Organizing Self-Organizing Systems

Toward a Theory of Industrial Symbiosis

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Summary

Industrial symbiosis examines cooperative management of resource flows through networks of businesses known in the literature as industrial ecosystems. These industrial ecosystems have previously been portrayed as having characteristics of complex adaptive systems, but with insufficient attention to the internal and external phenomena describing their genesis. Drawing on biological, ecological, organizational, and systems theory, a discontinuous three-stage model of industrial symbiosis is presented. The model proceeds from a random formative stage involving numerous actors engaging in material and energy exchanges, to conscious recognition and intentional pursuit of network benefits, to institutionalization of beliefs and norms enabling successful collaborative behavior. While there is much variation, with no single path to this outcome, the recognition of benefits is seen as an emergent property characteristic of these self-organized systems that move beyond the initial stage.

Introduction

Industrial symbiosis examines cooperative management and exchange of resource flows—particularly materials, water, and energy—through clusters of companies. Curiously, even as businesses have become increasingly attentive to the price and availability of these resources, the notion of interfirm coordination and management remains underdeveloped and collaborative opportunities are continually overlooked. This article sets out to move closer to a theory of industrial symbiosis by examining the emergence and development of what have been called, alternatively, industrial ecosystems or industrial networks,[1] drawing on a mix of biology and ecology, complex systems theory, and organizational theory. While describing several other models of industrial symbiosis toward the end of the article, the purpose of this effort is to bring together a clearer and more widely shared understanding of self-organizing industrial symbiosis as a type of mutually beneficial interfirm cooperation characterized within a complex adaptive framework.

Background

The underlying concept of industrial symbiosis is that one company's waste can become another company's feedstock (Frosch and Gallopoulos 1989). Having examined more than 60 instances of industrial symbiosis networks (Chertow and Portlock 2002; Curtin University of Technology 2007; and Table 1), we have come to use the term industrial symbiosis in two ways: (1) as the broad name for the branch of industrial ecology that seeks to understand the development and functioning of interfirm resource exchanges, and (2) as an inclusive descriptor for all arrangements where enterprises exchange outputs that, in the absence of a customer, would normally be discharged to

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Table 1 Ten examples of well-studied industrial ecosystems with some self-organizing properties categorized by spatial scale.

	Name of symbiosis	Typical facilities involved	Materials involved	Institutionalization	Stage of development
Primarily organized within a community					
1	Kalundborg, Denmark	Coal-fired power plant, pharmaceuticals, gypsum board, oil refining, fish farming	Water, wastewater, sulfur, steam, sludge, fly ash, yeast and organic residuals	Symbiosis Institute	Embeddedness, Stage 3
2	Guayama, Puerto Rico	Coal-fired power plant, chemical refining, pharmaceuticals	Wastewater, condensate, steam, ash	Wastewater Advisory Council	Embeddedness, Stage 3
3	Campbell Industrial Park, Hawaii	Coal-fired power plant, oil refining, cement, water reclamation, recycling	Wastewater, waste oil, steam, ash, shredded tires, activated carbon	Informal	Uncovering, Stage 2
4	Shenzhen Huaqiang Holdings Ltd. (formerly Guitang Group), China	Sugar refining, alcohol, pulp and paper mill, cement, alkali recovery, agriculture	Sludge, alcohol, fertilizer, alkali	Private owners of facility	Embeddedness, Stage 3
5	Ulsan, Korea	Oil, chemicals, incineration, metal processing, paper mill	Wastewater, biogas, steam, metal	The Korean Industrial Complex Corporation (KICOX)	Sprouting, Stage 1
Primarily organized within a broader regional area					
6	Kwinana, Australia	Coal-fired power plant, chemicals, fertilizer producers, cement, construction, oil refining	Organic waste, sludge, acid, ash, dust, chemical catalysts, organic waste, energy production	Kwinana Industrial Council, Centre for Sustainable Resource Processing (CSRP)	Embeddedness, Stage 3
7	Styria, Austria	Sawmills, mining, textiles, chemicals, power plant, board industry, plastic production, ceramic industry, cement plant, material dealers, iron manufacturing, agriculture associations	Ash, plastics, sludge, iron scrap, wood and paper, heat, petrol coke, slag, dust, oil	Karl-Franzens-Universität Graz Partnership	Embeddedness, Stage 3
8	Tianjin Economic Development Area, China	Pharmaceuticals, food and beverages, electronics, machinery, others	Water, metals, chemical substances, ash, slag, organic residues	Tianjin Economic Development Area Environmental Protection Bureau	Uncovering/embeddedness, Stage 2/3
9	Rotterdam Harbor, The Netherlands	Chemicals, cement, oil refining, incinerator	Heat, energy	Rotterdam INES	Embeddedness, Stage 3
10	UK Industrial Areas	Coal-fired power plant, oil refining, plastic, rubber, plastic recycling, paper mill, chemicals, food and fish processing, metals, furniture	Steam, electricity, technology, waste carpets, fuels, edible oil, electronic waste	National Industrial Symbiosis Programme (NISP)	Sprouting/uncovering, Stage 1/2

the environment and hence become treated as environmental externalities. These resources include reused water, recovered energy, and material by-products—categories often called wastes (as in wastewater, waste heat, or solid waste).

By-products can be difficult to define distinctively. Some are used directly in the manufacture of other products. A familiar example is the interchange of chemical species coming from petrochemical and refining operations to other processes. The petrochemical industry relies on such interchanges. Others are organized or converted by a "middleman" or intermediate process to useful (i.e., valuable) materials. The intermediaries range from the ancient ragpicker to the modern recycling broker.

Implicit in this description is that the overall life cycle impact of the type of by-product reuse discussed here is positive, thus necessarily excluding instances where reuse of by-products is worse than disposing of them.

Looking to science, industrial symbiosis reflects the notion of biological symbiotic relationships in nature in which at least two otherwise unrelated species exchange materials, energy, or information (Miller 1994). When symbiosis benefits both species, it is called mutualism. An example from nonhuman species is the body of lichen formed of both alga and fungus. The fungus provides a habitat for the alga and protects it against extreme temperatures, and the alga prepares food through photosynthesis and delivers it to the fungus. Mutualism is further described by ecologist Thomas Burns as

> one of the most important relationships that may obtain between two living entities. This does not mean that mutualism occurs, as a local relationship, more frequently than other relationships. Rather, where and when mutualism does occur, there exists the potential for positive feedback leading to the growth and development of new ecological structures (Burns 1993, 248).

This dynamic observation of mutualism in an ecological framework parallels the modern understanding of ecosystem dynamics broadly, replacing a simpler, more linear, "steady-state" view with a more complex one including the role of exogenous forces such as fluctuation and disturbance as integral parts of determining ecosystem outcomes (McCann 2000; Oliver and Larson 1996; Ruth 1996). Such thinking has led ecologists to the generally accepted conclusion that ecosystems are, in the words of Simon Levin (1998, 431), "prototypical examples of complex adaptive systems."

Turning to the anthropogenic analog, figures 1a, 1b, and 2 illustrate three examples of industrial symbiosis. Figure 1a portrays a small section of a very large industrial area in Tianjin, China, where several public and private organizations have come together to turn by-products from power generation, pharmaceutical, and other nearby industrial operations into soil and soil amendments for landscaping what was previously a salt flat (Shi et al. 2010). Figure 1b involves symbiotic exchange of wastewater, energy, and materials supporting an industrial park in Guayama, Puerto Rico (Chertow and Lombardi 2005). Figure 2 shows the multi-industry example of Kalundborg, Denmark. Not only was the term "industrial symbiosis" coined there in 1989, but knowledge of the Kalundborg system has become foundational to industrial ecology. High levels of environmental and economic efficiency by the participants have been achieved through an evolutionary process that began more than 40 years ago with the chronology shown in figure 2 (Chertow 2009; Ehrenfeld and Chertow 2002; Engberg 1993; Gertler 1995; Jacobsen and Anderberg 2005; Symbiosis Institute, 2011).[2]

While mutualism is described above as leading to new ecological structures in the context of biological symbiosis, we argue that, in the context of industrial symbiosis, mutualism can also be seen to lead to new economic structures—reconfigured relationships among economic actors enabling new interactions. In one example, Jacobsen (2006) carefully studied the reorganization in Kalundborg over time of numerous individual water systems to a common resource pool. For one actor, the coal-fired power station, industrial symbiosis enabled the plant "to replace groundwater with surface water, surface water with cooling water, and cooling water with wastewater" (Jacobsen 2006, 244). In addition to natural resources such as water, companies also became willing to share other assets for mutual benefits, such as personnel, equipment, and information.

In a broader view, the system of exchanges described as industrial symbiosis converts negative environmental externalities in the form of waste that used to be discarded into positive environmental externalities such as the spillover benefits of decreased pollution and reduced need for raw material imports. Still, these processes may not be visible to the public until well after many exchanges have been instituted (Chertow 2007; Ehrenfeld and Gertler 1997). Until that time neither the collective nor the environmental benefits are fully appreciated.

Shortly after Levin (1998) identified ecosystems as complex and adaptive, ecologist James Kay (2002) described "an ecosystem approach for industrial ecology" and challenged industrial ecologists to examine arguments from the study of complexity and self-organization to understand industrial systems. In addition to the changing ecological and economic structures described above, Boons (2008) found that new or reconfigured institutional structures are also observed as part of industrial symbiosis, as in the example of the Rotterdam Harbour and Industrial Complex. Following Kay, it was explicitly observed that industrial ecosystems, with their dependence on market forces, are subject to rapid, nonlinear, and discontinuous changes in direction and so it was suggested that they, too, share characteristics of complex adaptive systems (Chertow 2009; Spiegelman 2003). That notion is further explored here.

Overall the theory of complex adaptive systems, categorized as special cases of complex systems, and ultimately of systems theory, has been one of the most influential ideas of the 20th century in many disciplinary fields (Johnson 2001). Myriad social scientists, inspired by biology, have broadly applied lessons from the theory of complex adaptive systems to enrich social theory, organizational development, political economy, economics, and business (Axelrod and Cohen 2000; Beinhocker 2006; Brown and Eisenhardt 1997; Buckley 1967; Sawyer 2005).

A further examination of complex adaptive systems reveals the fundamental characteristic of self-organization as a significant theoretical strand. Self-organization is a process by which systems of diverse component entities form stable structures with many interactive links that pass energy, material, and information across their various nodal points. An observer might attribute some purpose to the arrangement, but self-organizing systems form without any overarching intention or teleology (see figure 3). As discussed by Boons (2008) with respect to self-organization in industrial ecology, the structures, or organizations, emerge as a result of local interactions between system elements.

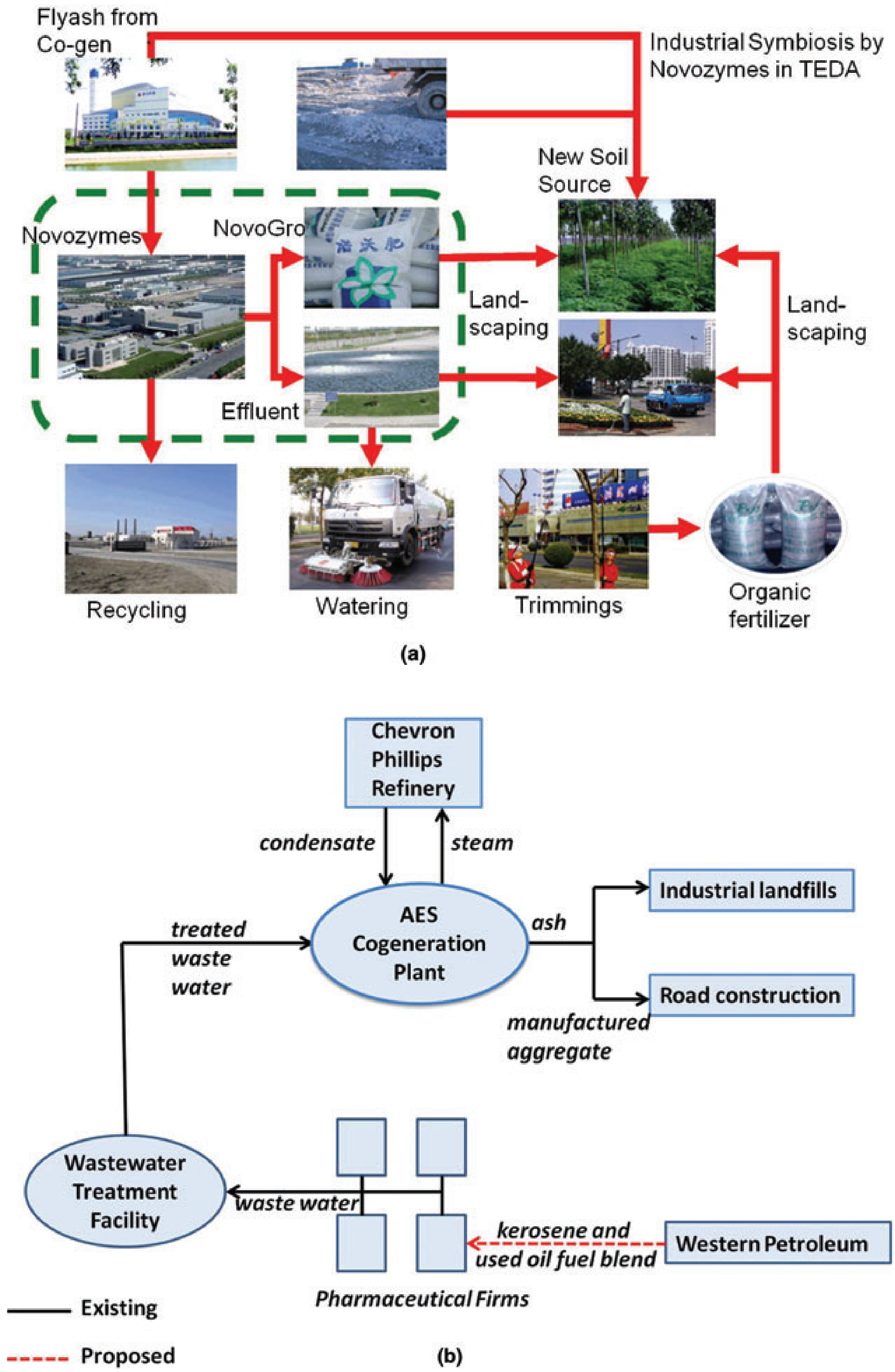

Figure 1 Two examples of industrial symbiosis across firms. (a) Creating landscaping materials through interfirm symbiotic exchange in Tianjin, China—2009. TEDA = Tianjin Economic-Technological Development Area. Source: H. Shi. Used with permission. (b) Symbiosis in Guayama, Puerto Rico, anchored by a coal-fired power plant—2008.

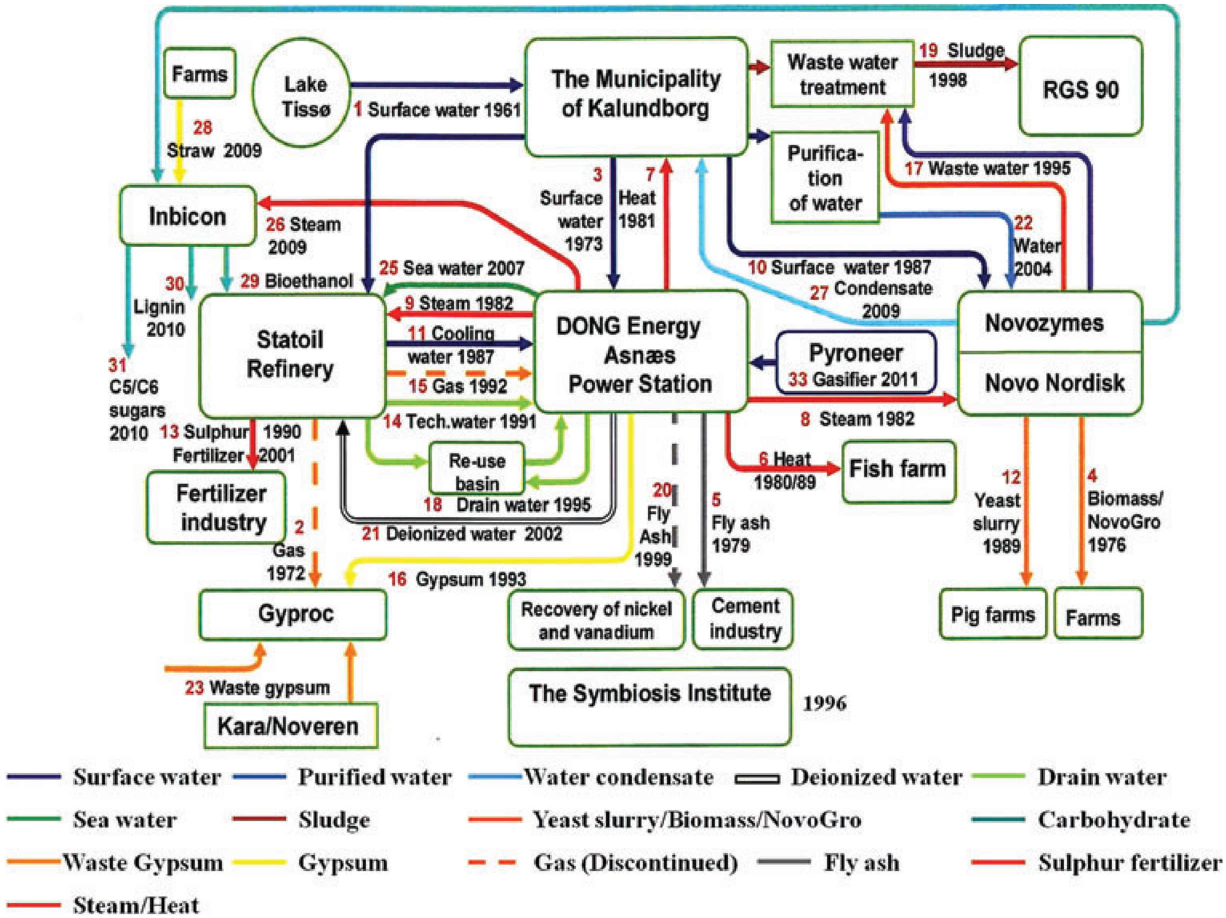

Figure 2 The Kalundborg industrial symbiosis. Actors and exchanges of materials and energy. Exchanges are numbered from 1 to 33 and the years shown indicate when an exchange began. Discontinued links are shown as dotted lines. Modified from http://www.symbiosis.dk/en/system.

Many biotic systems, from cells to ecosystems, and physical phenomena, such as crystals, self-organize, increasing in order and complexity as they grow and use available energy to reconfigure and develop new structures (Kay 2002; Spiegelman 2003). Similarly, human constructs can be self-organizing; markets, for example, have been seen in this way since Adam Smith's notion of "the invisible hand." Self-organization may also occur within individual enterprises or units; one type that has become well known in the business literature engages employees in nonhierarchical relationships managing themselves in what are often called "learning organizations" (Coleman 1999; Wheatley 2000). Elinor Ostrom has made self-organization a centerpiece not only of her work on common-pool resources such as fisheries and irrigation systems, but this work "is part of a broader effort to develop an empirically supported theory of self-organizing and self-governing forms of collective action" (Ostrom 2003). This article proceeds in a similar spirit.

Complex Systems and Industrial Symbiosis

The early contribution of Kalundborg directly or indirectly influenced widespread activity that advanced the development of industrial ecosystems in locations ranging from a mineral processing area in western Australia (Van Beers et al. 2007) to a seven-year study of Puerto Rico (Ashton 2008, 2009; Chertow et al. 2008; Deschenes and Chertow 2004), to the creation of large demonstration projects by the National Development and Reform Commission in China (Shi et al. 2010), to the idea of retrofitting heavy industrial parks in South Korea (Park and Won 2007), to the comprehensive program that began in the United Kingdom under the banner of the National Industrial Symbiosis Programme in 2005 (NISP 2011).

In the United States, the President's Council for Sustainable Development (PCSD 1997) in 1996 put its imprimatur on 16 projects of different types labeled as "eco-industrial parks"—most were planned but did not come to fruition. With time to reflect, the failure of most of these projects has been analyzed (Chertow 2007; Gibbs and Deutz 2007), leading to the conclusion that, translated into the language of complexity theory, the most robust industrial ecosystems more closely follow the model of complex adaptive systems rather than a centrally planned, conscious development model that attempts to predetermine industrial park tenants and, in so doing, places by-product reuse

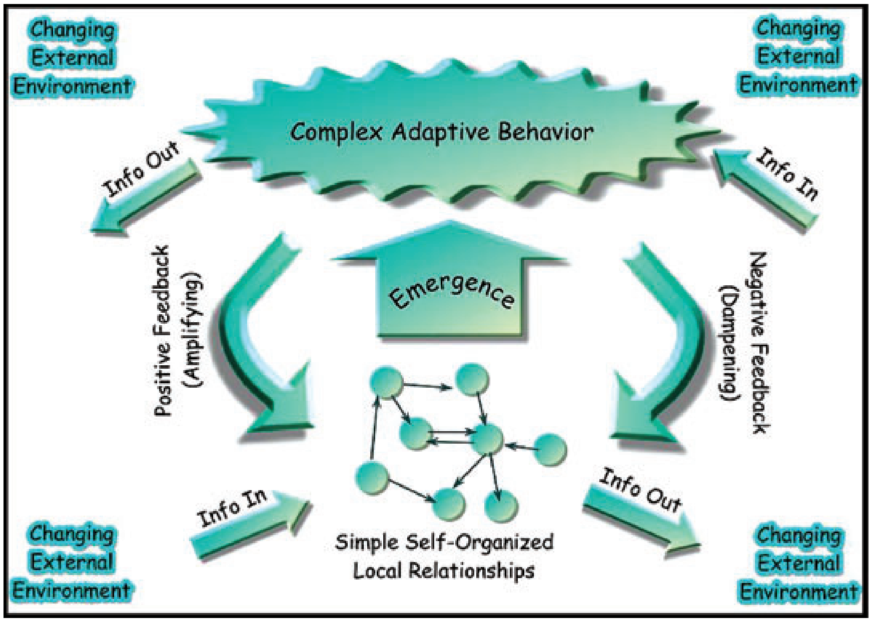

Figure 3 Generic model of a complex adaptive system. Identifies characteristics of self-organization, the interactions of multiple agents, feedback, and emergence of complex behaviors. Source: http://en.wikipedia.org/wiki/File:Complex-adaptive-system.jpg by David Calvin Andrus © Wikipedia Commons, Creative Commons ShareAlike 3.0.

as a far higher business priority than it seems to merit economically (Chertow 2009).

Nor is this conclusion surprising. While natural ecosystems are highly efficacious in converting the embodied material and energy of one organism's waste into another organism's feedstock, they evolve in a Darwinian fashion without any deliberate plan. Economic systems, alternatively, evolve only after communication links are formed among the actors in the network; that is, a social network connecting individual people is always present in an industrial network alongside the network of material and financial flows. While such networks can be formed under some institutional aegis, they more frequently arise spontaneously, often involving such informal channels as family ties or community and civic organizations. In seeking to build a theory for the evolution of industrial symbiosis, this finding is very significant.

Consequently, the progression of this article is to elucidate the dynamics of industrial ecosystems from which the simpler activities of the agents—the enterprises and managers in a given geographical area—self-organize. Generally, complex adaptive behavior emerges that is iteratively shaped by positive and negative feedback loops from within the system as well as by constant changes in the external environment (figure 3). In select cases, positive environmental externalities also emerge and become visible through feedback to the broader group of system actors. Discerning the emergence of these benefits and capturing them more routinely becomes a conscious goal of the industrial network as actors become embedded in the system and their beliefs become institutionalized. We argue that one of the most distinctive elements of industrial symbiosis is that, while all industrial actors seek to reduce private costs and increase private benefits, those in the symbiotic networks that have been studied also participate in the creation of public environmental benefits. A three-stage model, then, is hypothesized along the lines of what sociologist Robert Merton defined as "theories of the middle range" that mediate "between gross empiricism and grand speculative doctrines" (Merton 1968, 1994).

Theoretical Possibilities

We do not yet have enough knowledge about industrial ecosystems to understand fully their life cycles and the categories into which they fall. Yet, what we are proposing moves beyond the biological notion of mutually beneficial exchange by two organisms toward network configurations involving many more. Specifically, the model we offer here applies to nascent or established industrial ecosystems we have observed, such as those identified in Table 1, that share the following aspects:

- Spatial configurations ranging from very local to broad regional groupings (Schwartz and Steininger 1997).
- Temporally, exchange patterns that take from years to decades to evolve to maturity (Chertow 2000; Gertler 1995; Van Berkel 2007; Zhu et al. 2007).
- Resource sharing across firms, including material, water, and/or energy, and may also include service sharing, information, and other coordination activities (Cohen-Rosenthal 2000).
- Those symbioses built around "anchor tenants" producing large, relatively constant flows of by-products, for example, in agriculture, energy generation, chemicals, or brewing (Ehrenfeld and Gertler 1997).

- Firm actors, themselves, instigating cooperative exchange activity in a self-organizing fashion rather than through a preprogrammed process, even if the actors' purpose is to seek private benefits such as reduced costs or increased revenues rather than specifically to reduce environmental damage (Chertow 2007; Ehrenfeld and Gertler 1997; Gibbs and Deutz 2007).
- While there is no agreement on the total number of firms constituting a symbiosis, a minimum of at least three different entities, not primarily engaged in recycling-oriented businesses, exchanging at least two different resources is required to reflect the network elements. This "3–2 heuristic" emphasizes the need to deal with multiple actors in a complex system rather than a series of one-way transactions (Chertow 2007).

A review of the industrial symbiosis literature and the processes that guide economic behavior, complex systems, and network formation and dynamics suggests several possible foundations for developing a comprehensive theory drawing upon work by three research teams. Schwartz and Steininger (1997) were the first to focus attention on the conscious and unconscious aspects of Kalundborg and describe it in a systematic way through reference to their disciplinary backgrounds in economics and their own experience in the industrial state of Styria in Austria. Baas and Boons, working principally from a large-scale planned symbiosis in Rotterdam Harbour, evinced many social science insights from the industrial ecosystem in a series of articles published over 10 years. Our own writing (Chertow and Ehrenfeld) has spanned a broad interest in the biological analogy of industrial ecology, complex adaptive theory, and business dynamics. A three-stage model drawing on these sources is summarized below:

1. **Sprouting.** Firms begin to exchange resources on a random basis for a variety of reasons. A limited network of interlinked flows takes shape (Schwartz and Steininger 1997). Chertow (2007) refers to the initial exchanges as "kernels" of industrial symbiosis that face a market test and, even when successful, may or may not lead to further exchange activity. Schwartz and Steininger add the argument that the positive network externalities created may change decision analysis in firms such that new exchanges become desirable. Up to this stage, standard market-driven industrial organizational theories apply.
2. **Uncovering.** The realization that some networks have created positive environmental externalities becomes consciously revealed or "uncovered," typically through the observations of an actor whose focus is beyond the private transactional network (Chertow 2007). Baas and Boons (2004) associate this stage with regional learning where both goals and range of membership broaden.
3. **Embeddedness and institutionalization**. In addition to self-organization, further expansion of the network becomes intentionally driven by an institutional entity created at an earlier stage that becomes more deeply established during this stage. As for how long this might last, we have evidence that industrial symbioses can persist over many decades, as is the case of Kalundborg, Denmark, and Kwinana, Australia, but still little information about the collapse of industrial ecosystems.

Although the boundaries between the stages may be fuzzy in practice, we have expanded this three-stage complex adaptive system model below with the understanding that the stages are discontinuous, the progress across them is nonlinear and cannot be predicted, and that as a result, there are many more examples of Stage 1 assemblages than Stage 2 or Stage 3 systems.

Stage 1: Sprouting

During this stage, a few linkages form, but the system is relatively disordered with respect to the flows of materials and energy back into trade rather than into waste disposal sinks in the broader environment. There is nothing particular about these early events that may be visible to an observer, rather, they are indistinct relative to the background at this point. These linkages occur for many reasons, including economic efficiency (Baas and Boons 2004), response to regulatory pressure, social relationships, resource security, rising cost of waste disposal, and so forth. In most cases these linkages come and go just as traditional trade linkages rise and fall along the supply chains of firms, even if they are ones that produce public goods benefits to the environment, since that happens without notice or intent. We do not need a novel theory to explain this phenomenon.

Indeed, that there are positive externalities associated with the colocation of businesses has its own name, *agglomeration economies*. Based on his studies of English textile districts in the late 1800s, economist Alfred Marshall (1890) attributed these economies to three main sources, as summarized by economist Paul Krugman (1991). These positive externalities are the presence of a large and concentrated pool of firms and skilled workers (labor pooling), the availability of industry-specific inputs at lower costs resulting from supplier economies of scale (input sharing), and the opportunities for information exchange essential to the innovation process (knowledge spillovers). In a more modern context, similar positive externalities have been noted in the high-tech industries of Silicon Valley. Importantly, agglomeration theory to date has not incorporated environmental benefits such as resource sharing to any substantial degree, and these are only loosely acknowledged in the agglomeration literature (Duranton and Puga 2003; Enright 2003; Feser 2002; Parr 2002). An earlier article describes how industrial symbiosis can be seen to enhance the theory of agglomeration economies by expanding its scope to include these parallel environmental benefits (Chertow et al. 2008).

From a local or regional perspective, industries exhibit dynamic patterns over time, with new firms appearing and older ones dropping out or being merged into others (Hannan and Freeman 1977). Firms are interconnected via pursuit of new market opportunities, supply chains and product distribution networks, and product disposal activities. By-product exchange, to an outside observer, may not be distinct from other supply chain activities, as they are all recognizable as forms of material exchange. We make the distinction here only to maintain focus on industrial symbiosis. Decisions to create any of these interfirm links are based on whether the new arrangement is expected to produce sufficient gain for the firm, and there is no fundamental economic distinction among these three types of linkages, as they all contribute to the bottom line, but they are generally handled quite differently within the firm (Porter 1980).

New market opportunities, that is, attention to market share, tend to be the paramount interests attracting the attention of the most senior management. Next in line come opportunities for cost-cutting improvements in the supply chain. While top management may get involved, these opportunities are usually handled by middle managers within the manufacturing divisions of the organization. The third area, disposal activities, are generally delegated to a lower level within the firm's formal organization, as wastes traditionally carry a negative image among higher-level managers; out of sight is out of mind. We have, however, begun to see firms push by-product issues higher up in the management hierarchy, as the message that waste equates to inefficiency or lost opportunity has reemerged in the business literature (Esty and Winston 2006; Hawken 1993; Porter and Van der Linde 1995).

For resource exchanges among firms to be sustained, total private benefits must exceed total private costs. In the case of industrial symbiosis, this becomes a multifirm collective action problem in which all parties involved in the collaborative network must achieve positive net private benefits (Boons and Janssen 2005). As long as this balance is maintained, firms will be indifferent as to whether they make purchases from conventional suppliers or from neighboring firms. Purchase price alone, however, is not decisive without consideration of the transaction costs that must be added to the production costs. Several types of transaction costs come into play when considering industrial symbiosis:

- search costs (costs of locating information about opportunities for exchange),
- negotiation costs (costs of negotiating the terms of the exchange), and
- enforcement costs (costs of enforcing the contract).

Of these, search costs are most immediate in the early stages of developing resource exchanges. Identification of potential partners is usually expensive in the absence of frameworks designed specifically to minimize this cost factor. Waste exchanges (institutions that post information about available wastes and facilitate trade among firms) and other by-product databases can reduce search costs sufficiently such that two firms find it beneficial to enter into a transaction (Kincaid and Overcash 2001). While such systems may lead to occasional cooperative exchanges, however, they do not provide sufficient information to ensure the development of robust networks. Thus, given the generally high cost of transactions—finding technically compatible streams, and creating and enforcing a system of contracts outside of the normal purchasing regime—networks developed in this way are not likely to grow beyond a few pairs of resource-exchanging entities.

These transaction costs, however, can be small in comparison to costs created by sufficiently stringent regulatory requirements to reduce various forms of pollution. Without invoking additional theory, this factor alone could explain the growth of eco-industrial networks where mutual benefits accrue to a much larger set of firms following the imposition of regulations. However, we also see the emergence of symbioses in places where regulatory regimes are weak or absent. Nonregulatory stimuli played key roles in the symbioses in Honolulu, Hawaii (Chertow and Miyata 2011), and Kwinana, Australia (van Beers et al. 2007). As with the early partnerships in Kalundborg, scarce water supplies led firms in Kwinana to seek cooperative arrangements, while the high price of coal was a driver in Hawaii.

In all cases, a series of dyadic relationships among simple actors, even if each linkage successfully reduces private costs, cannot explain nor does experience suggest it will often become industrial symbiosis. Certainly the number of linkages is not distinctive. Indeed, it is well known that many firms link materials and energy between them, yet very few of these kernels of symbiosis become part of active industrial symbiosis networks.

Stage 2: Uncovering

Stage 2 would not exist unless some of the structures forming and unforming in Stage 1 arose sufficiently so as to be distinct to develop in a more orderly fashion. Such emergent behavior eventually becomes visible to an observer gazing down at the system. We have also seen that many business clusters exchanging materials and energy for mutual economic benefit can produce positive environmental externalities relative to the social costs of practices that involve discarding waste directly into the environment, thus causing the negative effects of waste disposal and pollution. Two firms can accomplish this together through linked resource exchanges that reduce such negative externalities. To the extent that additional firms join the network and further reduce preexisting negative externalities, the public benefits will be greater. At some point the system begins to produce the positive environmental externalities discussed, which serve two functions. They enable the system to remain in stasis by preventing the deterioration of the milieu and the factors of production. When these externalities become known to the actors, they carry a value that can be used to provide stability and even growth. Interestingly, however, such positive externalities or public goods may not be noticed for a long time, or, if they are, the parties to the transactions may not take them into account in maintaining the network, its logic, and its linkages. This was the case in both Kalundborg, Denmark, and Styria, Austria, for many years. While such networks can develop initially based on a variety of incidental factors as described in Stage 1, any net public benefits created are, by definition, an indirect result—or external to—these transactions between the firms. Even though the production of unobserved positive environmental externalities increases public benefits, we argue that it is only after these benefits are recognized, enter the public consciousness, and result in further steps to ensure their continued production that the activities of the business cluster generating them can be classified as a distinct environmental phenomenon. In this way, a standard industrial park could be considered to be an eco-industrial park upon public recognition of the environmental benefits and the subsequent organization of further activities to pursue more such benefits.

It is important to treat the initial bilateral pairs differently from later exchanges in which norms and beliefs are being shared, a more cooperative culture begins to develop, and the notion of value starts to broaden when considering environmental actions. Assume, for example, that the first few firms come to recognize that the positive environmental externalities being created amount to net public benefits at the same time they are saving private costs. If this information remains private, nothing exceptional will ensue and the process will continue as long as it is rational for participants of each exchange.

If, however, the net benefits become known to and are voiced by some advocate in the public sphere, and "stick" in the form of an incipient institution, then further institutionalization can lead to additions to the network beyond those first few exchanges created by economic efficiency alone, as the new norms and beliefs are dispersed. The further growth of the network "caused" by such institutional processes is, then, some form of *intentional* industrial symbiosis. Chertow (2007) has characterized this process as "uncovering" industrial symbiosis. It comprises the process of (1) the explicit recognition by some actor or actors of the positive environmental benefits being created by interfirm networking followed by (2) the emergence of an incipient institutional structure.

Taking the evolutionary process beyond the addition of the early exchanges relies on "champions" who believe that symbioses have value for the world outside the firm and who transmit that belief to others. Institutional processes begin with human carriers of new beliefs. Such individuals are frequently called "boundary spanners" (Cross and Prusak 2002; Daft 1989). They transport cultural values and beliefs across intra- and intercompany boundaries. If others pick up the message and carry it home, they may attempt to institute new behaviors. To do so, however, they will have to convince those in power that some new practice is worthwhile. Two such individuals assessed in the industrial symbiosis literature conducting projects in the Ukraine and in Devens, Massachusetts, discuss the need to bring people together who "normally don't understand that they need to go together" (Hewes and Lyons 2008).

The external institutions that connect network actors play a critical role in further strengthening interfirm relationships, and grow stronger with the success of the champions. One of the originators of the Danish symbiosis has emphasized the "short mental distance" across firms in Kalundborg as critical to enabling the idea of resource sharing to become rooted in the community (Christensen 1998). Senior managers belonged to an Environment Club, and a coordinative organization, the Symbiosis Institute, was subsequently launched in 1996 as part of Kalundborg's industrial development agency, specifically working to accelerate the number and complexity of new exchanges—each of which fostered a sense of community among the relevant actors in and around Kalundborg (Jacobsen and Anderberg 2005).

Coordinating institutions can arise in various forms to organize and seek new environmental benefits. The organization may be newly formed or emerge as a new function from an existing entity. It may be formal or informal, primarily public or private, elected or appointed. What is needed, however, are explicit institutional forms that appreciate and express the public values that have been newly created or articulated. This gives them sufficient weight to successfully compete with other norms within firms—especially the pervasive norm of profit maximization—such that these values can coexist and, all things being equal, the network that has developed can continue to thrive and grow. Consequently, the most observable pattern in existing coordinating bodies is that they are constituted primarily of representatives of participating companies, but also include representation by government and academia in some capacity. Examples include the Symbiosis Institute in Denmark, the Kwinana Industry Council in Australia, the Kawasaki Liaison Center for Creation of Industry and Environment in Japan, and the National Industrial Symbiosis Programme in the United Kingdom.

The boundary between the uncovering stage and the next is somewhat porous. The institutions that are critical in the uncovering and promoting of early stage industrial symbioses certainly can and do continue to play key roles in the next stage as well.

Stage 3: Embeddedness and Institutionalization

The critical difference between the emergence of an industrial ecosystem beginning in Stage 1 and the continued development of the network following its revelation in Stage 2 is the evolution of an institutional frame tying together the actors and interpenetrating whatever other structures may influence their behaviors discussed in this section. Institutionalization serves the purpose of validating the new public consciousness and intentionally channeling it toward environmental outcomes (Lawrence et al. 2002). The institutions convert the existence of public goods into tangible entities that enter the calculus of firms in a positive way, facilitating the formation of more linkages. Significant aspects of this longer-term institutionalization include embeddedness of network actors, the role of locational factors, and the ways in which social capital comes into play. At the end of the section, some tools are mentioned that have been found to be useful in advancing industrial symbiosis at this stage.

Construing both managerial interactions and resource exchanges across companies as ties within eco-industrial *networks* leads straight to the core of social/organizational theories of embeddedness (Granovetter 1985). Network ties enable the development of shared norms and shape opportunities for collaboration, but such norms and opportunities, in turn, shape the growth and development of the network (Powell et al. 2005). The idea of dynamic recursivity, drawn from the literature on other types of cooperative networks, suggests that shared norms and perceptions facilitate further and more complex exchanges.

Uzzi (1996) describes a structural embeddedness approach combining organizational theory with social network theory to argue that the

> structure and quality of social ties among firms shape economic action by creating unique opportunities and access to those opportunities. The type of network in which an organization is embedded defines the opportunities potentially available; its position in that structure and the types of inter-firm ties it maintains that define its access to those opportunities. (p. 675)

The concept of industrial symbioses as important sources of environmental benefits is still new, and no single archetype has emerged as being the most effective in bringing about exchange networks. The four specific coordinating institutions mentioned at the end of the Stage 2 discussion provide models that distinctly reflect their surroundings, but these have not been subject to comparative analysis that would lend insight into the structural issues.

Embeddedness occurs over time. On the positive side, it can continually reduce transaction costs and uncover new benefits not considered in earlier economic calculations, although the possibility also exists that relations could become insular and thus inhibit innovative activity (Granovetter 1985). Narrower forms of interfirm cooperation include serving on each other's personnel committees and sharing large pieces of equipment across firms, such as a compressed air production facility used jointly in Rotterdam (Baas and Boons 2004). There are also broader possibilities, such as bolstering supply security and intentionally tinkering with discarded material to improve its value, thus using industrial symbiosis as a "platform for innovation" (Van Berkel 2007). These activities further spread norms of cooperation as they develop new economic, social, and technological opportunities that can become recognized as industrial symbiosis.

Geographic proximity—or locational factors more broadly—do not *cause* the formation of an exchange network, but, importantly, enable it. Some of the examples in Table 1 are located in large cities, but others occupy smaller suburban or exurban communities where higher levels of social capital are available. Geographic proximity, then, becomes an enabler—along with other characteristics such as industry mix, availability and value of resources, information, and regulatory structures—of what ultimately drives industrial symbiosis: the ease with which relationships and institutions form.

Social capital is well known to accelerate the formation of relationships. According to sociologist Robert Putnam (1995), social capital includes "networks, norms, and social trust that facilitate coordination and cooperation for mutual benefit." In so doing, we also see that increased social capital with respect to industrial symbiosis networks reduces transaction costs, including the search and negotiation costs involved in identifying exchange partners—what economists call transactional friction (Williamson 1985)—and thus raise the potential for further exchanges. Enforcement costs are generally lower among familiar transacting players. In Kalundborg, the symbiosis continues 40 years later, well past the retirements of the original actors and in spite of a typical series of business mergers and acquisitions (meaning all major companies have changed ownership, dramatically increased in size, or even split in two, as in the case of Novo Nordisk and Novozymes). This example demonstrates the embedding of coordination and cooperation in local norms that have continued to foster and grow the quantity and quality of activities there, establishing a culture of cooperation/symbiosis.

An interesting counterexample is provided by a community where graduate student researchers intentionally set out to "uncover" industrial symbiosis in Jacksonville, Florida (Quan et al. 2007). The study found that bottom ash, fly ash, steam, wastewater, gypsum, and agricultural residues were all being actively exchanged in the region. The relationships among the companies, however, were primarily dyadic and triadic without the benefits of strong coordination or the embedding of cooperative norms among the firms located in the industrial area. The industrial ecosystem that formed was observed to be unstable, with fragile relationships across sectors at risk of demise when a single vendor or participating company became unavailable. Although more work needs to be done in this area, it is plausible that if collective knowledge or social capital among actors had been more widespread, leading to cross-sectoral institutionalization, the industrial ecosystem would have been more resilient to such short-term obstacles.

Measuring social capital is not methodologically straightforward. The first formal social network analysis of an industrial ecosystem to be published was part of a multiyear study of industrial symbiosis initiated by the author in Puerto Rico, an island commonwealth of the United States with a high concentration of manufacturing, especially in the pharmaceutical and electrical sectors. Weslynne Ashton's ensuing social network analysis found that trust and the central position of managers in the region's social structure correlated highly with the observed industrial symbiosis linkages between firms, but not with supply chain linkages, which were much more common in the region (Ashton 2008). This reinforced earlier findings from Kalundborg about the role of professional groups that facilitated interaction, familiarity, and trust among managers (Jacobsen and Anderberg 2005).

A report on industrial symbiosis from Australia uses the term "facilitating structure" as the context in which eco-industrial networking takes place. The authors point to the need for "engaging with key stakeholders and creating a conducive policy framework" (CECP 2007, 130). Their work highlights the importance of informational resources and technical assistance in facilitating network organization, finding it to be at least as effective as conventional upfront planning of eco-industrial parks.

Industrial Symbiosis and Related Models: Theory to Practice

To determine if the preceding three-stage theoretical explanation of the development of symbiosis holds, we examine how it compares with industrial symbiosis models in practice. We consider a stylized model of standard industrial park development, the build and recruit model, and then compare and contrast it with four models of symbiosis characterized from the literature.

The Build and Recruit Model

An example of a very common path to economic development of interest to those promoting eco-industrial development is the straightforward build and recruit model. Simply put, public or private developers create an industrial park or zone and then seek compatible tenants to whom land can be leased or sold. The preparation of the park or zone may require a greater or lesser degree of infrastructure development and a variety of marketing techniques may be applied. Sometimes an "anchor tenant" is already known; sometimes attracting such a tenant becomes the linchpin for additional development. Build and recruit can describe new projects on greenfield or brownfield developments as well as park or zone expansions. It is an established and successful model of economic development without emphasis on environmental considerations beyond standard planning practices.

The Planned Eco-Industrial Park Model

The planned eco-industrial park (PEIP) model (Chertow 2007, 2009) draws most directly from the build and recruit model. It adds another step, which is a directed effort to identify companies from different industries with a plan to locate them together so that they can share resources across and among themselves. The underlying assumption is that once the park is built and tenants with compatible resource flows can be recruited, they will be drawn to the opportunity to use each other's by-products and consciously create environmental public goods at the same time. Versions of the PEIP model have proven to be the least successful of the various approaches so far, particularly in Europe and North America (Chertow 2007; Gibbs 2003; Gibbs and Deutz 2005, 2007; Heeres et al. 2004). The overemphasis on the technical aspect of symbiosis—the matching of flows—narrows the field of possible recruitment targets too much, adding rigidity to a system that needs adaptability in the face of market demands. When such parks have been started from scratch, often with strong government subsidies, they have not proven to be sustainable, even with conscious recognition and coordination of environmental goals. In addition to economic hurdles, the shortcut of recruiting what appear to be technically compatible firms does not consider the gradual but essential process of embeddedness and institutionalization to foster and disperse the norms and beliefs inherent to industrial symbiosis.

The Self-Organizing Symbiosis Model

The self-organizing symbiosis (SOS) model discussed in earlier articles (Chertow 2007, 2009) most closely resembles what has been described in this article. In this model an industrial ecosystem emerges from decisions by private agents economically motivated to exchange resources to meet goals such as cost reduction, revenue enhancement, or business expansion. Significantly, individual initiatives to begin resource exchange face a market test, and if the exchanges are successful, more *may* follow if there is ongoing mutual self-interest. Thus the SOS model does not automatically convert to recognized symbiosis; alternatively it could remain as a series of bilateral exchanges—it is dependent on the situation and behaviors of the individual agents. It is also possible that, as happened in Kalundborg in Stage 3, the public benefits become known and institutionalized and lead to increased participation. The SOS model is quite opposite from the build and recruit model, as it occurs among existing firms, although newly located firms can join subsequently. The theoretical model set forth above has emerged largely from observations of these cases.

The Retrofit Industrial Park Model

In the retrofit industrial park (RIP) model, existing industrial parks are targeted for conversion to eco-industrial parks *after* build and recruit has occurred. The National Plan for Eco-industrial Park Development in Korea provides an apt example, as it is driven by a desire to update aging industrial park infrastructure, reduce costs through increased cooperation, and identify new business opportunities based on available flows recognized sometimes decades after initial park development. The risk to retrofitting models based on the theory outlined is that shared norms and values about resource exchange have *not* yet embedded widely, although frequently a base of exchanges and social relationships can be found, and it is not certain that an engineering retrofit will simultaneously incorporate the needed social change. Success is likely to hinge on the degree to which firms in these parks come to accept the norms and values that enable collaboration and interfirm exchange.

The Circular Economy Eco-Industrial Park Model

The circular economy eco-industrial park (CE-EIP) model is a new form emerging in China associated with the implementation of the Circular Economy Promotion Law in 2009. With a goal to continue growing the economy while at the same time reducing environmental impact, implementing the idea of a circular economy has been proposed at three levels: the individual facility, the industrial park, and regionally (Yuan et al. 2006). So far more than 20 existing sites have been designated as "demonstration eco-industrial parks" as part of the circular economy preparations. Most are retrofits rather than build and recruit models, although many are significant expansions closer in concept to the PEIP model. There is evidence that the phenomenon of "uncovering" existing but hidden material exchanges also pertains in China (Shi et al. 2010). Large Chinese industrial parks already have coordinating institutions—typically parkwide management committees—and so are powerfully poised to use public authority to establish strong norms supporting resource sharing and other environmental opportunities as a means of reducing private costs while creating public environmental benefits. Our theory suggests that a very positive context for the evolution of symbioses in China now exists.

To summarize, we now observe and understand that industrial symbiosis networks follow a significantly different developmental pathway from build and recruit projects, and especially from the PEIP, where the institutional framework is created up front and from the top down. Too much direction on "who should locate where" is incompatible with market opportunities, even in China and Korea, where there is a stronger tradition of central planning. Short of overly ambitious planning, there is still a large role for enabling, facilitating, and coordinating these networks, and it seems very likely that institutionalization as described herein may be the best way to further the norms of resource sharing.

Discussion and Conclusions

Those industrial symbiosis networks that persist through the stages outlined in this article move in the direction of environmental sustainability. Key factors in their development include a broader view of economic analysis that includes local and regional variables, a bottom-up cooperation model across companies, and revealed and counted environmental benefits. Many less intrusive approaches accomplish economic development, but do not reach down far enough into corporate culture to provoke a change toward sustainability (Ehrenfeld 2005). Industrial symbiosis can be seen as an environmental phenomenon that not only encompasses material and energy exchange, but also offers a plausible means of building cooperative relations across businesses.

We have observed several characteristics that distinguish industrial symbiosis/eco-industrial networks from other industrial clusters. They are identified below and originate from a range of theoretical perspectives that are blended into the three-stage model at the heart of this article and a deeper understanding of cooperative business practices.

1. The identification of symbiotic networks as complex adaptive systems where self-organization by agents plays a critical role in contrast to other types of industrial clusters.
2. The origination of both positive and negative environmental externalities that are created collectively, even if actors in identified clusters of firms are not consciously aware of them, but that become known through an uncovering process that makes the realization conscious.
3. The recognition that actors in eco-industrial networks are producing public as well as private goods (and bads). Our model suggests that these networks may develop spontaneously in the presence of strong institutional norms. Standard environmental economic theory also suggests that, in some cases, public assistance may be needed to offset the private costs to the firms involved in the network and so the model points to regulation and other mechanisms to achieve the needed offset.
4. The way in which embedded norms of exchange and other elements of culture and structure coevolve to include environment as part of the institutionalization process.
5. The need for facilitation and coordination through a more or less formal body to sustain the norms as they evolve from initial self-organization. The goal of the coordinating entities, whatever specific form they take, is to further opportunities for collaboration and collective action.

The three-stage model we have described is also consistent with complex adaptive ecosystem models (Gunderson and Holling 2002). In these models there is a cyclic progression from the intensive use of resources through to their release and regeneration, but there has been little empirical documentation of these phenomena in industrial ecosystems (Ashton 2009). Another analogous model emerging from the field of information and communication technology (ICT) is based on findings from studies of open source software combining standardization theory and complex systems and has been called "inverse infrastructure." It has in common with the three-stage model described here that it is based on bottom-up self-organization and is facilitated by the related coordination mechanisms that underlie it (Egyedi et al. 2007).

Further research is needed to understand a variety of points, such as

- why initial exchanges most often do not expand very far beyond the first set of actors, whether there is a pattern of agent behavior and feedbacks associated with successful network formation;
- how "explicit recognition of the symbiosis" as discussed in the second stage affects and expands outcomes over the expected case if the symbiosis were not made conscious;
- the constitution and characteristics of useful coordinating entities and some formal cross-project comparisons based on contemporary work on organizational change (Aldrich and Ruef 2006; Ostrom 2005); and
- whether the sort of problem of an unstable network found in the example of Jacksonville, Florida, is widespread and if a coordinating entity can be appended post facto to strengthen it.

We have offered a model of collective corporate environmental advantage that illuminates successes and failures of industrial symbiosis in this article. On the one hand, there are many obvious and available economic benefits for companies exchanging materials with neighbors. On the other hand, it is difficult to plan for these advantages, especially given the important role of self-organization in early success. Our midlevel theory puts a great deal of emphasis on the corporate actors themselves who are located in a particular industrial cluster and who must first find, or even stumble upon, economic value in initial exchanges and then, as occurs even more occasionally, become part of a set of firms whose ideas and business objectives overlap with a growing set of norms that place greater value on environmental knowledge and performance. Indeed, organizing these self-organizing systems is an ironic, but essential system goal.

Being well-intentioned is only somewhat useful in navigating the twists and turns of a complex economy not always penetrable by adaptations of its members. The current rise in concern over global environmental problems from climate change to resource shortages, and for sustainability more broadly, however, are pushing old values and slowly changing norms both in business and in the larger society. Industrial symbiosis, by itself, can be seen simply as a more efficient use of energy and materials. But when concerns about unsustainability become a more dominant driving force, then eco-industrial networks will have an important role to play in our approach toward a sustainable world.

Notes

1. We use the terms industrial "ecosystem" and "network" and also "eco-industrial network" in a similar fashion throughout this article as the manifestations of industrial symbiosis. In the literature, "industrial ecosystem" has been used in numerous ways. The geographically based systems described here are one type of industrial ecosystem. Other types mentioned in an early study published by the National Academy of Engineering (Allenby and Richards 1994) include the life cycle of a single product or material, an industry, or a group of interrelated subsystems at different temporal or spatial scales. Networks in general have become widely used descriptors in multiple disciplines for interlinked phenomena. Here we refer to networks of firms and other organizations exchanging material by-products, energy, and water (Chertow et al. 2008). Because these have environmental characteristics, some prefer the label "eco-industrial networks."
2. While the first exchange (#1) in Figure 2 is shown to have begun in 1961, bringing water from a nearby lake to the power station, some industrial ecologists prefer to think of the first industrial symbiosis exchange there as #2, with the link between a waste gas of the oil refinery reused at the gypsum board plant beginning in 1972, since it clearly illustrates by-product reuse.

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