offer a promising springboard for disseminating IE
practices.

The networking experience repeatedly highlights the importance of
personal contact for inter-firm collaboration, and this result is readily
supported by the Kalundborg case study. As noted earlier, "many are
convinced that trust and communication are the essential starting points for
effective inter-firm collaboration. Personal relationships can facilitate
problem solving and accelerate the information flows that lead to higher
levels of innovation\textsuperscript{160}." It is therefore no surprise that lack of institutional
linkages has been identified as a significant barrier to collaboration. Thus,
those who wish to develop industrial ecosystems should endeavor to create
venues in which participants can develop and foster personal relationships.

The implications for industrial ecosystems drawn from the experience
with flexible networks and inter-firm collaboration are by nature speculative,
but such speculation is justified by the apparent parallels. While there are
note-worthy differences, the two fields confront many of the same issues in
bringing firms together to achieve results they could not do so acting alone.
As a result, both fields of endeavor could benefit from cross-talk between
them, a result that embodies the philosophy of both.

\textsuperscript{160} Bosworth and Rosenfeld "\textit{SIGNIFICANT...}" p. 23. emphasis added.
Chapter 7.
The Development of Industrial Ecosystems

The previous chapters have endeavored to assemble a body of experience with industrial symbiosis and similar inter-firm arrangements, as well as to examine the effect of the current regulatory framework on such development. It is now appropriate to consolidate that information, to arrive at a holistic picture of the development of sustainable industrial structures. Drawing on the experience currently available, this chapter discusses salient issues affecting the establishment of industrial ecosystems both now and in the future.

Information requirements

The development of industrial ecosystems requires information above and beyond that necessary for traditional development. Industrial symbiosis requires awareness and coordination among industries, which draws on an expanded base of information, including:

*System boundaries and who is inside*

'The system' in the case of industrial symbiosis is the set of companies or other economic entities who are potential suppliers or recipients of byproduct feedstocks. In some cases, the system is defined by a property boundary, as in the case of proposed eco-industrial parks (EIPs). In an EIP the focus is primarily on the interactions among tenants, although firms outside the park may also be considered as potential symbiosis participants. In lieu of
an EIP, a geographic area may delineate 'the system,' as is the case in Kalundborg. Due to the town's relative isolation, the four large industries that are located there form a natural locus of interaction, although firms outside of Kalundborg also participate in the symbiosis.

To the extent that the size of the system under consideration determines the number of possible inter-firm linkages, a large system is likely to produce more possibilities. At the same time, however, a small and clearly defined system, such as in Kalundborg or as envisioned in an EIP, is more manageable conceptually and makes it easier to foster a sense of community.

The system concept is of key importance because industrial symbiosis represents an effort to optimize (or at least increase) the systemic efficiency of material and energy use. This is in contrast to the more limited focus of previous approaches to environmental management on individual firms and processes. Industrial symbiosis is an implicit acknowledgment that larger efficiencies can be realized by also considering potential interactions among disparate industrial units. The notion that expanding the scope of concern to a larger set of industries can yield results that treating them separately cannot is at the core of industrial ecology.

**Material and energy flows**

It is clear that materials and energy exchanges among firms require a clear understanding of the inputs and outputs of each participant. It is less clear to what extent firms are aware of their byproduct streams. Eco-audits, which identify the environmental impact, energy use, and waste generation of a firm's activities, are well-suited for providing that information. It is only appropriate that if a firm is to redefine its byproducts from waste to resources, then it take account of those byproduct streams.

**Amount and temporal distribution**

This follows from the above. Byproduct re-use need not be all-or-nothing, meaning that another firm's byproducts need not cover the entire feedstock needs of a firm which uses those byproducts to substitute for virgin feedstocks. Re-users of byproducts can either mix byproducts with virgin feedstocks as needed or receive byproducts from multiple sources. There are several examples of this type of arrangement in Kalundborg. For example, Asnæs Power Plant substitutes Statoil flue gas for its usual coal fuel to the extent that such gas is available, while Gyproc uses Statoil flue gas exclusively.
when it is available, switching to a butane backup system only when necessary.

The temporal distribution of byproduct streams is likely to vary by repetitive or irregular cycles. Seasonal fluctuations are to be expected in many cases, including beer brewing. Accordingly, the ZERI demonstration project that is looking to cluster fish farming and beer brewing is proceeding under the assumption that more beer and therefore more beer cake will be available during the summer months than the rest of the year. Symbiotic arrangements therefore need to accommodate cyclical variations and be sufficiently robust to respond to irregular fluctuations in byproduct availability and feedstock demand.

Quality and reliability

Byproducts can only compete with virgin materials if they are comparable in quality and reliability. By approaching byproducts as resources, industrial ecology enables companies to expand the range of their products that have economic value. Such an expansion requires a concomitant expansion in management responsibilities. Byproducts have traditionally been the uncontrolled elements of a firm's throughput; while attention to quality has been focused on outputs designated as products, the properties and composition of the byproduct stream have been allowed to vary. The sale of byproducts as feedstocks requires quality control for what was formerly the waste stream. Such expanded responsibility can be expected to cause some loss of flexibility and to require the commitment of resources to managing the byproduct stream.

Regulatory considerations

As discussed in the chapter on the Resource Conservation and Recovery Act, the management of solid waste is tightly regulated in cases where that waste qualifies as hazardous. Since industrial symbiosis deviates from common waste management practice, the regulatory response to it is not well established. There is reason to believe that most if not all symbiotic linkages are possible given some regulatory flexibility. Developers of industrial ecosystems are advised to work closely with regulators to ensure

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161 At least until end-of-pipe treatment.
162 Dan Whitney, Principal Research Associate, MIT Center for Technology, Policy, and Industrial Development. Personal communication.
163 Ibid.
public-sector approval and support. The Environmental Technology Initiative’s Eco-Industrial Park Project is in the process of preparing policy recommendations to facilitate eco-park development, and these recommendations will hopefully lend credibility to industrial symbiosis in the eyes of regulators.

**Three roles to keep in mind**

Three roles are critical to the development of industrial ecosystems. They are:
- The analyst/planner;
- The change agent; and
- The company decision maker.

*The analyst/planner* identifies opportunities for symbiotic linkages, evaluates the parameters that need to be known to gauge the viability and desirability of the potential symbiotic arrangement, and carries out the necessary design tasks.

*The change agent* introduces the concepts of industrial ecology and industrial symbiosis to decision makers and champions the pursuit and implementation of symbiotic linkages.

*The decision maker* is that person or persons within companies who has the authority to commit company resources to pursue symbiotic linkages and to enter into both formal (contractual) and informal relationships with other companies.

These roles are assumed by different individuals depending on the avenue by which industrial ecosystem development proceeds. Any person may play two or even three of them at a time. The different mechanisms for development can be analyzed in large part by the allocation of these roles, and it is these various avenues to which we now turn our attention.

**The organization of industrial ecosystem development**

In the ideal form of an industrial ecosystem, all material inputs go into products and all energy consumed is used to do work. The process of approaching this ideal may be viewed as one of optimizing the systemic use of materials and energy. As this ideal is approached, the final system boundary is likely to expand toward the inclusion of all human activity; in
the meantime it is the hallmark of the industrial ecology paradigm to expand the focus from single firms and processes outward.

Optimization is a term and endeavor that has traditionally been resident to the disciplines of systems engineering and operations research. In such a context, optimization entails finding a system, establishing system boundaries, parameters, and decision variables, developing a model, and manipulating the inputs to that model to get the best output, given some measure of preference. Implicit in this construct is the existence of an analyst/planner and a decision maker. It is the analyst/planner who develops or selects the appropriate model and uses it to predict the optimal allocation of inputs. It is generally assumed that the decision maker holds the values according to which the optimization is carried out, and accordingly it is he or she who implements the results. Optimization is thus carried out by the analyst/planner to further the interests of the decision maker and his or her constituency. In a broader sense, optimization need not be a formal mathematical exercise; it may be viewed as goal-directed change based on a set of values and measures of performance.

If the process of approaching the ideal form of an industrial ecosystem entails optimizing the flows of materials and energy within an industrial ecosystem, then someone has to be doing the optimizing according to some set of criteria, which may itself evolve over time. If the model (which encodes the system boundary) or criteria to be used are new and differ from existing practice, then a change agent is required to affect the necessary shift. The decisions to explore and commit to byproduct-as-feedstock linkages are ultimately made by corporate decision makers. The question, then, is, who is optimizing, and how are the decision criteria which are conducive to the development of industrial ecosystems felt by the decision makers?

Three scenarios emerge from the developments detailed in this thesis: optimization from outside, optimization from within, and third-party intervention. Each is discussed below. They are points on scale that runs from a centralized command economy in which the roles of analyst/planner, decision-maker and change agent are unified to the completely autocatalytic development situation entailed by Kalundborg.

The centralized command economy is an interesting limiting case, because it is only here that optimization of material and energy flows could be achieved in the formal sense of the word. As alluded to above, the reason for
this arrangement's unique position is that the three roles are unified, such that there is but one coherent set of goals¹⁶⁴ which are pursued by a unified decision-maker with control over the industrial system. This scenario sets one endpoint on the spectrum, which is most closely (or rather least distantly) approached by an eco-industrial park.

Optimization from outside

The Environmental Technology Initiative's Eco-Industrial Park Project sets the system boundaries for an EIP around an industrial park with a common management authority. This authority is entrusted, among other things, with maintaining 'the right mix' of companies needed to best use each other's byproducts as feedstocks and with encouraging and facilitating such exchanges¹⁶⁵. In this case, it is assumed that the park's management authority internalizes the goal of optimizing the utilization of materials and energy by park tenants¹⁶⁶. It is park management that acts as the optimizer, and it is meta to the system. While park tenants see bilateral exchanges that improve both their environmental and economic performance, park management sees an industrial ecosystem with resulting loop-closing benefits. The implied goal of the park's management is to bring about such an ecosystem.

This arrangement raises a number of questions, like, how is it in the business interest of the park authority to optimize for materials and energy utilization? How is it in the business interest of each of the tenants to be optimized? Would they go along? And, what factors other than direct economic benefit would make symbiotic arrangements attractive to tenants?

Wielding no coercive power, it is extremely unlikely that park management could compel tenants to organize into an industrial ecosystem if that is not economically beneficial to them. However, the management authority has the systems view and system goals, and can play the role of the analyst/planner. Park management can thus provide joint provision of services, information linkages, and facilitation of byproduct reuse

¹⁶⁴ At least in theory; the history of command economies speaks against this assertion.
¹⁶⁶ This may or may not be a reasonable assumption. Such an EIP management entity has never existed, (as far as I can tell), and is not assured of being brought forth effectively by fiat. Park developers, like other businesses, are interested in return on investment, so that optimizing the utilization of materials and energy by tenants has to contribute to that end in some fashion for it to be maintained as a stable, long-term goal.
arrangements, as well as providing the institutional context for interaction among park tenants. Decision remains with the tenants, so that the role of the park management as optimizer is to create conditions such that tenants, by acting in their own best interest, further the goals of the system.\footnote{As defined by the park authority.}

**Optimization from within**

More general is the situation without meta-management in the form of a park authority or similar entity. Then each element of the system needs to act individually, or in cooperative arrangements, so that the system as a whole is optimized. That's optimization from within, also referred to here as autocatalytic or self-organizing development.

Take entropy to be the degree of disorder in a system. Safe to say that industrial symbiosis reduces entropy over no symbiosis because it reduces dissipation. For example, by definition energy cascades increase the proportion of energy consumed that is available to do work. And that ties into one of the classic definitions of entropy. Next, conditioning and reuse of byproducts gives more of everything in economically useful concentrations and mixtures than their conventional fate as waste.

So industrial symbiosis reduces the production of entropy, raising the prospect of evolutionary pressure toward the development of industrial ecosystems. As Prigogine has written:

We can consider the evolution of living organisms up to the stationary state as taking place under a certain number of constraints determined by the outside world...Whatever the nature of the [constraints], the stationary state may probably to a good approximation be considered as a state of minimum production of entropy per unit time. This description fits in excellently with some striking characteristics of living organisms. First, the well known stability against external perturbation has its analogue in the stability of stationary states corresponding to a minimum production of entropy. Further, the fact that during growth living organisms actually experience a decrease of entropy production during evolution to a stationary state. Also, the fact that their organization generally increases during this evolution corresponds to the decrease of entropy...\footnote{I. Prigogine, *Thermodynamics of Irreversible Processes* C.C. Thomas, Springfield IL 1955 p. 91}
Evolution results in decreasing entropy production. It is not much of a rhetorical leap to argue that, as follows from the concept of evolution, those organisms, or rather those interdependencies of organisms, survive in a given niche which operate with the least production of entropy. This is because, by definition, the less entropy, the more efficiently organism/ecosystems function in a closed system. Those that are more efficient crowd out those that are less efficient, to get the lowest overall production of entropy; they have the most survival value. The others die off. And in that way is the system of organisms optimized from within.

Now to apply this line of reasoning to industrial ecosystems. We claim that the optimization of material and energy flows results in more sustainable industrial activity. (Optimization may be too strong a requirement; greatly increased efficiency should suffice.) This optimization is directly coupled to a state of minimum entropy production. In ecosystems, inefficient organisms and linkages produce more than the minimum possible amount of entropy and are crowded out by more efficient arrangements producing less entropy. This would then be an implicit decision rule that drives ecosystem evolution. Its influence is exerted on ecosystem participants in the form of results; those participants that are more eco-efficient than others survive to continue evolving. Those that are not, die off. In this way, the system evolves.

For the economic system to be self-optimizing, then, decision rules need to be in place which reward increases in eco-efficiency and penalize the laggards. In the ecosystem case, failure to keep up results in the death of the particular evolutionary line. The direct analogy applied to the industrial system would call for corporate death or shut-down. However, participants in this system are more adaptive. The possible outcomes are not limited to death versus survival and procreation; mid-course adjustments are possible. But if industrial ecosystems are to be self-optimizing in that they entail an evolution toward the minimization of entropy, then the decision rules applied to the system participants, be the rules implicit or explicit, must provide the same signals as they do in natural ecosystems: efficient arrangements thrive at the expense of inefficient ones.

The decision rules currently applied to the industrial system are in the form of the price system and regulation. If this line of thought is accepted, then these signals need to be tailored by public policy to transmit the correct
evolutionary pressures. The concept of economic efficiency needs to be expanded to include eco-efficiency; clearly this entails some form of ‘getting the prices right’. In addition, public policy needs to allow for and support the creation and maintenance of industrial ‘niches’ or arrangements that minimize entropy.

Kalundborg is the prime example of this sort of evolutionary development. The definition of industrial symbiosis comes from Valdemar Christensen of Asnæs Power Station, and includes reference to ‘increased viability’ among participating firms, which ties directly into the evolutionary argument developed here. In Kalundborg, the initial wave of links that made economic use of unexploited (by)products was followed by a second wave that was the outgrowth of pollution control measures and pollution control technologies. These latter linkages are more expensive than no pollution control, but represent least-cost compliance strategies. As such, they are adaptations to the changing operating environment in which the Kalundborg firms have been functioning. Regulatory and community requirements have applied evolutionary pressure, in the form of demands for reduced environmental impact. By setting performance standards, instead technology standards, public policy allowed this sort of evolution.

All documented examples of industrial symbiosis to date have evolved in such an autocatalytic way, but this may simply be due to the fact that until recently no public or private organizations actively encouraged the development of symbiotic linkages among industries.

*Third-party intervention: the role of the broker*  

As public and private agencies take up that cause, they should not lose sight of the importance of the institutional context and social fabric within which cooperation takes place. Emilia-Romagna, the origin of the flexible networks and inter-firm collaboration movement, echoes the lessons of Kalundborg in that regard. In both places, participants are part of a web of social interactions that support face-to-face contact and extend beyond the realm of business.

When normal business practice does not foster interpersonal relationships among various firms, there is a niche for a broker role in bridging the gap. This has been the case in the Danish network experience, as

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169 This section is based in part on discussions with Ernie Lowe of Indigo Development.
well as in U.S. efforts to foster inter-firm collaboration. In this country, students of flexible networks have identified a lack of institutional linkages among firms. As a result, potential value-adding collaborations are not consummated due to lack of an effective venue and supportive cultural norms. The role of the broker in flexible networks, as it promises to be in industrial symbiosis, is to overcome those barriers to collaboration and to 'complete the circuit.'

In the EIP model of industrial symbiosis, the eco-industrial park is the staging area for inter-firm linkages, and park management is entrusted with playing an organizing and catalyzing role. The analyst / planner function is hard-wired into the EIP; park management is clearly identified as meta to the industrial subsystem of the park. The autocatalytic or evolutionary model of industrial symbiosis development is at the other end of the spectrum. Here participating businesses individually feel evolutionary pressure toward the formation of an industrial ecosystem and enter into bilateral arrangements. The system is self-organizing, but such self-organization relies on a institutional connections among firms that are largely absent in the U.S.

The resulting void creates the niche for a broker role. Though not structurally 'above' the system he or she acts on, a broker can have the systems perspective that individual firms lack. The networking experience in both Europe and the U.S. indicates that brokers can effectively catalyze mutually beneficial collaborations that would not come about otherwise. By helping companies perceive their common opportunities in byproduct-to-feedstock arrangements (and in possibly others), and in championing the formation of such linkages, the broker furthers the system goal of increased material and energy utilization while furthering the interests of participating firms. The broker thus plays the role of both analyst / planner and change agent.

For such a role to be viable, the broker must have an economic self-interest in bringing about symbiotic linkages. Since it can safely be assumed that symbiotic arrangements will come about only when they are financially beneficial or least-cost, the 'value added' by the broker can serve as the basis for compensation. Whether there is enough money to be made in playing such a role is an open question, but experience indicates that at least one firm has successfully achieved that result (see box next page).
VP Resources: "Finding a home for orphan chemicals"

More than a waste exchange, VP Resources of Clearlake, Texas, finds a home for orphan chemicals and does everything necessary to ensure their adoption. Proprietor Vance Purcell used to be an executive in the chemical industry before he found a niche in developing secondary markets for chemical byproducts - something which chemical companies have largely failed to do. Byproducts were burned or deepwelled before environmental pressures increased the cost of disposal to where alternative arrangements became attractive.

A variety of waste exchanges have been attempted in recent years but with only limited success. While such endeavors merely list available byproducts, VP Rescues performs every function required to turn a byproduct into a feedstock, including finding appropriate uscs, dealing with regulatory agencies, brokering necessary agreements, and even transporting the materials from the generator to the user.

What sets VP Resources apart is its full-service, cradle-to-reuse approach to secondary markets for byproducts. Relying on industry knowledge and personal contacts, VP Resources has succeeded where others have failed.

Source: Vance Purcell, Personal Communication. VP Resources: (713) 488-3496

A different allocation of roles is present in the case of the Zero Emissions Research Initiative. Here the focus is on designing and co-locating zero emissions, symbiotic industry clusters. Because this arrangement can be expected to involve a smaller number of participants than an EIP and because the focus of development is cluster-, not site-specific, a tighter coupling can be expected between the analysis and planning roles and those of the decision maker. ZERI represents an entrepreneurial approach whose realization results in environmental benefits, which in turn aid in achieving entrepreneurial results.

The above classifications are regions along a continuum, not distinct and separate arrangements. The table on the following page summarizes some relevant attributes of various approaches to industrial ecosystem development, listed in order of decreasing centralization.

The venue: green and brown, new and pre-existing developments

The main distinction between greenfields and brownfields is that greenfields are undeveloped areas (hence the color) while brownfields are existing developments. From the perspective of industrial symbiosis, brownfields can be further subdivided into sites currently occupied by industry and those that have been abandoned. Abandoned sites of former
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<th>Organizational Form</th>
<th>System bounds</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Command Economy</td>
<td>Up to entire economy</td>
<td>Central planner</td>
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<td></td>
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<td>Central planner</td>
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<td></td>
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<td>Central planner</td>
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<tr>
<td>ZERI</td>
<td>A cluster of industries</td>
<td>Businesses, entrepreneur</td>
</tr>
<tr>
<td></td>
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<td>Entrepreneur / researcher</td>
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<td></td>
<td></td>
<td>Entrepreneur / researcher</td>
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<tr>
<td>EIP</td>
<td>Industrial park</td>
<td>Tenants, park management</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Park management</td>
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<td></td>
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<td>Park management, community</td>
</tr>
<tr>
<td>Brokered Network</td>
<td>Diffuse set of industries</td>
<td>Businesses, broker</td>
</tr>
<tr>
<td></td>
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<td>Broker</td>
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<tr>
<td>Autocatalytic Network</td>
<td>Diffuse set of industries</td>
<td>Businesses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Self-organizing</td>
</tr>
</tbody>
</table>

Development of Industrial Ecosystems by Organizational Type

Industrial activity are just as brown, if not more so, as sites of current industrial use, due to likely contamination. From an environmental point of view, there is compelling reason to re-develop brownfields in lieu of converting greenfields. The reasoning is simple: why degrade a pristine (or at least undeveloped) ecosystem when an already disturbed one is available? This is a choice with regard to EIP development in Chattanooga, and the specter of liability for past contamination is the single greatest obstacle to re-development of the brownfield Central Business District.

From the perspective of industrial symbiosis development, the main distinction is between new and pre-existing developments, because the context in which symbiosis development proceeds depends in part on whether the industrial facilities are designed and built with symbiosis in mind or are retrofitted. For pre-existing developments, the standard of comparison, or baseline situation to contrast with symbiotic arrangements, is business as usual. The necessary condition for establishing symbiotic linkages with other firms is reasonably straight-forward: go ahead with retrofits if the linkages are feasible and financially beneficial.

New developments provide an additional dimension, in terms of the extent to which this ecopark or ecosystem prospect influences the decision of firms to move to the area and establish operations. If a number of firms are
set to locate in somewhat of a cluster, without any consideration of possible symbiotic arrangements, then introducing the concept to them at some early part of the development process (by some agent of action) creates the potential to choose process technologies and develop operations in some sort of cooperation to enable symbiotic linkages. This is probably the most attractive situation for symbiosis development, assuming the companies are there, are compatible, cooperative, and interested. In the limit, new developments provide the opportunity to aim for 'zero emissions' along the lines envisioned by the Zero Emissions Research Initiative. Such development is in the planning stages for the downtown Chattanooga EIP proposal.

There are of course variations on this situation; for example one or more new companies may be moving into an established industrial area and could explore prospects for symbiotic arrangements. The earlier in the design and process selection process that symbiotic possibilities are considered, the better. But this is not to say that these possibilities will be considered when companies establish operations, only that this would be a good time for them to be.

So if a greenfield is turning brown of its own accord, or a brownfield is being redeveloped, then the IS concept could and should be introduced (by some agent of action / analyst / planner) since early consideration provides the most flexibility in developing linkages. This is not really in conflict with the evolutionary nature of symbiosis development in Kalundborg, because many of the links were developed in a microcosm of the 'new development' situation, as firms looked for symbiotic arrangements when they had to change processes anyway. Thus the flexibility advantage of greenfields can be captured in smaller parts as brownfield participants change over time.

The second greenfield/new development alternative, which is implicit in the ecopark concept being developed as the PCSD/ETI/Eco-Industrial Park project, is that companies will locate at a certain park or area specifically because it is an ecopark and offers advantages of symbiotic arrangements. In situations involving pre-existing development, symbiotic links tend to be retrofits or least-cost ways of achieving necessary changes, and therefore they have to be better than 'business as usual' ways of dealing with the change. That is, if at some point my firm has to do X, and doing X by way of a symbiotic link is feasible and cheaper than doing X in some traditional way, then that condition should be enough to give rise to a symbiotic link.
If the draw of a new development is the ecopark concept, then the necessary condition to be met is likely to be more rigorous. Now the alternative to symbiosis is not business as usual in that given cluster, but rather a range of possibilities including location elsewhere or no new facility. The question in this greenfield situation is whether symbiosis and the other benefits offered by the EIP are enough to attract businesses when the standard of comparison is more broad in scope. In a pre-existing development, any net savings warrants a link, but a more complete evaluation of the economics of symbiosis seems necessary to attract firms to a new ecopark. The ability of EIPs to draw tenants is still very much in question.

The Chattanooga and Baltimore EIP projects reveal differing approaches to symbiosis development based on their new or pre-existing nature. For the pre-developed Baltimore site, Cohen-Rosenthal and colleagues are proposing ambitious goals for continuous improvement rather than zero emissions. The goal of such an approach is to reclaim dirty areas and make current locations survive and work. In contrast, the Downtown Business District EIP in Chattanooga calls for new development of an existing site, with a goal of zero emissions. The Gunter Pauli / ZERI approach entails designing processes for symbiosis (what they call zero emissions). Such an undertaking can only occur before the industrial structures in question are built or are about to be radically altered. As such, zero emissions and continuous improvement are complementary approaches, paired to new and pre-existing development, respectively (see table).

<table>
<thead>
<tr>
<th>Ecopark</th>
<th>New Development</th>
<th>Pre-existing Development</th>
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<tbody>
<tr>
<td></td>
<td>Zero-Emissions possible; Concurrent genesis; 'Meta' analyst</td>
<td>Continuous Improvement; Brokered or 'Meta' analyst</td>
</tr>
<tr>
<td>'Diffuse' Ecosystem</td>
<td>Zero-Emissions(?) or Evolutionary; Brokered or Autocatalytic</td>
<td>Evolutionary; Continuous improvement in result but not express goal; Brokered or Autocatalytic</td>
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</tbody>
</table>

Relationship of development venue to development organization
Factors influencing industrial ecosystem development

Experience and reflection have identified a number of factors which affect prospects for the development of industrial ecosystems. They include:

Economic viability

As a general rule, symbiotic linkages are unlikely to be developed and sustained unless they make money or cost less than more traditional arrangements of materials and energy use. Note that regulation and public policy can alter the costs and benefits felt by companies, and thereby influence the attractiveness of symbiotic linkages.

Public policy as evolutionary pressure

Regardless of any stories one can tell of closing loops and emulating ecosystems, businesses will only engage in symbiotic linkages if and when such arrangements are economically beneficial. Every single linkage in Kalundborg, the model of industrial symbiosis, is either a sale of a byproduct or a least-cost way of complying with environmental regulations. Therefore, the single best way to foster the development of industrial ecosystems is to make them economically attractive.

It is implicit in this argument that at any given time there are more potential byproduct-to-feedstock linkages available than are economically viable. The initial wave of links in Kalundborg derived value by selling byproducts which previously had been wasted. Later links developed only in response to stricter environmental regulations. These strategies, such as the use of Novo Nordisk's process sludge as fertilizer, were least cost ways of complying with regulation. In effect, as regulation forced companies in Kalundborg to internalize the environmental cost of their production, symbiotic links became attractive.

Imposing regulatory requirements and altering the price signals felt by industry are two ways in which public policy can apply pressure to encourage the evolution of industrial ecosystems. This strategy entails a form of 'getting the prices right.' Such external signals are not sufficient, however, since innovative and pioneering cooperation is required among companies for symbiosis to occur. Yet such cooperation is only viable if it makes economic, not just environmental, sense.

The evolutionary view of industrial ecosystem development would therefore hold that there is a natural progression towards symbiosis if the government response to the environmental impacts of industrial activity
sends the right signals and if the regulatory structure is conducive (see below). Of course symbiosis does not necessarily follow from a regulatory push for pollution control; there has to be some propensity. After all, industries in places other than Kalundborg have been forced to decrease pollution, without the effect of inspiring symbiosis. However, it would appear that government involvement is necessary to ‘level the playing field’ in favor of loop-closing arrangements by raising the relative cost of conventional practice (or lowering the cost of symbiosis). It is not, however, sufficient. Symbiosis requires information, cooperation, and creativity, and these requirements are more difficult to supply by public policy intervention.

*Institutional linkages and personal relationships among firms*

Both the Kalundborg case study and experience with inter-firm collaboration and flexible networks indicate very strongly the importance of personal contact among firms as a starting point for collaborative arrangements. Kalundborg is a small society in which managers of the various firms often run into each other, providing opportunities for face-to-face contact and informal discussion. The fact that the four firms are planted in the same interconnected society in which their employees live makes inter-firm cooperation more readily achievable.

Similarly, students of inter-firm collaboration have concluded that trust and communication are essential building blocks of networking activity. Given the necessary reliance on network partners, owners and managers who do not know and trust each other are usually unwilling to put their businesses at risk by entering into collaborative arrangements. Given the importance of personal relationships, lack of institutional linkages among firms is a major impediment to inter-firm collaboration, a result that carries over to industrial symbiosis.

Brokers who are credible in the eyes of all participants have been successful in bridging that gap in their bid to establish inter-firm collaboration, and the broker role also holds promise in the development of industrial ecosystems. Brokers are most appropriate in fostering linkages among industries in areas not bound together by existing ties. Other organizational forms may require less assistance from brokers. By focusing on environmental performance and entrusting park management with an expanded role, the eco-industrial park concept may be able to provide the institutional context necessary for fostering symbiosis. The more centralized
approach entailed by the Zero Emission Research Initiative effectively bypasses the need for a broker by focusing on designing and co-locating specific symbiotic industry clusters.

Personal relationships are also important in that the personalities of those involved with creating symbiotic linkages have a strong influence over the form of the outcomes produced. This effect is illustrated in the difference between the directions of the Chattanooga and Baltimore Eco-Industrial Park demonstration projects. The entrepreneurial approach of Gunter Pauli and his Zero Emissions Research Initiative in Chattanooga is contrasted by the more labor-oriented practices at the Baltimore E.I.P., whose development is headed by Ed Cohen-Rosenthal of Cornell’s Work and Environment Initiative.

A number of approaches avail themselves for overcoming the general lack of institutional linkages among firms in the United States. By and large they are in their nascence and their effectiveness remains to be seen. Initiatives currently underway hold the promise of creating elements of industrial ecosystems. However, widespread creation of symbiotic inter-firm linkages will most likely require a broader shift in business culture, one that is conducive not only to the exchange and reuse of material and energy flows, but to increased collaboration in general. In Kalundborg, the symbiotic linkages among local firms have expanded to other areas of collaboration, such as worker training and safety. In turn, experience with flexible networks and inter-firm collaboration indicates that collaboration in one area fosters collaboration in others. Thus, one way to promote industrial symbiosis is to strengthen inter-firm linkages in general.

**Awareness and Interest**

Symbiotic linkages will not come about unless decisionmakers within companies begin to see byproducts as resources, not wastes. While all businesses market their products, few are versed at marketing their byproducts. Finding possibilities for symbiotic linkages with other firms is new to the realm of business practice. Initiatives such as the Eco-Industrial Park project are therefore valuable not just for the tangible results they may produce, but also as vehicles for bringing industrial ecology into the mainstream. To the extent that industrial ecology is a lens through which to see material and energy flows, broader awareness of IE can only help in bringing about industrial ecosystems.
Regulatory reform and clarification

Two regulatory issues are salient with respect to the development of industrial ecosystems: clarification and increased flexibility of regulation under the Resource Conservation and Recovery Act (RCRA), and a preference for performance standards over technology standards for pollution control.

As discussed in a prior chapter, regulation of the management of waste under RCRA has created unintended barriers to the reuse of byproducts as feedstocks. While only about one-third of the industrial byproducts generated in the United States fall under the 'hazardous' label, uncertainty over the classification of particular waste streams and the significant requirements of hazardous waste management are a daunting force against byproduct reuse. EPA policy and regulations can be adjusted to reduce the burden on symbiotic arrangements while maintaining the required level of safety. Given the history of the RCRA program, any reform should begin with EPA headquarters issuing a policy statement in support of the legitimate reuse of industrial byproducts as feedstocks. EPA regions and states should then be allowed greater discretion in approving reuse/recycling activities, on a case-by-case basis and according to clear guidelines.

A more subtle point is the preference for performance standards over technology standards in pollution control regulation. As noted before, the second wave of symbiotic linkages in Kalundborg came about in response to regulatory pressure to decrease pollution. The stricter environmental regulations which have in large measure been the driving force for the more recent linkages have been performance standards, not technology standards.

This distinction is significant because it has allowed the local firms to choose pollution control technologies which rendered their waste streams usable as feedstocks elsewhere, yielding an additional benefit beyond pollution reduction. For example, from among several alternatives, Asnæs Power Station chose a scrubber technology which resulted in the production of gypsum as its byproduct. This gypsum is sold to Gyproc, reducing Asnæs' cost of pollution control and replacing a virgin feedstock. Flexibility in meeting environmental standards is an important requirement for the development of industrial ecosystems, and this issue is on the agenda of the Eco-Industrial Park project. That undertaking will result in
recommendations to greater flexibility, which, given the current political climate, will likely be acted upon.

The systems view and place-based development

From command-and-control regulation to pollution prevention, approaches to environmental problems that preceded industrial ecology have focused on individual plants and processes as the units of interest. Industrial ecology calls for a broadening of focus to encompass the system in which production takes place. Closing loops and increasing the efficiency of material and energy use requires a holistic view of firms as part of their surroundings, both natural and human-built. Place-based development is being advanced through the Eco-Industrial Park project and similar undertakings as a way to make use of local features and conditions and to better integrate industrial activity into both the natural and the man-made environment. This approach requires a heightened awareness and sensitivity to the interactions of a given process with its surroundings. From such awareness can spring novel synergies, such as finding valuable uses for byproducts.

...and some concluding thoughts

In some ways, this time, Spring of 1995, is the end of the dawn of a new field of inquiry, one that seeks to harmonize the workings of human economic activity with the natural systems that sustain it. Interest in industrial ecology has been steadily increasing since the notion was introduced in 1989-1990. The Clinton Administration's National Environmental Technology Strategy, Bridge to a Sustainable Future, identifies IE as the dominant paradigm for sustainable industrial development as we move into the twenty-first century. Other evidence of the ascendancy of industrial ecology confirms that IE, at least as a phrase, has moved into the mainstream and is unlikely to go away any time soon.

Interest in what has been referred to here as industrial symbiosis has taken longer to develop. The first article about Kalundborg that concerted effort could turn up was "A rebirth of the pioneering spirit," published in November of 1990 in Britain's Financial Times. A two-page description of

the Kalundborg industrial ecosystem in Hardin Tibbs’ 1993 novella *Industrial Ecology An Environmental Agenda for Industry* firmly entrenched the town in the mythology of this developing field. Holger Engberg, a Danish Professor of Finance and International Business at NYU’s Stern School of Business followed in October of 1993 with an extensive descriptive case study entitled “Industrial Symbiosis in Denmark.” Though it provides an excellent background on Kalundborg, this paper was never published (as far as I can tell) and was not widely circulated. In the realm of industrial ecology, Kalundborg was an often-referred-to, mythical place which inspired the imagination of many but about which little was known. Such was the backdrop to my own visit in July of 1994.

The Danes’ hospitality was moving; Asnæs Power Plant housed me in their little straw-roofed guest house 100 yards from one of the massive boiler buildings. The kitchen was stocked with food and coffee and I was provided with sustainable transportation: a bicycle. Five days of riding that bicycle to interviews and factory tours resulted in a case study detailing the development of the industrial ecosystem that comprises Chapter 2 of this document. Circulated since August of 1994 as a working paper of the MIT Technology, Business, and Environment Program, which has sponsored this research, the case study was well-received, indicating that interest in Kalundborg had far outstripped available information.

The notion of industrial symbiosis is now being advanced by, among others, the Zero Emissions Research Initiative (though not in so many words) and by the Eco-Industrial Park project. Spontaneous efforts to create that sort of development have been registered here at MIT and by others in various parts of the country. While far from being well-established, interest in industrial ecosystems is slowly on the increase.

In many ways, however, current interest in industrial ecology and industrial ecosystems is neither new nor novel. A journal called, curiously, *Industrial Ecology* was first published in the winter of 1970. It did not last long, but its discovery recently led industrial ecologist Brad Allenby to remark that there is, in fact, nothing new under the sun. Similarly, a study entitled “Systems-Integration Requirements for the Synergistic Co-Siting of

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173 Brad Allenby, Personal communication with John Ehrenfeld, Spring 1995.
Industrial Activities" was concluded in 1980 by researchers at the Georgia Institute of Technology\(^{174}\). Those previous efforts have faded, but the current period is one of great promise. As one artifact of this renaissance, *The Journal of Industrial Ecology*, unrelated to its namesake and predecessor, is about to be launched.

The notion of industrial ecosystems offers a very powerful vision to guide the development of sustainable industrial structures. This research has sought to identify the characteristics of such structures as well as the factors and conditions that effect their development. While public-sector interventions have a significant role to play in establishing the appropriate evolutionary signals, bringing industrial ecosystems into being will ultimately depend on pairs or groups of businesses that find novel, collaborative ways to make use of byproducts and meet environmental demands. For industrial ecosystems to make a significant mark on the business and environment landscape, groups of firms must independently adopt symbiotic linkages, like the "thousand points of light" in that bygone analogy. This result requires that individuals in businesses become aware of the latent possibilities provided by the structures around them. It also requires a regulatory climate and business culture that encourages such development.

Successful applications of industrial symbiosis should be publicized to encourage others to try. While Kalundborg is the most often-cited example and the one receiving the most attention here, industrial symbiosis can be found on a smaller scale in many parts of the U.S. Many of these examples are being collected in the *Fieldbook on the Development of Eco-Industrial Parks*, to which the reader is referred for details. Perhaps these accounts foretell of a shift to a new form of development, one in which human activity is harmonized with the workings of natural ecosystems.