Industrial Ecology in Practice

The Evolution of Interdependence at Kalundborg

John Ehrenfeld
Nicholas Gertler*
Technology Business and Environment Program
Massachusetts Institute of Technology
Cambridge, Massachusetts, USA

Keywords
eco-industrial park
green twinning
industrial ecosystems
industrial symbiosis
islands of sustainability
Kalundborg

Summary

The exchange of wastes, by-products, and energy among closely situated firms is one of the distinctive features of the applications of industrial ecological principles. This article examines the industrial district at Kalundborg, Denmark, often labeled as an "industrial ecosystem" or "industrial symbiosis" because of the many links among the firms. The forces that led to its evolution and to the interdependencies are described and analyzed. Key has been a sequence of independent, economically driven actions. Other potential forms of industrial linkages are critically reviewed in the light of the Kalundborg experience. The evolutionary pattern followed at Kalundborg may not be easily transferable to greenfield developments.

Address correspondence to:
John Ehrenfeld
Technology Business & the Environment Program
Massachusetts Institute of Technology
CTPID, E40-421
Cambridge, MA 02139
USA
jehren@rnit.edu

Volume 1, Number 1

* Nicholas Gertler is currently at Harvard Law School, Cambridge, Massachusetts, USA

Introduction

Industrial ecology is a new concept emerging in the evolution of environmental management paradigms (Ehrenfeld 1995), and springs from interests in integrating notions of sustainability into environmental and economic systems (Allenby 1992; Jelinski et al. 1992; Allen and Behmanish 1994; Ehrenfeld 1995). Environmental thinking has recently focused on a consciousness of the intimate and critical relationships between human actions and the natural world, and reflects limits in the current reliance on command-and-control regulation in much of the industrialized world. The critical problem is that, for the most part, the economy operates as an open system, drawing raw materials from the environment and returning vast amounts of unused by-products in the form of pollution and waste. The products that firms market are only a small portion of what their processes turn out; a significant portion of their output eventually leaves the economy as waste and returns to the environment in forms that may stress it unacceptably. As long as attention is limited to products and processes viewed in isolation, larger systemic problems, such as the accumulation of persistent toxic materials, will not be addressed.

Increased economic output will still cause increased environmental harm in such a frame of analysis. Strong links between environment and development emerged from the global consensus following the 1992 Rio Earth Summit. For example, the recent report of the President's Council for Sustainable Development (PCSD) in the United States concludes, "In the end, we found agreement around the idea that to achieve our vision of sustainability some things must grow—jobs, productivity, wages, profits, capital and savings, information, knowledge, education—and others — pollution, waste, poverty, energy and material use per unit of output — must not" (PCSD 1996).

Accomplishing economic growth and environmental protection simultaneously requires fundamentally new ways of examining and designing socioeconomic systems. One way to get beyond the analytic limits of standard economic theory is to draw on an ecological metaphor as a means to better understand energy and material flows and as a guide to the design of industrial structures and public policies (Daly 1991). Robert Ayres has called systemwide material flows the industrial metabolism of an economy (Ayres 1989; Ayres and Simonis 1994). Emerging models for operationalizing industrial ecology suggest simple principles for design, for example, closing material loops, avoidance of upsets to the metabolism of the natural system (toxics elimination and pollution prevention), dematerialization, and thermodynamically efficient energy utilization (Ehrenfeld 1995; Lowe 1994; Tibbs 1992). These principles have the potential of moving society away from unsustainable development patterns by greatly reducing the flows of energy and materials into and out of an economy.

Moving from linear throughput to closed-loop material and energy use are key themes in industrial ecology. Industrial activity based on such an ecological conception can greatly reduce harmful impacts associated with pollution and waste disposal, while easing the drain on finite strategic resources. Familiar practices such as reuse, remanufacture, and recycling represent a move in this direction. Industrial symbiosis is closely related and involves the creation of linkages between firms to raise the efficiency, measured at the scale of the system as a whole, of material and energy flows through the entire cluster of processes. Some of the firms, viewed independently, may appear to be inefficient compared to conventional measures of environmental performance. Yet environmental performance can be superior in the overall group of firms because of the linkages. The cascading use of energy and the use of industrial by-products as feedstocks for processes other than the ones that created them is fundamental to this approach. In such cases, by-products can replace virgin materials as feedstocks. Energy cascading involves the use of the residual energy in liquids or steam emanating from one process to provide heating, cooling, or pressure for another process. The evolution of a set of interrelated symbiotic links among groups of firms in an area gives rise to a complex that we (and others) call an industrial ecosystem. This article examines an example of the development of such an industrial ecosystem and the context in which it emerged, identifying characteristics that may be useful in policy design.

Stable ecological systems are steady-state, entropy-minimizing, highly interdependent collections of producers and consumers (Prigogine 1955). These characteristics are different from those of an economy modeled after standard (economic) premises—quasi-equilibrium systems of essentially independent entities. Observations of materials flows and energy consumption in industrialized economies indicate highly dissipative usage which translates into entropy-increasing processes (Ayres 1994). Ayres notes that ecological systems are dissipative, also. At steady state, however, they correspond thermodynamically to conditions of minimum levels of entropy production (Prigogine 1955). Prigogine notes further that **such** entropy-minimizing states in stable biological systems are accompanied by increases in the interdependence among the entities. The notion of food webs, including detritivores (the scavengers that consume the wastes of other species) as important members, highlights the idea of closed or nearly closed material loops in such stable systems.

The relationship between steady-state economies and thermodynamics was first elaborated by Georgescu-Roegen (1971) and further used **as** one of the key foundations in Herman Daly's steady-state economic framework (Daly 1991). Cloud (1977, 679) noted that, "materials and energy are the interdependent feedstocks of economic systems, and thermodynamics is their moderator." Interestingly, he refers to the "industrial ecosystem" in the article, perhaps the earliest use of this term. The importance of entropy is that it is a measure related to the practical availability of materials and energy in a system (Daly 1991). Entropy, as a measure of disorder in a system, always increases as energy is made available from its chemical potential in fossil fuels and wastes are dissipated in the environment. Regaining the utility of the energy and materials requires reversing the entropic flows which can be done only at the expense of using even more energy. Thus, economic arrangements that minimize the production of entropy have some long-term advantages in the context of sustainability, over and above arguments based solely on efficiency.

All of this is prelude to introducing industrial symbiosis, another ecological metaphor used to describe a practical economic arrangement. Symbiosis is a biological term referring to "a close sustained living together of two species or kinds of organisms" (Encyclopaedia Britannica 1992, 14: 1034). The term was used as early as 1873 by a German botanist, H. A. De Bary, to describe the intimate, mutually beneficial coupling of fungi and algae in lichens. Symbiosis in economic systems is manifest in the exchange of materials and energy between individual firms located in close proximity. It is a specific example of combining several generic industrial ecological behavior patterns, for example, loop closing and energy cascades (Ehrenfeld 1995). Although not a necessary condition for all loop-closing exchanges, in particular those for commodity materials like scrap paper or steel, proximity is a hallmark of industrial symbiosis. This article argues that symbioses are distinct and evolve through a different process from these more common market activities.

The Kalundborg Industrial Ecosystem

A highly evolved industrial ecosystem is located in the seaside industrial town of Kalundborg, Denmark (Gertler and Ehrenfeld 1996). Eleven physical linkages comprise much of the tangible aspect of industrial symbiosis in Kalundborg (see figure 1). The town's four main industries—Asnaes Power Station, a 1,500-megawatt coal-fired power plant; a large oil refinery operated by Statoil; Novo Nordisk, a maker of pharmaceuticals and enzymes; and Gyproc, a plasterboard manufacturer—and several users within the municipality trade and make use of waste streams and energy resources, and turn by-products into raw materials. Firms outside the area also participate **as** recipients of by-product-to-raw-material exchanges. The symbioses evolved gradually (see table 1) and without a grand design over the past 25 years, as the firms sought to make economic use of their by-products and to minimize the cost of compliance with new, ever-stricter environmental regulations.

At the heart of this system of arrangements is the Asnaes Power Station, the largest power plant in Denmark. By exporting part of the formerly wasted energy, Asnaes has reduced the

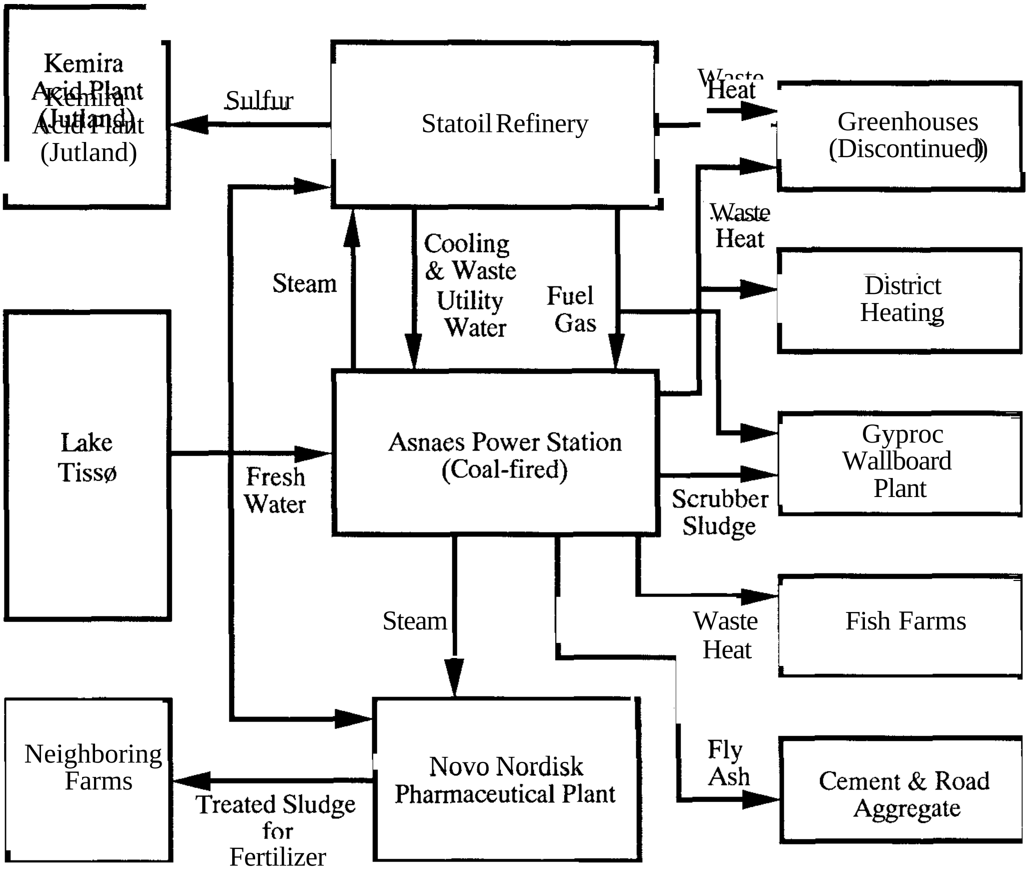

Figure 1 The industrial ecosystem at Kalundborg, Denmark

fraction of available energy directly discarded by about 80%. Since 1981, the town of Kalundborg has eliminated the use of 3,500 oil-fired residential furnaces by distributing heat from the power plant through a network of underground pipes. Homeowners pay for the piping, but receive cheap, reliable heat in return. The power plant also supplies heat to its own fish farm, exploiting an increase in growth rate from the warmer water. Sludge from the ponds is sold as fertilizer.

Asnaes also delivers process steam to its neighbors, Novo Nordisk and Statoil. The Statoil refinery receives 40% of its steam requirements while Novo Nordisk receives all of its steam requirements from Asnaes. The decision to rely completely on Asnaes for steam was made in 1982 when Novo Nordisk was faced with the need to upgrade and renovate its boilers. Buying steam from outside was seen as a cheaper alternative. The two-mile-long steam pipeline built for the interchange paid for itself in two years. In addition, thermal pollution of the nearby fjord from the former Asnaes discharge has been reduced.

The power station also provides a gypsum-containing feedstock to Gyproc, a neighboring wallboard maker. In 1993, Asnaes completed the installation of a $115 million sulfur dioxide scrubber that produces calcium sulfate, or industrial gypsum, as a by-product at a rate of 80–85,000 tons per year. Conveniently, gypsum is the primary ingredient of wallboard. Two-thirds of Gyproc's gypsum needs are met by Asnaes's scrubber, while much of the rest comes from a scrubber at a similar German power plant. Gyproc formerly obtained all its gypsum from Spanish open-pit mines which still supply a small portion of its needs. Fly ash and clinker, the remains of coal-burning power generation, are sold by Asnaes for road building and cement production.

Table 1 Chronology of Kalundborg development

Year	Action
1959	Asnaes power station commissioned
1961	Statoil refinery commissioned; water piped from Lake Tissø
1972	Gyproc A/S built; gas piped from Statoil
1973	Asnaes expands; draws water from pipeline
1976	Novo Nordisk begins shipping sludge to farmers
1979	Asnaes begins to sell fly ash to cement producers
1981	Asnaes produces heat for Kalundborg Kommune
1982	Asnaes delivers steam to Statoil and Novo Nordisk
1987	Statoil pipes cooling water to Asnaes
1989	Novo Nordisk switches from Lake Tissø to wells
1990	Statoil sells molten sulfur to Kemira in Jutland
1991	Statoil sends treated waste water to Asnaes for utility use
1992	Statoil sends desulfurized waste gas to Asnaes
1993	Asnaes supplies gypsum to Gyproc

The Norwegian-owned Statoil refinery, producing a range of petroleum products from light gas to heavy fuel oil, is located across the road from Asnaes. Since 1972, Statoil has been piping the gas to Gyproc to fire wallboard drying ovens, all but eliminating the common practice of flaring waste gases. This fuel gas supplies all of Gyproc's needs. For continuity, Gyproc installed a butane backup system for those periods when Statoil shuts down for maintenance. In 1990, Statoil built a sour-gas desulfurization plant producing liquid sulfur that is promptly trucked about 50 kilometers to Kemira where it is converted to sulfuric acid. With the sulfur removed, Statoil's gas is clean enough to be burned by Asnaes as well.

Freshwater scarcity in Kalundborg has led to water reuse schemes. Since 1987, Statoil has piped 700,000 cubic meters per year of cooling water to Asnaes, where it is purified and used as boiler feed-water. Statoil has also made treated waste water available to Asnaes, which uses about 200,000 cubic meters a year for cleaning purposes. Statoil's investment in a biological treatment facility produces an effluent sufficiently clean for Asnaes's use. Symbiotic linkages have reduced the water demand by around 25%.

A few miles from Asnaes and Statoil is Novo Nordisk, a world leader in the production of insulin, enzymes, and penicillin. The plant employs about 1,000 people, roughly 10% of Kalundborg's population. Novo Nordisk makes its product mix by fermentation, based on agricultural crops that are converted to valuable products by microorganisms. A nutrient-rich sludge remains after the products are harvested. Since 1976, Novo Nordisk has been distributing the process sludge to about a thousand nearby farms where it is spread on the land as fertilizer. After heat treatment to kill remaining microorganisms, the sludge is distributed throughout the countryside by a network of pipelines and tanker trucks. Novo Nordisk produces 3,000 cubic meters of sludge per day, but can only store three days' worth. The sludge is given away instead of being sold, reflecting the firm's concerns for disposal security. Three full-time employees coordinate its delivery. Distributing the sludge as fertilizer was the least-cost way to comply with regulations prohibiting Novo Nordisk from discharging the sludge directly into the sea.

Savings from more efficient utilization of resources and elimination of wastes are shown in table 2.

Symbiosis in Other Settings

Full utilization of by-products is a concept that has a long history in the petrochemical industry (Nemerow 1995). The Houston Ship Channel is an oft-cited example of the application of industrial ecosystem concepts to such a complex. The channel is lined with numerous chemical, petrochemical, and energy-generating facilities that have been using and exchanging by-products for decades. In a typical exchange, vent gas from an Amoco plant is rerouted to a neighboring Chevron facility where it is compressed and separated into its hydrogen and propylene components. Prior to this arrangement, the gas was burned in Amoco's flare stack.

The availability of a by-product stream can be a major factor in site selection in the petro-

Table 2 Waste and resource savings at Kalundborg

Annual resource savings through interchanges
Water savings
Statoil—1.2 million cubic meters from Asnaes
(Novo Nordisk is now producing 900,000 cubic meters of treated water that is available to replace fresh supplies, but is being discarded at present.)
Fuel savings
Asnaes—30,000 tons of coal (about 2% of throughput) by using Statoil fuel gas
About 19,000 tons of oil use by using fuel gas from Statoil in Novo Nordisk's boilers and Gyproc dryer fuel
Community heating via steam from Asnaes
Input chemicals
Fertilizer equivalent to Novo Nordisk sludge (about 800 tons nitrogen and 400 tons phosphorous)
2,800 tons sulfur
80,000 tons of gypsum

Wastes avoided through interchanges
200,000 tons fly ash and clinker from Asnaes (landfill)
80,000 tons scrubber sludge from Asnaes (landfill)
2,800 tons sulfur as hydrogen sulfide in flue gas from Statoil (air)
1 million cubic meters of water treatment sludge from Novo Nordisk (landfill or sea)
1,500–2,500 tons of sulfur dioxide avoided by substituting coal and oil (air)
130,000 tons carbon dioxide avoided by substituting coal and oil (air)

chemical industry. The inherent flexibility of petrochemical processes to accept a broad range of feedstocks is an important factor leading to widespread over-the-fence arrangements. Modern petrochemical plants can rearrange the molecules in a large variety of feed compositions to obtain the desired product mix.

A Novo Nordisk plant in North Carolina produces the same nutrient-rich sludge as its Danish counterpart. As in Kalundborg, the sludge is spread on farmland, providing fertilizer for 5,000 acres. Gypsum from the scrubbers of coal-fired power plants is used as raw material for wallboard in a number of American states, including Texas and Florida. Wisconsin Public Service, a public utility, is building a cogeneration power plant next to a paper mill in Rhinelander, Wisconsin. The power plant will burn wastes from Rhinelander Paper Company, while providing all of the mill's steam needs and electricity for two local counties.

Industrial symbiosis is now receiving increasing attention worldwide. A major initiative has arisen from the efforts of a Belgian economist and entrepreneur, Gunter Pauli. His recognition of the limits of a single firm to reduce wastes to zero, even with substantial efforts in pollution prevention, gave rise to Pauli's zero emissions vision: multi-industry symbiotic clusters of factories. Pauli and others would extend the "unplanned" evolution process at Kalundborg to create complexes of firms whose by-product streams are linked. The Zero Emissions Research Initiative, or ZERI, is an outgrowth of this thinking. Based at United Nations University in Tokyo, ZERI seeks to reduce a firm's emissions directly to the environment to zero while improving profitability. Based on the notion that complementary industries can form zero-emissions clusters, one ZERI project aims at coupling beer brewing with the raising of fish, mushrooms, and chickens. Through a carefully integrated coupling, ZERI predicts a sevenfold increase in the total amount of nutrients available for human consumption and a fourfold increase in jobs, all on the basis of the standard inputs to a beer brewery—cereals, yeast, and water (Pauli 1995).

One of the major policy thrusts of the report of the U.S. President's Council for Sustainable

Development is the creation of eco-industrial parks where the firms would be closely linked through waste and energy symbioses (PCSD 1996). **As** defined in the report, "Eco-industrial parks are an environmentally efficient version of industrial parks. They follow a systems design in which one facility's wastes becomes another facility's feedstock, and they ensure that raw materials are recycled or disposed of efficiently and safely." Specific projects are under way in Chattanooga, Tennessee, Brownsville, Texas/ Matamoros, Mexico; Baltimore, Maryland, and Cape Charles, Virginia. Each one has a different set of objectives and planning process (Gertler 1995). Chattanooga aims for the ZERI objective of zero emissions. Baltimore is planned around four integrated strategies: loop closing and industrial ecology; network manufacturing; continuous improvement; and high-performance workplaces and union-management cooperation (ETI 1995). Several planning guidelines for eco-industrial parks have been recently published (Lowe et al. 1995; Cote et al. 1994).

Patterns of Industrial Ecosystem Development

Although examples of closely linked or co-located symbioses as at Kalundborg are few, material exchange is a standard part of business practice. The basic exchange of materials between manufacturers and their suppliers and customers could be considered a kind of loose symbiosis with benefits accruing to all parties. The recovery of scrap metals in many economies is another example of well-established industrial symbiosis. Yet massive quantities of materials are routinely discarded as wastes by industrial systems throughout the world. This section discusses a set of factors that both promote and inhibit the development of symbioses and industrial ecosystems.

The Pattern of Economic Development at Kalundbog

Many visitors come to Kalundborg looking for the master plan. Despite its impressive results, Kalundborg was not explicitly designed to demonstrate the benefits of industrial symbiosis. Each link in the system was negotiated, over a period of some 25 years (see table 1), as an independent business deal and was established only if it was expected to be economically beneficial. Benefits are measured either as positive flows by marketing a by-product (or obtaining feedstocks at prices below those for virgin materials) or as savings relative to standard pollution control approaches. This is the strength of the Kalundborg approach: business leaders have done the "right thing" for the environment in the pursuit of rational business interests. The evolutionary nature can be interpreted as pointing to a need to have both positive technical and economic factors appear simultaneously, a condition that may be difficult or impossible to realize in a forward-planning process.

Besides the basic chemical and other technical compatibility requirements of symbiotic partners, both need to recognize a net cost savings relative to their options. The floor for economic feasibility occurs when the difference in cost of the by-product feed relative to virgin or other alternatives is less per unit throughput than the cost of waste management to the producer. The user can offer more than enough to the producer to offset the costs of waste treatment or disposal. In practice the differential would also have to be large enough to account for transaction costs and risks to both parties. Typical transaction costs include regulatory, discovery, contracting, and monitoring costs. Discovery costs, the costs required to learn of the existence of an opportunity for exchange, can be high, and may be the major impediment for material exchange of the types discussed below. Brokerages and markets serve to reduce these costs to the point that exchange is economically rational. Exchange of material recovered from municipal waste streams (e.g., paper, metals, plastics) is now increasingly managed through commodity exchanges and electronic networks such as the Chicago Board of Trade and the Global Recycling Network.

The buyer of by-products in a symbiosis takes some risk by tying the firm to a single, outside supplier and to the vagaries of supply continuity. The exchange of by-products and cascades of energy use, however, is not inherently different from traditional supplier-customer relationships. Differential financial implications may be insig nificant. Provisions for standby supplies will add cost. The seller also takes some risk given the possibility of upsets at the buyer's facility that could interrupt the outflow of the by-products. If this were to happen, the by-products would instantly become wastes to the seller and would need to be disposed of according to the relevant regulatory requirements.

Another economic factor is unrecognized environmental management savings to the firm that could be realized by an exchange of materials. The emergence of full-cost accounting, a form of activity-based accounting that more accurately identifies and allocates costs of complying with regulations and otherwise protecting the environment, should enlarge the opportunities for symbioses and other forms of material exchange (Ditz, Ranganathan, and Banks 1995). Future liability costs, for example, or the costs of maintaining a legal staff for regulatory compliance have been generally overlooked in evaluating innovative opportunities.

Organizational Arrangements and Transaction Costs

In theory, symbioses can follow any of the common types of industrial organization described, for example, by Williamson (1979) who suggests that organizational arrangements between firms are shaped by efforts to minimize transaction costs. Kalundborg is based on a complex of contracts and alliances that have arisen with little or no institutional intervention. Unlike a spot market such as is typical in handling metal scrap, this type of structure affords symbioses more certainty and continuity than exchanges in pure markets can offer. Vertical integration, the common ownership of one or more successive stages in the production process, would go even further and might arise if continuity in the movement of by-products becomes a critical factor. The cluster approach of ZERI appears to be heading in this direction.

Other forms of industrial organization more common outside the United States have some relevance to the emergence of symbiotic arrangements (Lenox 1995). The cross-ownership structure of the Japanese **keiretsu** is a highly elaborated form of integration in which the transaction costs and risks could be spread among potential participants in an exchange of by-products. Another possibility is centralized ownership, as is found in Germany where banks may own substantial equity in and participate actively in the management of a number of firms. Other financial institutions could play a similar role. To reduce the coordinative problems with ecoparks discussed above, some form of common ownership or institutional management power vested in the developer of the park could improve the context for the emergence of symbiotic patterns. The eco-industrial park concept has many common characteristics with the more general notion of the manufacturing network form of industrial development presented by Piore and Sabel (1984) in their analysis of the success of the artisan-based economy in the Emilia-Romagna region of Italy. Active trade associations; shared services, such as purchasing and quality assurance; close family and community ties are among the factors that contribute to the success of such industrial districts.

Impediments other than strictly economic ones exist as well, although Williamson might argue all can be represented in terms of transactions costs. Symbiosis requires exchange of information about nearby industries and their inputs and outputs that is often difficult or costly to obtain. Kalundborg's small size of about 12,000 residents and its relative isolation have made for a tight-knit community in which employees and managers interact socially with their counterparts on a regular basis. This cultural feature leads to what a local leader calls a short mental distance between firms (Christiansen 1994). Cultural pressures are also important. As in many Scandinavian settings, there is a backdrop of environmental awareness.

In Kalundborg, no deliberate institutional mechanism was needed to promote conversations among the potential partners. Interfirm trust is important in establishing alliances or contracts among participants (Gulati 1995). An atmosphere of trust in Kalundborg existed even in the absence of specific experience between firms. In the United States, where there is a strong tradition of company privacy, such natural communication is much more difficult to find. The absence of a cultural context for exchange can be mitigated through institutional mechanisms such as brokers or planning agencies. Such a broker's role is played by VP Resources of Clearlake, Texas, which defines its role as more than a waste exchange ("finding a home for orphan chemicals") (Purcell 1995). Where typical waste exchanges merely list available by-products, VP Resources performs every function required to turn a by-product into a feedstock, including finding appropriate uses, dealing with regulatory agencies, brokering necessary agreements, and even transporting the materials from the generator to the user.

Technical Factors

In general, symbiotic industrial facilities need to be in close proximity in order to avoid large transportation costs and energy degradation during transit. High-value by-products such as pure sulfur from sour-gas treatment, such as that at Statoil, are exceptions. Contrary to the notion of pollution prevention and zero waste at a plant boundary, such as is, for example, the underlying policy goal of the U.S. Pollution Prevention Act of 1990, symbiosis may work best when plants produce large quantities of waste. This situation seems to be contrary to the notion of eco-efficiency as applied to individual firms. It is not always best for either the bottom line or the environment to reduce a single plant's waste to zero.

The cluster notion of ZERI works best, if not requires, plants with large, continuous waste streams. Wastes that are largely organic in nature like the effluent from fermentation of all sorts (e.g., pharmaceuticals or brewing), or raw agricultural or forestry wastes, are attractive as it is the organic carbon that is useful as a feedstock. Supply security is important to the user of the by-product streams exactly as would be the reliability of an otherwise virgin feed supply. Use of organic streams from fermentation as feed or fertilizer requires little or no matching of chemical characteristics other than assuring that toxic components or organisms are absent. Materials production, such as the manufacture of wallboard, is more technically challenging and requires much closer matching of compositions.

Early links at Kalundborg tended to involve the sale of waste products without significant pretreatment. This pattern includes the initial sale of Statoil's flue gas, Asnaes's 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 simply involved rerouting of what was formerly waste, without any significant alteration. The more recent links, however, have been created by and depend on the application of pollution control technologies. These links, which comprise just over half of the interconnections, do not just move process by-products around. The processes and disposal practices are controlled to make them more environmentally benign and, at the same time, to render them more attractive as feedstocks. The interposition of pollution control systems is important in an industrial ecosystem as these technologies serve to concentrate dilute by-products into economically and technically attractive forms. The symbiotic relationships that comprise these links would not be attractive in the absence of such pollution control measures.

Regulatory Context

The manager of the Asnaes plant believes that existing economic incentives alone were generally sufficient for much of the Kalundborg symbiosis (Christiansen 1994). Further symbiotic arrangements yielding environmental benefits are potentially available, but cost more than conventional practices. Political impetus is necessary to go further, for example, requiring emission reductions or adjusting prices to make symbiosis economically attractive. Yet such external signals alone are not sufficient, given that innovative and pioneering cooperation is required among companies for symbiosis to occur.

The Danish regulatory framework has encouraged the evolution of industrial symbiosis in Kalundborg. Compared to the United States, the Danish regulatory system is consultative, open, and flexible. Instead of being put on the defensive as is characteristic of a command-and-control framework, firms are required to be proactive by submitting plans to the overseeing county government detailing their efforts to continually reduce their environmental impact.

A dialogue then ensues in which the regulators and the firm establish goals. A more flexible, cooperative relationship is fostered between government and the regulated industries, and as a result, firms tend to focus their energies on finding creative ways to become more environmentally benign instead of fighting with regulators. A key aspect of the flexibility is that regulatory requirements are mainly in the form of performance standards stating the degree of the desired decrease, instead of technology standards as is common in the United States. Technology standards assure that uniformly effective pollution-control methods are adopted throughout a given industry. They tend to hinder technological or infrastructural innovation, however (Banks and Heaton 1995; Porter and van der Linde 1995; Sparrow 1994). Many of the creative arrangements found in Kalundborg are only possible where firms have flexibility in the approaches employed to meet pollution-reduction targets. In the United States, little discretion is left to firms. There are disadvantages to the Danish system, including potentially lower levels of technical compliance and high transaction costs incurred in extensive consultations around permitting. Although U.S. technology standards are inflexible, they ensure a certain minimum level of pollution control.

Regulatory requirements may preclude exchange or serve as very strong disincentives. In the United States, for example, the Resource Conservation and Recovery Act (RCRA) regulates the treatment and disposal of industrial waste, but inadvertently impedes one of its objectives—conservation and recovery of resources. The statute is primarily concerned with averting risks stemming from the improper management of hazardous waste. RCRA regulations pursue this goal through a very extensive set of specific, inflexible, and often confusing rules governing the treatment, storage, and disposal of industrial by-products (Hill 1991). RCRA regulations set forth specific detailed procedural and technical requirements for the management of an exhaustive list of particular types of waste streams. With by-products being matched to a particular, mandatory protocol, little room exists for innovative schemes for their reuse as feedstocks elsewhere. This inflexibility is based in large part on a deep-seated fear of sham recycling, which is an undertaking where the generator of a waste product makes a show of reusing that by-product merely to escape treatment requirements (Comella 1993). Industrial symbiosis must be distinguished from such efforts if it is to develop within the current regulatory system.

Barriers and Limits to the Development of Symbiotic Communities

The current vision of eco-industrial parks closing material loops needs to be examined carefully in light of the Kalundborg experience. Opportunities for symbioses or clusters in the sense of ZERI certainly exist, but not for more than a small fraction of extant and planned industrial development zones in older economies like the United States. The cluster approach appears more fitted to and is being promoted for so-called greenfields or new initiatives in developing economies. Symbiosis, as in Kalundborg, is not likely to become the main loop-closing form for such complexes as it requires the presence of two or more firms that produce and consume a continuous stream containing useful by-products. Such process industries are only a small fraction of the typical manufacturing firms that comprise local industrial development areas. Many are small companies making parts or assembling products, working metals and wood, molding plastics, or cutting textiles. Finding firms to colocate at the site of existing primary sources of by-products, like breweries, would be another form of this notion. Brownfields, as abandoned or decaying industrial districts are termed, are also candidates for the cluster model. At the Second Annual World Congress on Zero Emissions, Edgar Woolard, DuPont's recently retired CEO argued that such existing sites should be developed before new greenfields are taken out of their more natural uses (Krieger 1996). Developing economies with few brownfields might disagree.

Companies that manufacture product components or assemble products produce two kinds of wastes. One is essentially single material wastes, such as unused or dirty solvents, paints, or plastic or metal scrap. Such wastes can be used directly by other companies. According to an informal survey done by MIT in 1994 (unpublished), waste exchanges acting as brokers handle a very small fraction of such wastes. Unlike the continuous and relatively reliable production of process-industry by-products, these manufacturing by-products have variable compositions and appear in small quantities. The second waste type is mixed manufacturing wastes including off-specification products. Such wastes are similar to end-of-life durable goods. To be useful, these materials must be either separated into their components or recycled into an application that can use the bulk properties of the composite waste. Electronic scrap might, for example, contain precious metals that could be recovered and reused.

Exchanges of single material wastes lack the technical and economic appeal of continuous sources of feedstocks. Transaction costs for identifying and transferring such wastes are very high and lot sizes are small. Loop closing by reusing mixed wastes is unlikely to be viable in a localized area such as an ecopark. There is not enough of any stream to provide for a freestanding, economically viable recovery activity. Very high-value components such as precious metals might lend themselves to closed loops, and there might be opportunities for downcycling of mixed plastics. Downcycling refers to material recycling in products tolerating lower performance specifications than the original use—plastic lumber, for example.

The critical missing factor is positive economical linkages as at Kalundborg. Recovery of materials from mixed process waste is no different from recovery from end-of-life products. Except for precious metals, such recovered materials are generally more expensive than virgin materials, reversing the economic calculus. It would take some form of public intervention, such as imposing large disposal costs or subsidies, to recovery firms to create the favorable economics that led to the evolution of Kalundborg. Taxes on pollution, waste disposal, and virgin materials (rather than the current set of subsidies for many raw materials) would create incentives to keep more resources circulating in productive use, while reducing the environmental impact of industrial activity. But even with such policy intervention, it may be difficult to produce conditions where positive economics and environmental factors arise simultaneously among a large number of firms.

It was the arrival of such pairing dubbed by some as "green twinning"—over time that, arguably, produced the prerequisites for the development of the Kalundborg industrial ecosystem. Together with the institutional context that raised environmental values and enabled a high information flow (and lower transaction costs), the emergence of individual arrangements is the expected outcome of a rational decision-making process that should be reproduced in other similar contexts. Designing an industrial ecosystem from the ground up is different and cannot follow the evolutionary path that contributed so strongly to Kalundborg's positive development. Simple probability suggests a very low chance of finding pairs of coexisting positive environmental, technical, and economic factors among more than one or two firms at any one time. If one assigns a binary value of zero (nonpositive linkage) or one (positive linkage) to each of these three factors with equal probability, basic combinatorial theory leads to an overall probability of only 1 in 64 that all three factors for both parties are nonzero, such that the product is also nonzero, that is, favorable. Adding more firms reduces the joint probability even further. Interventionist public or private initiatives can increase the probability of positive values for each term, but the overall probability may remain small.

The evolutionary path, on the other hand, captures the opportunistic arrival of such joint conditions, one case at a time. In this sense, the evolution of a symbiotic industrial ecosystem is little more than a special case of Williamson's transaction cost model of the development of patterns of industrial organization. Broad public policy initiatives can nudge the process along by creating the overall conditions that promote the emergence of positive factors in individual cases over time, but may falter where the promoters of an eco-industrial park are attempting to create all the linkages up front. An integrated and continuous planning process that explicitly seeks to identify opportunities and barriers to symbiotic development should increase the likelihood of attracting firms willing to make the necessary arrangements. Such a middle-ground approach between pure laissez-faire and heavy-handed policy intervention would seem to offer the best chance of success to institutional developers.

A final barrier lies in the cognitive domain. Wastes have such a long history of being ignored that it is difficult for firms to integrate these outputs of their activities into their strategic processes. For firms to think strategically and systematically about their entire production chain, they must change the mind-set that often sees the world beyond the fence-line as only customers. This way of seeing the world is quickly changing. New tools, such as life-cycle analysis and new codes of practice like the Responsible Care initiative of the chemical industry or the ISO 14000 environmental management system standards, are slowly introducing more systematic and worldly models into the underlying consciousness of firms and reducing the rigidity of traditional regulations (Freeman and Belcamino 1996). Together with new institutional approaches, these more deep-seated cultural changes can provide a foundation from which symbioses and other forms of material exchange begin to actually move economies toward sustainability.

References

Allen, D., and N. Behmanish. 1994. Wastes as raw materials. In The greening of industrial ecosystems, edited by B. R. Allenby and D. Richards. Washington, DC: National Academy Press.

Allenby, B. R. 1992. Achieving sustainable development through industrial ecology. International Environmental Affairs 4(1): 56–68.

Ayres, R. U. 1989. Industrial metabolism. In Technology and environment, edited by J. H. Ausubel and H. E. Sladovich. Washington, DC: National Academy Press.

Ayres, R. U. 1994. Industrial metabolism: theory and policy. In Industrial metabolism: Restructuring for sustainable development, edited by R. U. Ayres and U. E. Simonis. Tokyo: United Nations University Press.

Ayres, R. U., and U. E. Simonis, eds. 1994. Industrial metabolism: Restructuring for sustainable development. Tokyo: United Nations University Press.

Banks, R. D., and G. R. Heaton. 1995. An innovation-driven environmental policy. *Issues* in Science and Technology 12(1): 43–51.

Christiansen, V. 1994. Personal communication. May.

Cloud, P. 1977. Entropy, materials and posterity. *Geologische Rundschau* 66(3): 678–696.

Comella, P. 1993. Understanding a sham: When is recycling, treatment? Environmental Affairs 20: 433-436.

Côté, R., R. Ellison, J. Grant, J. Hall, P. Klynstra, M. Martin, and P. Wade. 1994. Designing *and* operating industrial parks as ecosystems. School for Resource and Environmental Studies, Dalhousie University, Halifax, Nova Scotia.

Daly, H. E. 1991. Steady-state economics. 2d ed. Washington, DC: Island Press.

Ditz, D., J. Ranganathan, and R. D. Banks, eds. 1995. Green ledgers: *Case* studies in corporate *environ*mental accounting. Washington, DC: World Resources Institute.

Ehrenfeld, John R. 1995. Industrial ecology: A strategic framework for product policy and other sustainable practices. In Green goods, edited by E. Ryden and J. Strahl. Stockholm: Kretsloppdelegationen.

Encyclopaedia Britannica. 1992. The *new* Encyclopaedia Britannica. Chicago: Encyclopaedia Britannica 14: 1034.

ETI. 1995. Eco-industrial park progress report. Office of Science and Technology Policy.

Freeman, D. J., and G. R. Belcamino. 1996. Brownfields redevelopment and ISO 14000: A marriage that makes sense. Corporate *Environmental* Strategy 3(2): 73–76.

Georgescu-Roegen, N. 1971. The entropy law and the economic process. Cambridge: Harvard University Press.

Gertler, N. 1995. Industrial ecosystems: Developing sustainable industrial structures. Master's thesis, Massachusetts Institute of Technology.

Gertler, N., and J. R. Ehrenfeld. 1996. A down-to-earth approach to clean production. Technology Review 99(2): 48–54.

Gulati, R. 1995. Does familiarity breed trust? The implications of repeated ties for contractual choice in alliances. Academy of Management Journal 38(1): 85–112.

Hill, R. 1991. An overview of RCRA: The "Mind-Numbing" provisions of the most complicated environmental statute. Environmental *Law* Reporter 21(May): 10255–10275.

Jelinski, L. W., T. E. Graedel, R. A. Laudise, D. W. McCall, and C. K. Patel. 1992. Industrial ecology: Concepts and approaches. Proceedings of the National Academy of Sciences 89 (February): 793–797.

Krieger, J. H. 1996. Zero emissions gathers force as global environmental concept. **Chemical & Engineering News** 74(28): 8–16.

Lenox, M. 1995. Barriers and opportunities for industrial symbiosis: A critical examination of alternative forms of industrial coordination. Unpublished paper. Massachusetts Institute of Technology.

Lowe, E. 1994. Industrial ecology: Implications for corporate strategy. ***Journal* of Corporate *Environmental* Strategy** 2(1): 61-65.

Lowe, E. A., S. R. Moran, and D. B. Holmes. 1995. **Fieldbook** for **the development** of **eco-industrial** parks. Draft report. Oakland, CA: Indigo Development Company.

Nemerow, N. 1995. **Zero pollution** for **industry.** New York: Wiley Interscience.

Pauli, Gunther. 1995. Personal communication. April.

PCSD (President's Council for Sustainable Development). 1996. **Sustainable *development*: A *new* consensus.** Washington, DC.

Piore, M. J., and C. F. Sabel. 1984. ***The* second *industrial* divide.** New York: Basic Books.

Porter, M. E., and C. van der Linde. 1995. Green and competitive: Ending the stalemate. **Harvard Business Review** 73(5): 120–134.

Prigogine, I. 1955. **Thermodynamics** of **irreversible processes.** Springfield, IL: C. C. Thomas.

Purcell, V. 1995. Personal communication. February.

Sparrow, M. 1994. **Imposing duties: Government's changing *approach to* compliance.** Westport, CT: Praeger.

Tibbs, H. B. C. 1992. Industrial ecology—An agenda for environmental management. **Pollution Prevention Review** 2(2): 167–180.

Williamson, O. 1979. Transaction cost economics: The governance of contractual relations. ***Journal* of *Law* and Economics** 22: 233–262.

This article has been cited by:

1. Olli Salmi, Aino Toppinen. 2007. Embedding Science in Politics: “Complex Utilization” and Industrial Ecology as Models of Natural Resource Use. *Journal of Industrial Ecology* **11**:3, 93-111. [Abstract] [PDF] [PDF Plus] [Supplementary material]
2. John R. Ehrenfeld. 2007. Would Industrial Ecology Exist without Sustainability in the Background?. *Journal of Industrial Ecology* **11**:1, 73-84. [Abstract] [PDF] [PDF Plus] [Supplementary material]
3. Marian R. Chertow. 2007. “Uncovering” Industrial Symbiosis. *Journal of Industrial Ecology* **11**:1, 11-30. [Abstract] [PDF] [PDF Plus] [Supplementary material]
4. Noel Brings Jacobsen . 2006. Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects. *Journal of Industrial Ecology* **10**:1-2, 239-255. [Abstract] [PDF] [PDF Plus] [Supplementary material]
5. Tohru Morioka , Kiyotaka Tsunemi , Yugo Yamamoto , Helmut Yabar , Noboru Yoshida . 2005. Eco-efficiency of Advanced Loop-closing Systems for Vehicles and Household Appliances in Hyogo Eco-town. *Journal of Industrial Ecology* **9**:4, 205-221. [Abstract] [PDF] [PDF Plus]
6. Stephen H. Levine . 2003. Comparing Products and Production in Ecological and Industrial Systems. *Journal of Industrial Ecology* **7**:2, 33-42. [Abstract] [PDF] [PDF Plus] [Supplementary material]
7. Catherine Hardy , Thomas E. Graedel . 2002. Industrial Ecosystems as Food Webs. *Journal of Industrial Ecology* **6**:1, 29-38. [Abstract] [PDF] [PDF Plus] [Supplementary material]
8. Marquita Hill , Thomas Saviello , Stephen Groves . 2002. The Greening of a Pulp and Paper Mill: International Paper's Androscoggin Mill, Jay, Maine. *Journal of Industrial Ecology* **6**:1, 107-120. [Abstract] [PDF] [PDF Plus]
9. Pierre Desrochers . 2001. Cities and Industrial Symbiosis: Some Historical Perspectives and Policy Implications. *Journal of Industrial Ecology* **5**:4, 29-44. [Abstract] [PDF] [PDF Plus]
10. Derya B. Özyurt , Matthew J. Realff . 2001. Combining a Geographical Information System and Process Engineering to Design an Agricultural-Industrial Ecosystem. *Journal of Industrial Ecology* **5**:3, 13-31. [Abstract] [PDF] [PDF Plus]
11. Michael T. Rock , David P. Angel , Tubagus Feridhanusetyawan . 1999. Industrial Ecology and Clean Development in East Asia. *Journal of Industrial Ecology* **3**:4, 29-42. [Abstract] [PDF] [PDF Plus]
12. Sara E. Keckler , David T. Allen . 1998. Material Reuse Modeling: A Case Study of Water Reuse, in an Industrial Park. *Journal of Industrial Ecology* **2**:4, 79-92. [Abstract] [PDF] [PDF Plus]
13. Daniel C. Esty, Michael E. Porter. 1998. Industrial Ecology and Competitiveness: Strategic Implications for the Firm. *Journal of Industrial Ecology* **2**:1, 35-43. [Abstract] [PDF] [PDF Plus]