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INDUSTRIAL SYMBIOSIS: Literature and Taxonomy

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■ **Abstract** Industrial symbiosis, as part of the emerging field of industrial ecology, demands resolute attention to the flow of materials and energy through local and regional economies. Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity.

This paper reviews the small industrial symbiosis literature and some antecedents, as well as early efforts to develop eco-industrial parks as concrete realizations of the industrial symbiosis concept. Review of the projects is organized around a taxonomy of five different material exchange types. Input-output matching, stakeholder processes, and materials budgeting appear to be useful tools in advancing eco-industrial park development. Evolutionary approaches to industrial symbosis are found to be important in creating the level of cooperation needed for multi-party exchanges.

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INTRODUCTION

The emerging field of industrial ecology demands resolute attention to the flow of materials and energy through local, regional, and global economies. The part of industrial ecology known as industrial symbiosis engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity. Eco-industrial parks are examined as concrete realizations of the industrial symbiosis concept.

According to the first textbook in the field, the concept of industrial ecology “requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle, from virgin materials, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital” (2, p. 9).

Industrial ecology allows focus at the facility level, at the inter-firm level, and at the regional or global level. Industrial symbiosis occurs at the inter-firm level because it includes exchange options among several organizations (see Figure 1).

The expression “symbiosis” builds on the notion of biological symbiotic relationships in nature, in which at least two otherwise unrelated species exchange materials, energy, or information in a mutually beneficial manner—the specific type of symbiosis known as mutualism (3). So, too, industrial symbiosis consists of place-based exchanges among different entities. By working together, businesses strive for a collective benefit greater than the sum of individual benefits that could be achieved by acting alone. This type of collaboration can advance social relationships among the participants, which can also extend to surrounding neighborhoods. As described below, the symbioses need not occur within the strict boundaries of a “park,” despite the popular usage of the term eco-industrial park to describe organizations engaging in exchanges.

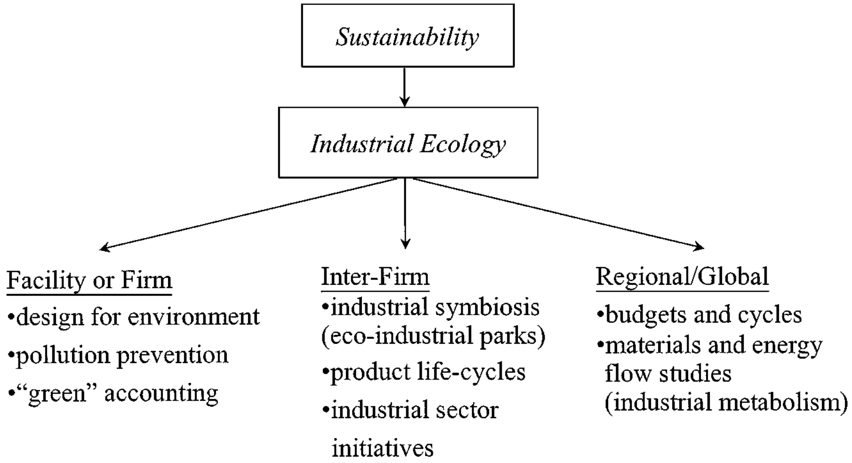

Figure 1 Industrial ecology operates at three levels.

At the same time that interest began to develop in industrial symbiosis and eco-industrial parks, a number of other parallel tracks advanced that might be construed, broadly, as "green development." These include sustainable architecture, green building, sustainable communities, and smart growth, among many other terms. In the Rocky Mountain Institute's *Green Development: Integrating Ecology and Real Estate*, the authors point out that there is no single face to this kind of enterprise because "for one project, the most visible 'green' feature might be energy performance; for another, restoration of prairie ecosystems; for yet another, the fostering of community cohesion and reduced dependence on the automobile" (4, p. 4).

Rather than take on the broad task of green development, this paper focuses on predominantly commercial and industrial activities that include a materials exchange component to qualify the activity as industrial symbiosis. This paper examines these collective exchanges from the perspective of industrial ecology rather than from an economic development, environmental planning, or land use perspective. It reviews the limited literature on industrial symbiosis and also reports on eco-industrial parks and exchanges that are beyond the earliest planning stages and are beginning to move, or have moved, toward implementation in the United States and other parts of the world.

INSPIRATION: Kalundborg, Denmark

The model of industrial symbiosis was first fully realized in the eco-industrial park at Kalundborg, Denmark. The primary partners in Kalundborg, an oil refinery, power station, gypsum board facility, pharmaceutical plant, and the City of

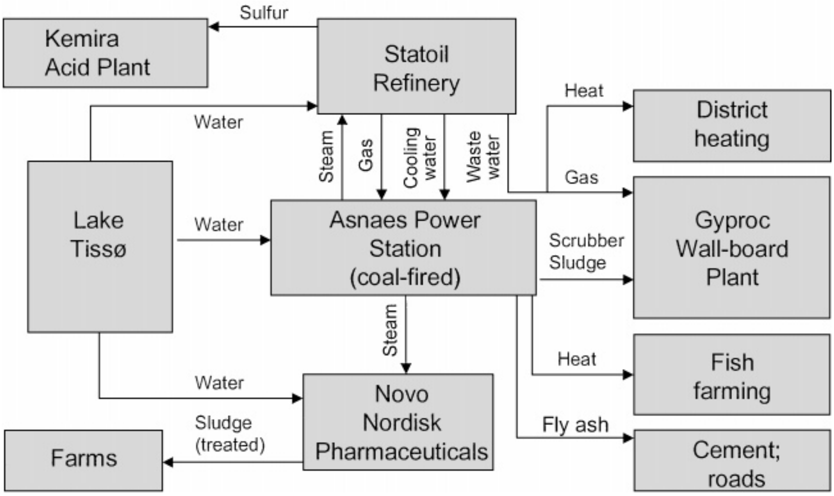

Figure 2 Industrial symbiosis at Kalundborg.

Kalundborg, literally share ground water, surface water and waste water, steam and electricity, and also exchange a variety of residues that become feedstocks in other processes (see Figure 2). The waste exchanges alone amount to some 2.9 million tons of material per year. Water consumption has been reduced by a collective 25%, and 5000 homes receive district heat (5). Cooperation of this nature has significantly increased environmental and economic efficiency, and at the same time, has created many less tangible benefits for these industries, involving personnel, equipment, and information sharing (J Christensen, personal communication). Indeed, the very term industrial symbiosis was coined by the power station manager in Kalundborg, meaning "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" (7, p. 42).

Only in the late 1980s did the participants in Kalundborg first recognize the environmental implications of the partnerships and exchanges that had evolved since the early 1970s. Two early references to Kalundborg in the international press appeared in 1990 and 1992 in the *Financial Times*, which began to raise awareness of Kalundborg: one by Peter Knight called "A Rebirth of the Pioneering Spirit" (8) and one by Hilary Barnes called "Fertile Project Exploits Recycled Wastes" (9). One of the Kalundborg participants, Jørgen Christensen, who was plant manager of the Novo Nordisk pharmaceutical plant, gave a paper in 1992 outlining Kalundborg's achievements at the International Industry Conference for Sustainable Development in Rio de Janeiro (9a).

A REVIEW OF RELATED LITERATURE

In any multi-disciplinary field such as industrial ecology, there are strands from many disciplines and paths of research that are the antecedents of current understanding. Although the quantity of literature on industrial symbiosis and eco-industrial parks is quite small (with the exception of documents relating to specific eco-industrial projects), some of the related literature is described here.

To the extent that industrial symbiosis deals with local and regional economies, there is some tie to the environmental economics literature that recognizes the spatial dimension of environmental and resource systems and attempts to model its inputs, outputs, and residuals (10). More directly, there is a significant literature on locational advantages, including Piore & Sabel (11), Krugman (12), and Porter (13), which builds on the body of economic theory that seeks to explain and predict the spatial pattern of the location of economic agents (14). This economics literature has long considered the effect of proximity to major inputs and transportation costs in determining business location decisions and the resulting spatial pattern of development, but has not considered the effect that strategic colocation of facilities with complementary input/output needs can have on locational advantage.

The literature on industrial districts dates back 100 years to economist Alfred Marshall, who examined them to understand Britain's leadership in textile production. A recent doctoral dissertation brought some of these topics together to discuss how industrial colocation and inter-firm networking could lead to significant economies in environmental management related to infrastructure, information flows, and regulatory enforcement, as well as to decreased conflict over land use (15).

In international development, the term industrial estate is used to describe "a large tract of land, sub-divided, and developed for the use of several firms simultaneously, distinguished by its shareable infrastructure and close proximity of firms" (16). The United Nations (U.N.) Environment Programme issued a study in 1997 on environmental management of industrial estates. Although managing industrial estates in an environmentally sound manner is different from industrial symbiosis, this study mentions Kalundborg and describes how industrial estates are excellent places to apply principles of industrial symbiosis because the estates contain diverse industries and can achieve economies of scale (17).

The underlying concept of industrial symbiosis is the metaphor of an industrial ecosystem that mimics a natural ecosystem, which appears early in the industrial ecology literature. In 1989, Frosch & Gallopoulos inspired much of the industrial ecology that was to come when they wrote about "an industrial ecosystem" in which "the consumption of energy and materials is optimized and the effluents of one process ... serve as the raw material for another process" (18, p. 144). The same year Ayres wrote about both the biosphere and the industrial economy "as systems for the transformation of materials" and how studying this "industrial metabolism" could lead to shifts in the direction of increased efficiency in materials flows and waste streams (19). In fact, in the inaugural issue of the *Journal of Industrial Ecology,* editor-in-chief Reid Lifset commented on the symbiotic exchange of materials and the excitement over Kalundborg, but reassured readers that the *Journal* "is not simply about co-located facilities exchanging wastes" (20). A special issue on industrial ecology in the *Journal of Cleaner Production* features an article on the origins of industrial ecology by science journalist Suren Erkman. Erkman tracked back some of the ideas underlying industrial symbiosis to agencies of the U.N. in the 1970s, including papers delivered at a 1976 meeting of the U.N. Economic Commission for Europe on "non-waste technology and production" (21).

With regard to the sustainability literature, researchers of regional socio-economic systems have hypothesized that the transition from unsustainable to sustainable is an evolutionary process most likely to be introduced at the local level. Calling these "islands of sustainability" that are thought, like biological evolution, to move in a process "toward higher rates of circulation of materials within the system, and toward an increase of the total solar energy flux through the system," industrial symbiosis is specifically cited in this literature as on the evolutionary path toward higher diversity and complexity of regional systems (22, 23).

Having become aware of Kalundborg, two Austrian researchers asked the question of whether the systems concept of an "industrial recycling-network" was unique to Kalundborg. They discovered a network with a higher degree of diversity and complexity in the Austrian province of Styria, which benefited the region ecologically and economically. Specifically, they found:

> In 1992, the following aggregated amounts were recycled: 34,000 tons of power plant gypsum, $>$200,000 tons of steel mill slag, $\sim$85,000 tons of blast furnace slag, 28,300 tons of sawdust (fine ground), 15,600 tons of sawdust from uncoated wood, 100,820 tons of recyclable paper and board, 445,000 tons of residual wood, 28,000 tons of bark, 310 tons of waste textiles, 650 tons of shives, 5,500 tons of used tires and tire chips, 4,500 tons of oil coke, 5,400 tons of slaughter house and meat waste, 45,000 tons of spent malt, 3,100 tons of fodder year, 350 tons of rape seed cake, 130,000 tons of nonalloy iron scrap. Also, district heating, fly ash, used oil, halogen-free solvents, whey, plastics, and grape cake were distributed through the network (24).

As the authors commented, both geographic regions developed over time, but while the Kalundborg participants became conscious of the environmental characteristics of their exchanges, the Styrian companies have not been made conscious of the comprehensive networking in regional material flows, and are likely missing out on the benefits of a coordinating function such as exists in Kalundborg, which tries to increase exchange and improve internal and external communication. Another example of an unconscious network is described by Korhonen et al (25) in the city of Jyväskylä, Finland where the energy supply is organized around coproduction of heat and electricity and includes industrial wastes used as fuels in a highly efficient system. As with Kalundborg and Styria, the system arose for economic/regulatory reasons, but was never previously labeled as industrial ecology or industrial symbiosis. Many more such examples are likely to be uncovered and added to the literature, even if they consciously eschew an environmental label.

In several articles researchers have looked at applying a related discipline or tool to specific places where industrial symbiosis could occur. Audra Potts Carr examined the potential to retrofit an existing 107-acre industrial park in Choctaw, Oklahoma, into an eco-industrial park as a new challenge for landscape architects (26). Boyle & Baetz tested the use of a knowledge-based decision support system at an industrial estate in Trinidad. The team used this support system to identify wastes being produced by four industrial plants, specifying both mass and waste characteristics in more detail than had previously been done. From the analysis, recommendations were made regarding waste minimization considering inputs and outputs, as well as waste reuse and recycling (27). Keckler & Allen used a linear programming model to evaluate water reuse scenarios at a large industrial park in Houston, Texas. Through the model, facilities could be added or deleted, water separated or blended, and types of treatment differentiated. The researchers found there to be a number of economically desirable water reuse opportunities (27a).

One book-length treatment is called *Zero Pollution for Industry: Waste Minimization Through Industrial Complexes* (28). Dating back to the 1970s, Nemerow proposed creating an “environmentally balanced industrial complex” that included colocated businesses using each other’s wastes as feedstocks. In addition, there are several fieldbook or “how-to” approaches that synthesize much of the learning from industrial symbiosis, including a Canadian project led by Ray Côté of Dalhousie University in Nova Scotia called “Designing and Operating Industrial Parks as Ecosystems” (29). Around the same time, Ernie Lowe of Indigo Development led the preparation of the *Fieldbook for the Development of Eco-Industrial Parks* prepared for the US Environmental Protection Agency under a cooperative agreement with Research Triangle Institute in North Carolina (30). The Business Council for Sustainable Development of the Gulf of Mexico (BCSD-GM) issued a primer on “by-product synergy” in 1997, a term they use synonymously with “green twinning,” “industrial symbiosis,” “zero waste/zero emissions/100% product operations,” and “cradle-to-cradle eco-efficient manufacturing” (31).

The Zero Emissions Research Initiative’s Gunter Pauli has been involved with promoting multi-industry clusters working through the U.N. University headquartered in Tokyo (32). In 1997, Environment Canada issued *Opportunities for Eco-Industrial Parks in Canada*, which reports on five studies they have done concerning industrial ecology networks in different regions of Canada, as well as a national report (33).

ORIGINS OF US ECO-INDUSTRIAL PARKS

Interest in replicating the Kalundborg model as a means of US sustainable development began in the 1990s. In 1993, a professor from New York University, Holger Engberg, wrote a case study of Kalundborg (7). A 1994 MIT working paper on Kalundborg by Nicholas Gertler and John Ehrenfeld (34) was completed as a master's thesis by Gertler in 1995 (35). The President's Council on Sustainable Development (PCSD) began an eco-industrial park project (using industrial symbiosis and other sustainability concepts) in 1994 and the US Environmental Protection Agency (EPA) announced the availability of $300,000 for eco-industrial park design and development. According to Gertler, this represented "the first national initiative in the US to develop and foster applications of industrial ecology to industrial parks" (36, p. 59).

In 1995, the EPA-funded *Fieldbook for the Development of Eco-Industrial Parks* was drafted (30) and four demonstration projects were named in Chattanooga, Tennessee; Baltimore, Maryland; Brownsville, Texas; and Cape Charles, Virginia. Each site had ongoing development, and the logic was to shape these diverse projects using the vision of industrial symbiosis in the creation of eco-industrial parks. In October of 1996 the PCSD convened a meeting of eco-industrial park practitioners at the groundbreaking of the Port of Cape Charles Sustainable Technologies Industrial Park. The meeting included representatives from 15 proposed eco-industrial projects from around the United States and was organized "because all the communities face significant challenges to move eco-industrial parks from theory into practice" (36, p. 1). Beginning in December 1996, the Work and Environment Initiative at Cornell University's Center for the Environment has maintained a roundtable on eco-industrial development, which includes an excellent website and frequent updates on planned projects (37).

In practice, the notion of eco-industrial parks is still emerging. Even the definition of eco-industrial parks has proven to be elusive, given the early-stage development of the ideas. In general, however, two definitions are often quoted. According to the PCSD, an eco-industrial park is

> "a community of businesses that cooperate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat), leading to economic gains, gains in environmental quality, and equitable enhancement of human resources for the business and local community" (36, p. 1).

According to the EPA *Fieldbook,*

> an eco-industrial park is a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues including energy, water, and materials. By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize if it optimized its individual performance only" (30, p. 2).

Lowe et al (30) encourage a broad view of eco-industrial parks and go on to say, in a briefing and sourcebook on industrial ecology (38), that an eco-industrial park should be more than:

1. A single by-product exchange pattern or network of exchanges

2. A recycling business cluster (resource recovery or recycling companies)
3. A collection of environmental technology companies
4. A collection of companies making green products
5. An industrial park designed around a single environmental theme (i.e. a solar energy driven park)
6. A park with environmentally friendly infrastructure or construction
7. A mixed-use development (industrial, commercial, and residential)

At this early stage, the environment is not served by overly prescriptive determinations of what is and is not an eco-industrial park. The public sector developers of the Cape Charles Sustainable Technology Park, for example, designed common use of solar collectors into their first multi-tenant office building, as well as a water recycling loop and a constructed wetland for storm water runoff, and although there is no materials exchange, it could develop over time. The notion of an eco-industrial park has not taken one shape or form, and is unlikely to, given that each park involves long timeframes, significant capital investment with different risk profiles depending on the capital source, and multiple parties with numerous objectives in diverse cultural settings.

SELECTED ECO-INDUSTRIAL PARK MODELS

To organize further examination of industrial projects with a materials exchange component as suggested by industrial ecology, it is helpful to consider different eco-industrial park models. Chertow, following detailed study of 18 potential eco-industrial parks examined at the Yale School of Forestry and Environmental Studies from 1997 to 1999, proposed a taxonomy of 5 different material exchange types (39). These are discussed here as Types 1–5, listed below:

1. Type 1: through waste exchanges
2. Type 2: within a facility, firm, or organization
3. Type 3: among firms colocated in a defined eco-industrial park
4. Type 4: among local firms that are not colocated
5. Type 5: among firms organized “virtually” across a broader region

By definition, Types 3–5 offer approaches that can readily be identified as industrial symbiosis. Actual projects discussed below represent types 2–5 and are identified in Table 1.

Through Waste Exchanges: Type 1

Many businesses recycle and donate or sell recovered materials through third party brokers and dealers to other organizations. Historically, scrap dealers have organized in this fashion, as have charities such as the Salvation Army. More recently,

TABLE 1 A sampling of twelve industrial symbiosis projects in late planning, implementation, or operational stages

Type 2	EBARA Corporation, Fujisawa, Japan	Late planning stage
	Flow of personal computers at Yale University	Implementation stage
Type 3	Monfort Boys Town, Integrated Biosystem, Suva, Fiji	Operational
	Londonderry Eco-Industrial Park, New Hampshire	Implementation stage
	Riverside Eco-Park, Burlington, Vermont	Implementation stage
	Red Hills EcoPlex, Choctaw County, Mississippi	Implementation stage
	Burnside Industrial Park, Dartmouth, Nova Scotia	Operational
Type 4	Kalundborg, Denmark	Operational
	AES Corporation, Guayama, Puerto Rico	Late planning stage
Type 5	Triangle J Council of Governments, North Carolina	Project completed
	Brownsville, Texas	Late planning, inactive
	By-Product Synergy, Tampico, Mexico	Project completed

municipal recycling programs have become third parties for commercial and residential customers who supply recovered materials that are transported through the municipality to manufacturers such as glass plants and paper mills. This form of exchange is typically one-way and is generally focused at the end-of-life stage.

Waste exchanges formalize trading opportunities by creating hard-copy or online lists of materials one organization would like to dispose of and another organization might need. The scale of trades can be local, regional, national, or global and can involve highly specialized chemicals or even lists of items needed by area charities. The exchanges accomplish various input/output savings on a trade by trade basis, rather than continuously. They feature exchange of materials rather than water or energy.

Type 1 exchanges are not further examined because they are farthest from the definition of industrial symbiosis. These types of exchanges typically involve older, more traditional aspects of the material flow landscape. The role of brokers, however, appears to be in flux, and to the extent that brokers get more involved in creating the conditions for trading, this form of exchange will become increasingly important.

Within a Facility, Firm, or Organization: Type 2

Some kinds of material exchange can occur primarily inside the boundaries of one organization rather than with a collection of outside parties. Large organizations often behave as if they are separate entities and may approximate a multi-firm approach to industrial symbiosis. Significant gains can be made within one organization by considering the entire life cycle of products, processes, and services, including upstream operations such as purchasing and product design.

Approximating this model is a project being implemented by the Ebara Corporation at their Fujisawa plant complex in Fujisawa, Japan. Ebara is a leader in industrial machinery, and the eco-industrial park it is building is based on core technologies Ebara has developed in water purification, sewage treatment, incineration, power generation, and heat recovery. Through a zero emissions approach, they are beginning to integrate these technologies with nearby activities, including those of 700 households built around the commercial facilities (40, 41). One of the technologies Ebara is highlighting is a fluidized bed gasification, combustion, and ash-melting system that converts various wastes and plastic into commercially viable outputs of ammonia, methane, and hydrogen (41a).

A study undertaken at Yale of the flow of personal computers into and out of the University illustrated tracking of a specific intra-organizational flow. Using a materials budgeting approach, the study pointed to many opportunities for identification and recapture of computing equipment. Yale is currently reorganizing operations to facilitate recovery and reuse (42).

Among Firms Colocated in a Defined Eco-Industrial Park: Type 3

In this approach, businesses and other organizations located in the equivalent of an industrial park can exchange energy, water, and materials and can go further to share information and services such as permitting, transportation, and marketing. Type 3 exchanges primarily occur within the defined area of the industrial park, but it is possible to involve other partners "over the fence." The areas can be new developments or retrofits of existing ones.

Monfort Boys Town Integrated Biosystem, Suva, Fiji (43–45) The Fiji project was designed primarily to accommodate spent grain from breweries that would otherwise be discharged into the sea, smothering coral reefs (40). As shown in Figure 3, the brewery waste is brought to the grounds of a school for boys where the rest of this smaller scale industrial symbiosis is undertaken. Applying a process designed through the U. N. University, the system uses the brewery waste as a substrate to grow mushrooms; the mushrooms break down the waste, making it a high-value pig feed; waste generated from the pigs is processed through an anaerobic digester; and the treated waste is piped to fishponds where the nutrient rich water spawns food for four trophic layers of fish. The waste also creates fertile soil for growing vegetables. This sort of project, which mixes agriculture and industry, is known as an integrated bio-system (46).

Londonderry Eco-Industrial Park, New Hampshire The Town of Londonderry assembled a 100-acre parcel near the Manchester, New Hampshire airport specifically to create an eco-industrial park. The project was turned over to a private developer, Sustainable Development and Design, who agreed to purchase the land and follow a set of performance requirements and environmental guidelines and practices. A 720-MW combined-cycle gas power plant built by AES Corporation has been permitted and several other tenants have moved to the eco-industrial

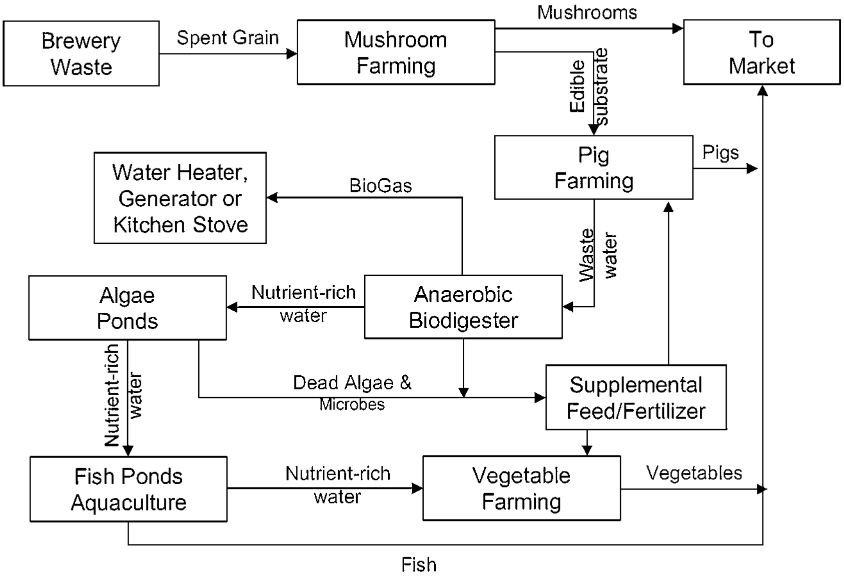

Figure 3 Process flow of the Monfort Boys Town integrated biosystem in Fiji. (Source: Robert Klee, Yale University)

park site. The power plant will use waste water from a nearby sewage treatment plant for use in its cooling towers (47). The Londonderry Eco Industrial Park is being financed with developer equity and conventional bank financing (J Bielagus, personal communication).

Riverside Eco-Park, Burlington, Vermont The waste heat from a 60-MW wood-fired power plant is the link to a series of agricultural activities planned for this project. These activities include food production, greenhouse space, "living machines" for processing organic waste into fertilizer and fish food, community gardens, a Gardener's Supply outlet, and a fish farming facility. The project received a $1 million grant from the Economic Development Administration in 1998 (37).

Red Hills EcoPlex, Choctaw County, Mississippi The core of this project, which broke ground in October 1998, is the construction of a $450 million power plant by Belgium-based Tractebel at the site of a lignite mine in rural Mississippi. Using circulating fluidized-bed technology to reduce sulfur emissions, the 440-MW plant will burn approximately 1.5 million tons of lignite per year. The project, supported by the Energy Division of the Mississippi Department of Economic and Community Development, has a 30-year power purchase agreement with the Tennessee Valley Authority (49). State officials are recruiting additional tenants to participate in a large-scale industrial symbiosis using by-products of the power facilities as feedstocks for new businesses (Energy Div., Miss. Dept. Econ. Community Dev.; 51).

Burnside Industrial Park, Dartmouth, Nova Scotia Burnside is an example of retrofitting an existing industrial park to improve environmental performance. The park is spread over 2,500 acres, with more than 1,200 businesses employing 18,000 people. Researchers from Dalhousie University have designed a project to work within the park "to investigate principles and strategies that would encourage transformation of an existing park into an industrial ecosystem" (52). There are currently only a few instances of materials exchange. A recent study, however, identified scavengers, decomposers, and other third parties that support material cycling functions within the park, raising the analogy of complex food webs and identifying roles taken from the study of ecology (53).

Among Local Firms That Are Not Colocated: Type 4

This type of exchange takes as a starting point what is already in place within an area, linking together existing businesses, with the opportunity to fill in some new ones. Kalundborg is an example of Type 4 exchange, in that the primary partners are not contiguous, but are within about a two-mile radius. Although this area was not planned as an industrial park, the proximity of the companies permitted them to take advantage of already generated material, water, and energy streams.

Kalundborg, Denmark It is important to note that Kalundborg, described above, is not static, but rather a dynamic example of nearby businesses continuing to seek exchanges of different types. Recently, A/S Biotechnical Soil Cleaning became a Kalundborg partner. The company uses municipal sewage sludge as a nutrient in a bioremediation project to decompose pollutants in contaminated soils (54).

AES Corporation, Guayama, Puerto Rico Although not identified as an eco-industrial development, a coal-fired power plant under construction in Guayama, Puerto Rico is involved in several symbiotic relationships. The 454-MW facility will provide electricity to the Puerto Rico Electric Power Authority as well as steam to a petrochemical facility owned by Phillips Petroleum Company (54a). Given that fresh water is often scarce on an island, and the plant requires about five million gallons of water per day, three sources of waste water will be used: treated waste water, agricultural runoff, and treated industrial water from Phillips. The facilities are located within about a mile of each other. The waste water is about one-tenth the cost of back-up well water.

Among Firms Organized Virtually Across a Broader Region: Type 5

Given the high cost of moving and other critical variables that enter into decisions about corporate location, very few businesses will relocate solely to be part of an industrial symbiosis. In recognition of this, the model of Type 5 exchanges depends on virtual linkages rather than on colocation. Although virtual eco-industrial parks are still place-based enterprises, Type 5 exchanges allow the benefits of industrial symbiosis to be expanded to encompass a regional economic community in which the potential for the identification of by-product exchanges is greatly increased owing simply to the number of firms that can be engaged. An additional attractive feature is the potential to include small outlying agricultural and other businesses, possibly by pipeline, as in Kalundborg, or by truck for those farther out. It could be argued that self-organized groups such as the network of scrap metal dealers, agglomerators, and dismantlers who feed particular mills or subsystems such as auto recycling could be considered as Type 5 virtual exchanges (55a). The examples selected below, however, represent a diversity of industries in each Type 5 project.

Triangle J Council of Governments, Research Triangle Park, North Carolina This prototype of the virtual eco-industrial park incorporates a 6-county region of over 3000 square miles in North Carolina, including Raleigh, Durham, and Chapel Hill. From 1997 to 1999, an inventory of business inputs and outputs was conducted, and 182 businesses representing 108 different 4-digit standard industrial classification codes responded to the inventory survey. Based on the results, the project explored potential partnerships for about half of the 182 companies, involving exchanges of 49 different materials. The 12 most probable exchanges involved acetone, carbon, desiccants, hydrochloric acid, methanol, packing materials, plastic bags, sawdust, sodium hydroxide, wood ash, wood chips, and wood fluff. The final project report includes cost saving data on many of the proposed exchanges as well as carbon emission reductions (56). The acetone partnership, for example, was found to save a gem manufacturer $11,000 in treatment and disposal costs per year and save the buyer of the acetone—a plastics company—some $18,000 per year. Reducing mileage for disposal of acetone as well as delivery of new acetone to the plastics company was projected to save nine tons of carbon annually with another five tons of carbon saved in the manufacturing process.

Brownsville, Texas One of the original grants funded by the PCSD, this project advanced the state-of-the-art of virtual parks. Following an inventory of businesses along the Texas/Mexico border in the Brownsville/Matamoros region, the Brownsville Economic Development Council used a proprietary computer model developed by Bechtel Corporation to match inputs and outputs across industries. Not only were potential matches identified, but the project team also used the computer information to develop leads for new businesses that might be attracted to the area based on available waste streams that could become feedstocks for newly recruited companies (57, 58).

By-Product Synergy, Tampico, Mexico The Tampico by-product synergy project refines the process used in Brownsville. The project, conducted from 1997 to 1999 and led by the Business Council for Sustainable Development–Gulf of Mexico (BCSD–GM), gathered together 21 local industries to demonstrate a systematic approach to industrial symbiosis. By bringing together key stakeholders, the input and output inventories were conducted in a timely way through mutual agreement. The Bechtel model was used to identify matches, as were face-to-face meetings with participants. Thirteen synergies became the focus for further investigation chosen, in part, because they had relatively short timeframes for implementation (59). A spin-off company of the BCSD-Gulf Coast, Applied Sustainability, conducted a similar project in Alberta, Canada in 1998 and 1999 with 15 sponsoring companies and identified 25 possible synergistic opportunities among Alberta's natural resource, energy, forest products, and oil sands companies (60).

TOOLS AND APPROACHES

The examination of these 12 sample industrial symbiosis projects representing four material exchange types yields a general understanding of useful tools and approaches. These are discussed below, also drawing on other project examples as appropriate. Three tools described are input-output matching, stakeholder processes, and materials budgeting. Different approaches include the extent to which a project is stream-based or business-based, and whether the eco-industrial park begins with new or existing operations.

Input-Output Matching

The first significant tool is one that helps to match inputs and outputs of various entities that could potentially participate in industrial symbiosis. The Triangle J, Brownsville, and Tampico projects are notable for systematically collecting input and output data of local companies and using the results to make links across industries. A research project at the U. N. University through the Zero Emissions Research Initiative has examined computer aided modeling, design, and optimization of zero emissions industrial clusters (61). In addition to the Bechtel computer model, by 1998, the US EPA had commissioned its own input/output matching models known as FaST (Facility Synergy Tool), DIET (Designing Industrial Ecosystems Tool) and REaLiTy (Regulatory, Economic, and Logistics Tool) (62). These models are planning tools that allow a community to investigate what mix of specific types of industries might support industrial symbiosis.

Developed for the US EPA by Industrial Economics, Inc., FaST is a database of industry profiles describing typical inputs and outputs of specific types of facilities such as a hospital or dairy farm. It also has a data input screen and search mechanism to identify possible input/output matches among facilities. DIET allows scenario analysis of different combinations of facilities. It includes a linear programming optimization model that allows the planner to optimize environmental, economic, or employment objectives and to change the relative weights of each. ReaLiTy helps sort out regulatory hurdles that are likely to be confronted depending upon the actual materials chosen for exchange. A geographic information system component has been used to locate businesses throughout targeted areas. A caveat on these models, however, is that they can overemphasize idealized “what if ” scenarios with little recognition of the time-consuming and frustrating processes involved in attracting any business, let alone the perfect suite of symbiotic partners.

Stakeholder Processes

It would be difficult to underestimate the complexity of developing multi-party relationships where the advantages to each party are not necessarily well understood. Therefore, a broad array of community involvement techniques and methods of achieving “buy-in” from participants is warranted in eco-industrial park projects. The Londonderry project was guided by a representative advisory committee and assembled many diverse potential stakeholders when it held a design charette, organized to seek input on what an eco-industrial park should look like in the local context. Cape Charles, Virginia, had a charette led by William McDonough & Associates and came up with the “Cape Charles Principles” that guided its development. Whether and how to pursue specific covenants and conditions as a type of deed restriction could become the subject of stakeholder meetings, and this topic is taken up in a handbook produced by Cornell University (63). Applied Sustainability has gathered experience convening stakeholders from business and government in its efforts to create by-product synergy in Tampico and Alberta. An economic analysis of the Brownsville project performed by Research Triangle Institute observed that because so much needs to be known about what are often the proprietary practices of companies, “the success of the eco-industrial park requires that members are open to depending on each other” (57, p. 27). Part of the success of Kalundborg has been attributed to “the short mental distance” among stakeholders there (64).

Materials Budgeting

Another tool that could be used more extensively is the materials budget used to map material and energy flows through a chosen system. The example of Styria, Austria, described above, determined the existence of an extensive network by tracking material flows. Formally, in industrial ecology, materials budgets embrace the concepts of reservoirs, where a material is stored; flux, which is the amount of material entering or leaving a reservoir per unit time; and sources and sinks, which are rates of input and loss of specific materials entering or leaving a system (2). In the study of the flow of computers through the Yale industrial ecosystem, a materials budget was developed showing that an estimated 4500 computers entered the university each year (not counting units personally owned by students), yet only 250 were known to be exiting the system through recycling and donations to other organizations. Because materials budgeting requires that each flow be identified and accounted for, and because computers last for several years, most were estimated still to be in use. Based on a user survey, however, a fifth of outdated computers (estimated as high as 1000 units) were thought to have become “closet fill”—neither recycled nor disposed, but tucked away in cubbies and closets throughout the university (42). The materials budget can be a basic building block of an industrial symbiosis analysis.

Stream-Based or Business-Based

Whether companies or material/water/energy streams come first in planning industrial symbiosis is a bit of a chicken or egg situation: on the one hand, there are no flows without companies; on the other hand, neither does a gathering of companies alone assure symbiosis. Some projects, however, are by their nature more business-based; that is, they begin with a developer seeking tenants in the hope that the interested companies will fit the industrial symbiosis or eco-industrial park model. Particularly with a private developer, as in Londonderry, New Hampshire, the developer's top priority is occupancy in order to begin the flow of monthly payments to finance project costs. The stream-based approach, captured in the EPA DIET and FaST models, presents a more idealistic vision of planning an industrial symbiosis from the beginning. Linkages are made based on the flow of specific physical resources through an eco-industrial system. Similarly, the approach pursued in the Type 5 virtual parks is to look for streams across businesses.

The preferred model would combine these two approaches, where businesses are proposed as tenants based on streams. This is the approach being pursued by the Red Hills EcoPlex. The master plan for the project identified primary target industries based on flows, including intensive aquaculture, hydroponic greenhouses, poultry processing, and compressed kenaf fiber panel manufacturing (65).

New or Existing Operations

Another key difference in approach is whether the planned project relies on new or existing elements. The Londonderry project was based on the town's acquisition of a 100-acre greenfield site. This site is adjacent to existing businesses, in particular, Stonyfield Farm, Inc., but relies on new development. Another greenfield site is the Red Hills EcoPlex. These two projects are examples of starting, more or less, from scratch.

Industrial symbiosis, however, need not entail this level of new development. Kalundborg, famously, did not spring from its creator fully formed, but evolved as a series of bilateral linkages over 30 years. The Burnside Industrial Park in Nova Scotia has been in existence for over 25 years. A proposed brownfield project in Dallas is based around a landfill. Mixing new and existing facilities is another way to maximize opportunities from industrial symbiosis.

KEY QUESTIONS

The projects described here illustrate that there is enormous potential for environmental improvement through industrial symbiosis in ways such as increasing energy efficiency through cogeneration and by-product reuse, recycling gray water to achieve overall reduction in drawdowns, recovering solvents, and reusing many, diverse residue streams that need not be rejected as wastes. Other nonmaterial-based linkages such as jointly planning transportation networks, sharing office, information, or security services, or less formal exchanges, may precede industrial symbiosis, laying the groundwork for cooperation, or may follow it, in the case in which early collaboration was based on physical flows. Given these advantages, one might ask why more companies are not engaged in these types of projects.

The Usual Suspects

First of all, there are the usual business reasons industrial symbiosis projects might not be attractive, based on barriers any venture faces: risk, finance, mobility of capital, or the availability of higher pay-back options elsewhere. In general, as Ehrenfeld & Gertler point out, the case for industrial symbiosis is unconvincing when there are not large, continuous process waste streams (64). Reliable research is clearly needed on the basic economics of symbiosis. If energy or water or waste disposal are but a small percentage of operating costs, these reasons alone will not cause the formation of eco-industrial parks. Neither can there be set heuristics about when symbiosis makes sense because of the enormous variability in ecological as well as economic conditions. For example, fresh water could be scarce at one site and abundant at another. As with all environmental projects, particulars are site-specific and the role of regulation is ubiquitous, both in promoting and obstructing progress, and must be carefully considered in nontraditional development projects.

The Question of Scale

A first-order consideration is whether there is sufficient flow of materials to make industrial symbiosis worthwhile. In a project designed from scratch, quantities could be carefully designed to match the required scale. However, this could prove more difficult when working with existing facilities. A project investigated at Yale, which included three steel companies and two chemical companies in reasonable proximity, makes this clear. Together, these firms had significant amounts of metal scrap, some 18 million pounds per year, but it was still an order of magnitude below the tonnage needed to feed a mini-mill. Neither did the types of metal scrap match across the three participating plants. The investigating team recognized that

> existing businesses are limited in the quantity of materials that they can provide to residue processors or purchase from new suppliers. It is questionable whether these transactions will be sufficient as to merit the siting of a new facility . . . If these barriers cannot be overcome, the viability of eco-industrial park development may be dependent upon shrinking the minimum efficient scale of target industries (66, p. 40).

Pollution Prevention versus Industrial Ecology

Industrial symbiosis raises the question of whether the desire to reuse waste streams comes at the expense of adhering to pollution prevention principles calling for the elimination of waste at the front end of the process. The same arguments could be applied to over-supply of water or energy, thus discouraging conservation. Also, do eco-industrial parks favor older, dying industries and keep them going rather than fostering a new generation of clean technology? Overall, industrial symbiosis could potentially discourage companies from updating their systems, plant, and equipment, substituting, instead, the veil of interdependence.

At the first level of analysis, it is reasonable to assume that companies will do what is in their economic interest. If, through incremental improvements or through broader scale process redesign, a company can eliminate waste in a cost-effective manner, then it will. In this sense, pollution prevention comes first. It is plausible, however, that the opportunity for symbiosis might make the proposed process improvement fall lower in priority in a company's capital outlay scheme, in which case the company's own economic decision-making might favor the symbiosis over pollution prevention.

Interestingly, recent experience in Kalundborg reinforces that the needs of the individual companies are of central concern. Over the last several years Kalundborg's Statoil Refinery has doubled its capacity based on North Sea claims, the Asnaes Power Station has switched from coal to a new fuel, orimulsion, for half of its 1500 MW of capacity to comply with mandated CO_2 reduction, and the pharmaceutical plant has eliminated some product lines and increased others. Although each individual business change alters the make-up of the industrial symbiosis, they have not, collectively, diminished the spirit of it. In the case of the gypsum board plant, the changes have made the benefits stronger. Because the power station now burns more sulfur and less carbon, more calcium sulfate is recovered from the flue gas desulfurization system and is available for raw material to make gypsum board. Like most large industrial operators, the pharmaceutical plant management must meet annual continuous improvement goals in many areas, including established percentages for waste reduction (J. Christensen, personal communication).

An industrial ecology perspective offers another cut at the issues raised above. Is waste a waste or an unused raw material? Industrial ecology, by demanding a systems approach, gives due consideration to each step and stage of process development to optimize material and energy flows. In some, or even most cases, reduction of a waste stream may be called for; in others, using a particular stream to feed another business may be optimal, depending on related logistics, economic considerations, and the state of technology. The analytic question is straightforward: which configuration leads to the lowest level of environmental damage at a given level of economic output?

Architect/designer William McDonough and chemist Michael Braungart also question current practice by asking whether eco-efficiency is a viable strategy. Successive 10% reductions, following Zeno's Paradox, never get you to zero, and certainly not to the goal the authors establish of regeneration rather than depletion. McDonough & Braungart make the point that nature itself does not seek efficiency as a goal; for example, plants may spawn thousands of seeds, but only a few germinate. Thus, they refer to nature's bounty not as eco-efficiency but as eco-effectiveness—"highly industrious, astonishingly productive and creative" (67 p. 86). By analogy, it is reasonable to conclude that industrial symbiosis may not appear to be an eco-efficient solution in every case, but it may often be an eco-effective one.

Industrial Symbiosis and Development

A review of the projects discussed above reinforces the critical importance of the private sector in industrial symbiosis. Although private actors need not be the initiators, they clearly must be committed to the implementation of industrial symbiosis because, in most instances, the industrial symbiosis flows either belong to private actors or will be shared with them in the case of municipal wastewater linkages. This is where the perseverance of "business as usual" presents a significant barrier. Many of the costs and benefits of industrial symbiosis fall first to private actors and then to the community at large. Whether the private actors can appropriate sufficient benefit from environmental gains is a challenge to industrial symbiosis. As a practical matter, all significant development projects take a long time and a lot of effort. This is compounded with eco-industrial park projects by the need for multi-party planning and coordination and the attendant transaction costs. Indeed, even explaining industrial symbiosis—the educational component—is arduous because industrial symbiosis is not business as usual, and requires a significant change to dominant, rugged individualist mental models.

WHERE DO WE GO FROM HERE: Three Evolutionary Approaches

Two key elements of sustainability are cooperation and perseverance. Currently, interest in eco-industrial parks is running high, from industrial clusters of brewers and cement manufacturers in Japan (68) to government planning in the Philippines (69), to sustained Canadian emphasis (33) and global curiosity. To date, however, few eco-industrial parks have broken ground. The most significant conclusion of this review of industrial symbiosis projects reinforces what was experienced in Kalundborg: cooperation develops over time. It can possibly be sped up through information sharing and effective stakeholder processes, but it cannot happen all at once. Therefore, evolutionary approaches are key, and three emerged from this research. Sometimes overlapping, they are presented here to offer ways to propel industrial symbiosis forward.

Approach One

Great promise lies in projects where some type of material or energy exchange already exists. Often called “green twinning,” or “by-product synergy,” it is much easier to identify and implement one exchange, such as cogeneration in the Londonderry project, and then use it to springboard other exchanges. Indeed, there are hundreds, if not thousands, of instances of green twinning in the United States alone, enough to convince many business leaders that this is not novel or risky, but a proven means of maximizing productivity. Each can be viewed as the initial stage of broader industrial symbiosis. The first by-product synergy project of the BCSD–GM was to work with Chaparral Steel and its related company, Texas Industries, which resulted in a new patented process to add slag from the steel plant to the raw material cement mix of Texas Industries (70). As a result, cement production has increased 10% and energy consumption has dropped more than 10%. The value of the slag increased 20 times over the previous market price offered by road contractors, and landfill costs have dropped significantly. Moreover, the twinning has led to additional by-product reuse including baghouse dust and automobile shredder residue.

Approach Two

Alternatively, pre-existing organizational relationships and networks can be the beginning of industrial symbiosis. In Kalundborg, companies became partners to meet a common need to find a surface water source. From this relationship, other symbiotic ideas emerged. The Tampico project relied on an existing industry association in the Tampico–Ciudad Madero–Altamira region that already included 18 of the 21 businesses choosing to participate in the demonstration project there. The report notes that the project was able to take advantage of the association’s structure and relationships (59). Sustainable Boston is working to develop industrial symbiosis concepts with well-established community agencies such as the Asian Community Development Corporation and the Medical Academic and Scientific Community Organization, which represents Boston’s extensive hospital/medical network.

Approach Three

A third evolutionary approach has been dubbed “the anchor tenant model.” Just as shopping malls are built around several large department stores that anchor the commercial development within, one or two large industries can provide the same critical mass for an eco-industrial park. Power plants are the anchors for many proposed projects, including the Red Hills EcoPlex and the Londonderry project. This concept is very important, given the restructuring in the electricity industry, because every new power plant could become the anchor tenant of a surrounding eco-industrial park (71). A resource recovery plant was the proposed anchor of an inter-industry collaboration in Arecibo, Puerto Rico (55). An existing nuclear plant anchors the Bruce Energy Centre in Tiverton, Ontario, which incorporates six additional companies to take advantage of waste heat and steam generation from the plant. The companies include a hydroponic greenhouse company, a food processor, and a manufacturer of commercial alcohols (72).

THE FUTURE

As eco-industrial parks move from planning to implementation, learning will greatly increase. Much variety and experimentation will shed light on what works and what doesn't, what the largest risks are, how regulatory hurdles can be overcome, what can be financed, and what is most environmentally beneficial. On the one hand, the form could splinter into specific industry clusters around key materials such as plastics or around wastes and recycling as in the Cabazon Resource Recovery Park in southern California begun by the Cabazon Band of Mission Indians (73). On the other hand, broader visions could prevail that combine eco-industrial parks with new urbanism trends in residential development such as at Mesa del Sol, New Mexico, or Coffee Creek, Indiana. The Japanese Central Government and the Ministry of Trade and Industry have designated several "eco-towns" to promote environmentally friendly practices such as zero-emissions and material exchanges (41a).

Conceivably, the private sector could grab hold of industrial symbiosis as a logical extension of resource productivity. Governments could latch onto eco-industrial parks as another way to redevelop brownfields. The roles of various public and private actors will sort themselves out over time. Of course, industrial symbiosis could also go in directions not now discernable. Over the past 30 years it has become unthinkable to pollute openly and aggressively in many parts of the world. Perhaps 30 years from now it will be just as unthinkable to use a resource only once or to overlook an opportunity for mutually beneficial symbiosis.

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