Understanding the Organization of Industrial Ecosystems

A Social Network Approach

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Supplementary material is available on the *JIE* Web site

Summary

Industrial symbiosis (IS) has been used to describe the physical exchange and shared management of input and output materials by geographically proximate firms. Firms that engage in IS are said to belong to an industrial ecosystem. Symbiosis has been found to be motivated by economic considerations, such as lowering costs for waste disposal, as well as by environmental ones, such as accessing limited water supplies. Communication and trust among managers are thought to play important roles in exchanges; however, empirical studies have not been previously conducted. This study used social network analysis (SNA) to identify the prevalence of industrial symbiosis linkages in Barceloneta, Puerto Rico. The study quantified patterns in various relationships among firms and managers, including formal relations through supply chains, and informal ones through interpersonal interactions. SNA and statistical methods were used to explore how these ties correlate with observed industrial symbiosis activities. IS linkages were found to be less prevalent than product sales among firms and were concentrated among pharmaceutical firms at the core of the regional network. Trust among managers and position in the social hierarchy were found to be correlated with IS but not supply chain links. SNA was useful for examining the organization of different relationships in the industrial ecosystem, but contextual information is still needed to add meaning to its findings.

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Introduction

In the industrial ecology field, the term *industrial symbiosis* (IS) was first used to describe the high level of resource cycling among separate firms in Kalundborg, Denmark. IS describes partnerships among firms in a region to physically exchange and share in the management of resources such as energy, water, and input and output materials (Chertow et al. 2008) as well as to pursue broader strategies for sustainable industrial development (Baas and Boons 2004). Actors engaging in IS are thought to be motivated by potential economic and environmental benefits, and most previous studies have focused on these technical aspects of symbiosis rather than the social facets (Jacobsen 2005).

Although communication and trust among actors have been recognized as important for symbiosis to occur, their exact roles have not yet been quantified in meaningful ways (Chertow 2000; Gibbs 2003; Jacobsen and Anderberg 2005). In the last few years, scholars have begun building a social science theoretical frame to understand how IS develops (Baas and Boons 2004; Chertow et al. 2008; Cohen-Rosenthal 2000; Hoffman 2003; Howard-Grenville and Paquin 2006; Jacobsen 2005). IS researchers have much to gain by drawing on organizational theories such as the open-systems view of the firm, which considers how firms are influenced by external forces, including regulations and accepted norms (Hoffman 2003; Howard-Grenville and Paquin 2006). Economic geography offers another approach focused on industrial networks or clusters and the benefits that result from interfirm competition, collaboration, and innovation (Chertow et al. 2008). The present study contributes empirically to this burgeoning area by using social network analysis (SNA) methods to explore how connectivity among firms and managers in the industrialized Barceloneta region of Puerto Rico relates to the observed IS linkages there. SNA was selected as the methodological framework for this study as it is a powerful tool currently being employed in a wide variety of disciplines to examine interactions among different types of actors, including plankton, humans, and countries (McMahon et al. 2001).

The next section introduces IS, social science theories proposed to understand IS, social network concepts and analytical tools, and the expectations for using these tools in studying IS. The case study is presented, along with the research methodology, followed by the results. I then discuss how these findings contribute to IS and how research in this area could be furthered.

Background

Industrial Symbiosis

IS refers to cooperation among geographically proximate individual firms to physically exchange by-products, share in the management of utilities, and share ancillary services (Chertow et al. 2008). Firms belonging to an *industrial ecosystem* utilize IS as a collective approach to competitive advantage and simultaneously realize economic and environmental benefits (Chertow 2000). In a successful industrial ecosystem, a group of firms with a diverse array of inputs and outputs exchange materials, such that the waste or by-product of one becomes an input for another (Frosch and Gallopoulos 1989). The firms can also share ancillary services, such as transportation, landscaping, and waste collection, and share in the management of their utilities, such as energy, water, or wastewater treatment.

Industrial ecosystems have sprung up all over the world, mostly in regions with large-scale, heavy industrial processes, such as Kwinana Industrial Area in Australia (Van Beers et al. 2007; van Berkel 2004) and Rotterdam Harbor in the Netherlands (Baas and Boons 2004), but also around small-scale agricultural practices, such as the Montfort Boys Town in Fiji (Zero Emissions Research and Initiatives 2005). In the United States, though more than a dozen eco-industrial developments were planned, none materialized as idealized industrial ecosystems (Chertow 2007; Gibbs et al. 2005). Many nascent industrial ecosystems are thought to exist, although they are not yet known to industrial ecologists. These include regions with by-product exchanges among small groups of firms or utility-sharing agreements to deal with local resource deficiencies (Chertow 2007).

Kalundborg, Denmark, remains the best-known example of IS. The chief reasons cited for Kalundborg's past and continued success are that partnerships are commercially sound, companies are close to each other, and exchanges provide environmental benefits. Also noted to be of significance are a "culture of cooperation" and "short mental distances" that facilitate ongoing communication and trust among managers in the region (Ehrenfeld and Chertow 2002,432; Jacobsen 2005).

Social Science Theories and IS

Scholars are paying increasing attention to the social and organizational forces at work in industrial ecosystems (Baas and Boons 2004; Cohen-Rosenthal 2000; Hoffman 2003; Howard-Grenville and Paquin 2006; Jacobsen 2005). Numerous social science theories could be applied to their study; however, only two approaches are considered here: organizational sociology and economic geography.

Organizational sociology examines how social forces shape the structure and function of organizations and the interactions among groups of organizations (Scott 2004b). An *open-systems* view recognizes that organizations are embedded in physical as well as social systems, from which they obtain materials necessary to function as well as the norms governing how they function (Hoffman 2003). An organization exists within a hierarchy of social systems that includes sets (others interacting closely with the organization), populations (others competing with it for similar resources), and fields (similar and dissimilar organizations that regularly interact with it; Scott 2004b). Studies in this area examine how shared beliefs, values, and norms develop within a social system and how these, in turn, influence an organization's behavior and function. Industrial ecosystems may constitute new organizational fields that are based on geography, compatible material flows, and coordinated resource management rather than industry classification. It is expected that new norms will emerge among members of an industrial ecosystem's field, including regular communication among different industries, consideration of traditional wastes as potential raw materials, and institutionalization of mechanisms for collaboratively managing resources (Jacobsen 2005).

Economic geography examines why industries tend to concentrate in particular regions and measures the resulting economic benefits to firms and the regions on the whole (Scott 2004a). These benefits include improved access to factors of production and reduced costs through economies of scale. Knowledge spillovers and innovation are thought to result from frequent interfirm communication and cooperation due to proximity. There are many types of successful regional industrial systems. Among these are diverse urban economies, clusters dominated by a few related industries, districts consisting of small and medium-sized enterprises that cooperate to innovate, and satellite districts that house subsidiaries of multinational firms (Markusen 1996). Regional systems are thought to evolve from (1) locations where colocated firms are unconscious of each other and simply benefit from economies of scale to (2) systems that include dynamic learning and coordination to boost regional competitive advantages (Harrison et al. 1996; Porter 1998). Within regional economies, personal relationships (social ties) are thought to provide noneconomic incentives for managers to cooperate in their mutual interest (Gordon and McCann 2000).

Industrial ecosystems can also be considered as a type of regional economy (Desrochers 2001). Collaboration in such systems centers on material exchanges and resource management issues, and there is awareness of the resulting public environmental benefits (Chertow et al. 2008). Social forces operate within both regional economies and organizational fields and are thus worthy of study to understand how interfirm collaboration takes place within industrial ecosystems.

SNA

Researchers can use SNA to study the systems in which firms operate by concentrating on the interactions among actors in the system and relating observed behavior to their relationships. Patterns in relationships, or social structure, result from repeated interaction among actors and can be represented as networks. A network consists of nodes representing the actors in the system

Table 1 Social network terms and descriptions

Social network term	*Description*	*Examples in this study*
Node	An actor in the network	Firms, managers
Tie	A relationship between a pair of nodes. Actors may share several different ties. A tie can be direct or indirect via another actor, quantified, and directional.	Among firms—selling or purchasing goods Among managers—trust A→B or A↔B
Degree	Number of direct ties for a given node	Number of firms to which the respondent sells goods
Dyad	A pair of nodes with a direct tie	A pair of firms exchanging by-products
Geodesic distance	Shortest path length or number of ties between two nodes	Distance equals 1 for two firms that have a direct tie
Nodal average	Average degree for all nodes in the network	Average number of firms to which respondents sell goods
Density	Ratio of number of existing ties to all possible ties in a network	Ratio of existing sales ties to all possible ties
Actor centrality	Measurement of how central a node is in a network	The firm that sells goods to the most others will be most central for this tie
Network centralization	Measurement of the degree to which ties are concentrated around a few nodes or spread out among many	A network is highly centralized if the majority of ties are with a few actors
Ego-network	The network of nodes and ties centered on a given node. Each node in a network has its own ego-network made up of itself, the nodes to which it is directly tied, and the ties between those nodes.	Firm X and all those to whom it sells goods, and their sales with each other
Whole network	All the nodes in a defined population and all the ties between them	The entire industrial ecosystem
Star network	A network configuration in which all ties are centered on a single node	The sole provider of a good or service is directly tied to its customers, who are not connected to each other
Fully connected network	A network configuration in which every node has a direct tie to every other node	All members of an organization have direct ties to each other

and ties depicting various connections between them. Actors may be discrete social units, such as individuals, or collective entities, such as organizations (Wasserman and Faust 1994). Ties represent different relationships, including friendship, group membership, and the flow of capital or materials. Analysis is usually performed on actors of the same type, such as all individuals, but can also compare relations among different types of actors. Table 1 highlights some important terms used to describe social networks in this study.

Every actor has a position in the network, determined by how each is connected to others. An actor's position reflects how others regard it and the degree of influence it exerts on others. By definition, actors in the center of a network are more connected than those on the periphery. Beyond characterizing the networks and the positions of actors, SNA can be used to determine how certain ties correlate with other ties as well as with the attributes of actors and how network positions affect strategic decision making by individuals and subsets of actors (Stevenson and Greenberg 2000).

SNA was used to illustrate different types of relationships among firms in an industrial ecosystem and among the managers within those firms. The ties of most interest were participation in IS initiatives (by-product exchanges, service and utility sharing) at the firm level and strength of acquaintance with and trust in others at the individual level. SNA can determine the degree of similarity in the network configurations associated with different types of relationships—for example, whether most relationships are mediated through a few actors in the network. Key research questions asked were as follows: (1) What is the prevalence of IS activities in this region? (2) Is the network structure for IS relationships similar to other types of interfirm or interpersonal network structures? (3) Does a firm's position in the network correlate with IS participation? (4) Do personal relationships and trust among managers correlate with IS participation?

Case Study: IS in Barceloneta, Puerto Rico

Barceloneta, Puerto Rico, and its neighboring municipalities, Arecibo and Manatí, were selected as the location to conduct this research as (1) several IS activities among pharmaceutical manufacturers in this region were previously identified, (2) earlier interviews suggested that there was frequent communication among managers, and (3) the region presents a diverse mix of firms in terms of size and industrial sectors. Barceloneta is often referred to as having one of the highest concentrations of pharmaceutical manufacturing facilities in the world, with 14 facilities located across the three municipalities. These include global leaders such as Abbott, Bristol-Myers Squibb, Merck, and Pfizer. In addition, there are food, chemical, packaging, electronic equipment, and metal fixture manufacturers and waste management firms.

Beginning in the 1950s, Puerto Rico, a U.S. commonwealth territory, promoted generous tax benefits and low labor costs relative to the continental United States to attract manufacturing firms. By 2002, over 70 pharmaceutical manufacturing facilities operated on the island (U.S. Census Bureau 2005), benefiting not only from tax incentives but from an increasingly well-educated labor force. Goods produced on the island are "made in the USA," as manufacturers must comply with all U.S. federal regulations, including those of the U.S. Environmental Protection Agency and the Food and Drug Administration.

The IS linkages in Barceloneta include utility and service sharing and by-product exchanges (see figure 1).

Several by-product exchanges occur—spent solvents are sold to paint and other manufacturers, fermentation residue is sold to a producer of animal feed, and organic treated sludge from the wastewater treatment plant is used as a fertilizer for growing hay. Closed-loop solvent recovery is a shared service provided by a waste management firm. Several firms participate in a utility-sharing agreement with the wastewater treatment plant, and the group has proposed energy cogeneration projects that would also be symbiotic. In addition, there are many traditional business relationships and informal collaborations among the firms, such as joint emergency management (Ashton 2003).

Eight regional firms participate in the Barceloneta Wastewater Treatment Corporation Advisory Council, a joint agreement, started in 1978, to construct and oversee operation of the region's secondary wastewater treatment plant, which handles 31,415 m^3 per day (8.3 million gallons per day). The plant is owned and operated by the Puerto Rico Aqueduct and Sewerage Authority. Advisory Council members provided 70% of the plants' operation and maintenance costs, as well as technical assistance to the Authority. The Advisory Council was made up of both senior and environmental/operations managers who met regularly to discuss issues related to the wastewater treatment plant, as well as more general resource management practices (Ashton 2003). This frequent interaction spawned a number of other initiatives. For example, the pharmaceutical firms have undertaken several feasibility studies to construct a cogeneration plant that can

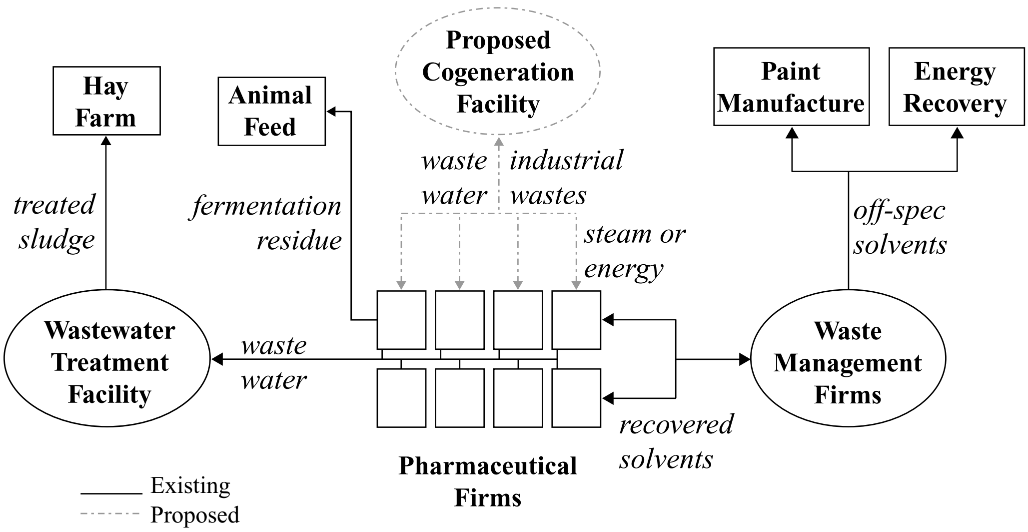

Figure 1 Industrial symbiosis linkages in the Barceloneta pharmaceutical cluster. The rectangles represent individual companies, and the ovals represent shared initiatives.

meet their electricity and steam needs; however, this project has not materialized, for economic and political reasons.

In the mid-1970s, a waste management firm moved to the region to collect and distill spent solvents from the growing number of pharmaceutical facilities and sell the recovered materials to other industries on the island (Inland Chemical 1973). It captured economies of scale from the high volume of solvents generated by over a dozen chemical manufacturers. It also provided closed-loop solvent recovery for many of the pharmaceutical firms by collecting designated solvent streams from each facility, distilling the materials (without mixing with any other streams), and returning them for the firms' use. The pharmaceutical firms benefited from this shared service through lower transportation and raw material purchase costs.

The pharmaceutical firms occasionally sell recovered solvents and other by-products to third parties, such as paint manufacturers, to be used as input materials.[1] The Advisory Council, along with the Puerto Rico Aqueduct and Sewerage Authority, developed a by-product exchange to utilize treated sludge[2] from the plant. These biosolids are used in a land application to grow hay on an adjacent farm, and farmers from the region regularly purchase the hay to feed horses and cattle.

Several reasons exist for the adoption of IS among the Barceloneta pharmaceutical firms. The U.S. Environmental Protection Agency's Clean Water Act mandated the creation of the wastewater treatment plant, but the pharmaceutical firms chose to share in its operation costs to benefit from economies of scale (Chertow et al. 2008). Regulatory flexibility in the definition of wastes allows solvent recovery and by-product exchanges, whereas raw material costs are the immediate drivers. Some managers have suggested that the potential for improving their environmental performance is also important in these decisions (Ashton 2003). This study focuses on the social structural forces that exist in the region, which could be enabling familiarity, communication, and trust among managers, as another possible set of reasons correlated to IS ties.

Research Design and Methodology

The research objectives were to determine the formal and informal relationships between firms, the interpersonal relationships among managers working in regional firms, and how both types of

Table 2 Company groupings according to NAICS categories

Group	*NAICS*	*No. firms*
Crop production and food manufacturers	111 and 311	8
Paper products and printing	322 and 323	3
Chemical manufacturers, including pharmaceutical	352	13
Fabricated metals manufacturers	332	2
Electrical equipment manufacturers	335	2
Wholesale and retail traders	423	3
Waste management	562	8

Note: NAICS = North American Industry Classification System.

relationships correlate with the existence of IS linkages.

Population Selection

The research was conducted over 2 months in 2004 by a team of students from Yale University and the University of Puerto Rico. The Manufacturers' Directory published by the Puerto Rico Industrial Development Company was used to identify manufacturing establishments in the region; 59 firms were listed. The team determined which firms were currently operating, and 39 were contacted for interviews.[3] I included all active firms, not just those with symbiotic linkages, to determine the prevalence of IS and measure how IS relationships compared with other business ties. The firms were categorized according to their three-digit North American Industry Classification System codes and placed in seven groups: crop production and food manufacture; paper products and printing; chemical manufacture, including pharmaceuticals; fabricated metals; electrical equipment; wholesale and retail traders; and waste management services (see table 2 for groups, North American Industry Classification System codes, number of firms, and representative icons used in figures).

Data Collection

The research team designed a standard survey to capture information uniformly from all interviewees. The survey (see the first supplement, available in the Supplementary Material for this article on the *JIE* Web site) asked managers to (1) provide basic information about their company's operations, including waste handling and by-product reuse; (2) identify other companies in the study with which their company had different types of relationships; and (3) identify other managers in those companies and how they knew and interacted with those managers. Interviews were conducted in person, in Spanish, with general managers and/or environmental managers[4] from 24 (62%) of these companies.[5]

The collected data were stored in two databases: An SPSS (data analysis and statistics) database (SPSS Inc. 2005) housed the quantitative data, and a Microsoft Access database (Microsoft Corporation 2002) stored the qualitative data. The quantitative data were analyzed with SPSS and UCINET 6 (social network analysis) software (Borgatti et al. 2002). NetDraw software was used to graph the relationships among the actors in the network (Borgatti 2002). NetDraw's multidimensional scaling algorithms were used to position nodes according to the similarity in their geodesic distances (shortest path lengths) to other nodes (Hanneman and Riddle 2005).

Results

The results are separated into three sections: relationships among companies, relationships among managers, and the correlations between both types of network ties and IS. To protect confidentiality, I identify firms and managers using only their industry and an assigned number—for example, Pharma#1 represents a pharmaceutical manufacturer.

Relationships Among Companies

Managers were first asked to identify the company names they recognized. Of those identified, they were asked to indicate which firms they

Table 3 Average network measures for various interfirm ties

Tie	*No. firms with tie*	*Nodal average (SD)*	*Network density (%)*	*Network centralization (%)*
Random	39	25.48 (1.59)	50	11
Recognition of firm name	39	22.67 (9.01)	39	43
Formal (contractual) relationship	39	6.21 (6.36)	10	49
Product sales	39	3.77 (7.27)	10	79
By-product exchanges	8	0.50 (1.20)	0.6	15
Industrial symbiosis (any by-product exchange, service or utility sharing)	15	2.20 (3.36)	5.1	21

bought products from, sold products to, had a formal (contractual) or informal relationship with, and exchanged by-products with. Table 3 lists the nodal average, network density, and centralization measures for a few of these types of ties.

Network measures were computed for a random matrix with 39 nodes, to compare actual ties in the network with what would be expected randomly.

In the random matrix, the average number of direct ties per node (nodal average) was 25. By comparison, managers recognized 23 of the 39 companies in the survey, had formal relations with 6, bought products from or sold to 4, and participated in symbiosis with 2. The network density for the random matrix was 50%, which means that only half of the possible ties were present. Comparatively, the network densities for the actual ties were much lower than if they were random—39% for recognition, 10% for both formal contracts and buying or selling products, and 5% for IS. The network centralization score indicates whether ties were randomly distributed or concentrated around one or a few nodes. In the random matrix, centralization was very low at 11%, whereas the actual ties were more concentrated—21% for IS, 43% for recognition, 49% for formal relations—and highly centralized at 79% for product sales.

The local supply chain network was drawn on the basis of reported relations for buying products or services. Figure 2 presents the supply

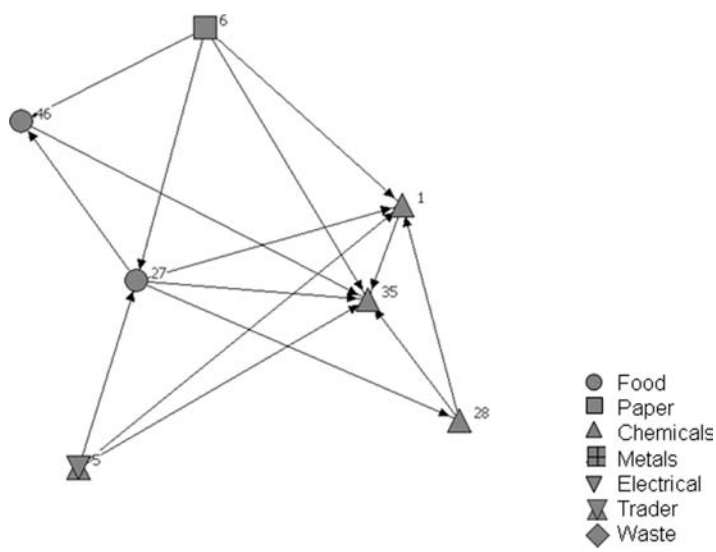

Figure 2 Company Food#27's ego-network for selling products to other regional firms. Each node represents a firm, and each line is the sale of a product or service between two firms (arrows point to the buyer).

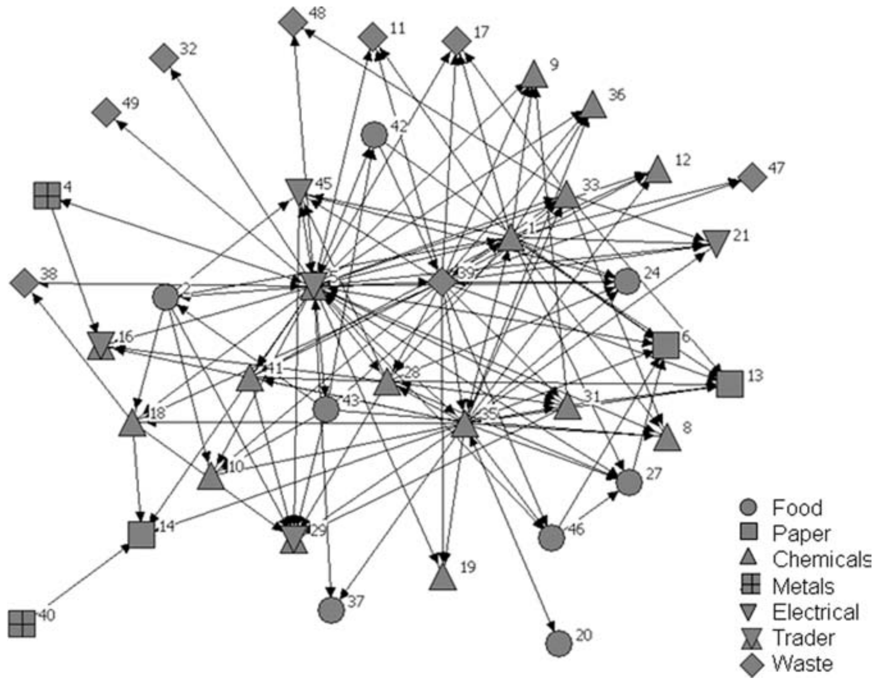

Figure 3 Whole network for buying or selling products within the region. Each node represents a firm, and the lines indicate the sale of a product or service between two firms (arrows point to buyers). The firms with the highest number of buyer/seller relationships are located in the center of the diagram, and those with fewer ties are placed on the network's periphery. A firm's position depends on the number of others to which it is directly tied and the geodesic (shortest) distances from all others in the network.

chain for a single company (Food#27), or its ego-network, which is the subset of companies with which the company has this relationship.[6] Food#27 only had six direct ties with other firms in the region, four to which it sold products (Food#46, Pharma#1, Pharma#28, Pharma#35) and two from which it bought products (Trader#5 and Paper#6). Also included in figure 2 are the buying/selling relationships among these other firms.

The whole network is illustrated in figure 3.

Every firm bought products or services from or sold to at least one other firm in the region. As indicated by the high network centralization score, this tie (buying and selling products) was concentrated around a few firms that made up the core of the network: Trader#5 (a wholesale trader of safety equipment in the center left), Pharma#1, Pharma#28, Pharma#35, and Waste#39 (pharmaceuticals and a waste management firm in the center right). The graph allows one to see how different industry groups relate to each other. Firms in the chemical industry were at or near to the core of the network. Waste management firms were most peripheral in the network with regard to this tie, most having just one or two ties with others in the network, with the exception of Waste#39 in the core. Food products, electronic equipment, and trading firms were scattered around the center. Some firms within the same industry were located together—for example, Paper#6 and Paper#13, or Food#27 and Food#46—which indicates that they supplied products or services to the same firms. Others in the same industry, such as Trader#5, Trader#16, and Trader#29, were far apart, indicating that they supplied different firms within the region.

In contrast to the supply chain, only 15 of the 39 firms engaged in IS. Figure 4 shows the different IS linkages, and table 4 describes in what ways each company participated.

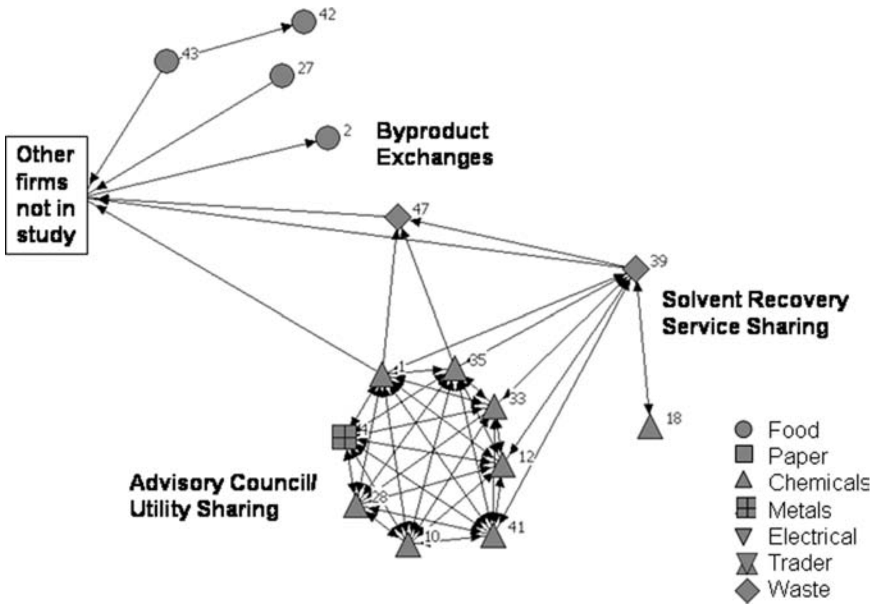

Figure 4 Network organization for different industrial symbiosis activities in region. Each node represents a firm, and each line represents either the movement of a material between two firms (arrow points to recipient) or utility-sharing agreement co-membership. By-product exchanges involve eight companies in three industry groups: waste management, chemicals, and food manufacturing.

By-product exchanges involved 8 companies in three industry groups: waste management, chemicals, and food manufacturing. Six of the 10 by-product exchanges in this network were with firms that were not in the study. Six chemical manufacturers shared the closed-loop solvent recovery services of Waste#39. Eight chemical manufacturers participated in the wastewater utility-sharing agreement. Only 2 firms participated in all three symbiosis activities—Pharma#1 and Pharma#35. Three of the 9 pharmaceutical firms in the study (Pharma#9, Pharma#31, and Pharma#36)[7] did not participate in any regional IS activities.

The graphical layout of the IS network points out distinct patterns in the organization of different IS activities and demonstrates what one may intuitively think about them. By-product exchanges were mostly dyadic (one-to-one) relations between unrelated pairs of firms. Solvent recovery was a star (many-to-one) network centered on a single actor that provided this service to chemical manufacturers. Utility sharing was a fully connected network in which every actor was directly connected to every other through the Advisory Council.

Relationships Among Managers

In the second part of the study, I asked managers questions about their acquaintance with all other managers in regional firms. Managers recognized 24% of the other managers. Of a possible 1,482 ties, only 412 ties were reported, which represents a density of 28% and a nodal average of 3.5 ties per actor. The network centralization score was 40%, on the basis of recognition of other managers, which is roughly the same as the interfirm network centralization scores for recognition.

Individuals who continuously interact are thought to form a social structure or hierarchy, and their positions within the structure reflect the patterns of interaction with others (Uzzi 1996; Wellman 1988). The CONCOR (CONvergence of iterated CORrelations) algorithm in UCINET assigns individuals to "block" groups such that all members within a block hold similar structural

Table 4 Industrial symbiosis activities by firms in the study

Company	*Activity*
Pharma#1	• Wastewater Advisory Council member
	• Closed-loop solvent recovery
	• Sends off-spec materials to buyers via waste broker
	• Involved in cogeneration plant discussions
	• Organic fermentation residue used as ingredient in animal feed
Food #2	• Receives animal manure that is used to fertilize crop
Metal#4	• Wastewater Advisory Council member
Chem#10	• Wastewater Advisory Council member
Pharma#12	• Wastewater Advisory Council member
	• Closed-loop solvent recovery
Chem#18	• Closed-loop solvent recovery
Food#27	• Sends dough scraps to smaller bakeries for hand-kneading and baking
Pharma#28	• Wastewater Advisory Council member
	• Involved in cogeneration plant discussions
Pharma#33	• Wastewater Advisory Council member
	• Closed-loop solvent recovery
Pharma#35	• Wastewater Advisory Council member
	• Closed-loop solvent recovery
	• Sends off-spec materials to buyers via waste broker
	• Involved in cogeneration plant discussions
Waste#39	• Performs solvent recovery
	• Sends off-spec materials to buyers via waste broker
Pharma#41	• Wastewater Advisory Council member
	• Closed-loop solvent recovery
Food#42	• Sells rice bran to make animal feed and sells broken rice to brewery
Food#43	• Receives rice bran to make animal feed
Waste#47	• Collects off-spec materials from pharmaceutical and other firms to sell to other industrial users across US

positions in the network (Borgatti et al. 2002; White et al. 1976). All members of a block interact with each other and relate to those outside the block in comparable ways. Block density measures how many actual versus possible ties exist within and between blocks. It is generally expected that, for any block, density is higher within the group than outside and that individuals in lower ranked block groups claim more ties (greater density) to those higher up than vice versa.

Table 5 presents the density for the blocks that were formed on the basis of the tie recognition among general managers only.[8] Rows represent respondents, and columns are subjects, or those who are being commented on. Block 1 was the highest in the social hierarchy, as evidenced by its high recognition of itself and lower recognition of other managers (row 1) and by the high recognition of these managers by others (column 1). Those individuals in Block 2 recognized the members of Block 1 more than they recognized others in Block 2 (i.e., they looked up to those in Block 1); Block 2 respondents recognized few members of Block 3 and none in Block 4 (row 2). Respondents in Block 3 had a low level of recognition of all blocks except their own. Members of Block 4 claimed zero awareness of any of the other managers in the network.

Table 5 Block group densities based on managers' recognition of each other

Block	*1*	*2*	*3*	*4*
1	0.673	0.136	0.061	0.091
2	0.398	0.196	0.083	0.000
3	0.121	0.083	0.500	0.250
4	0.000	0.000	0.000	0.000

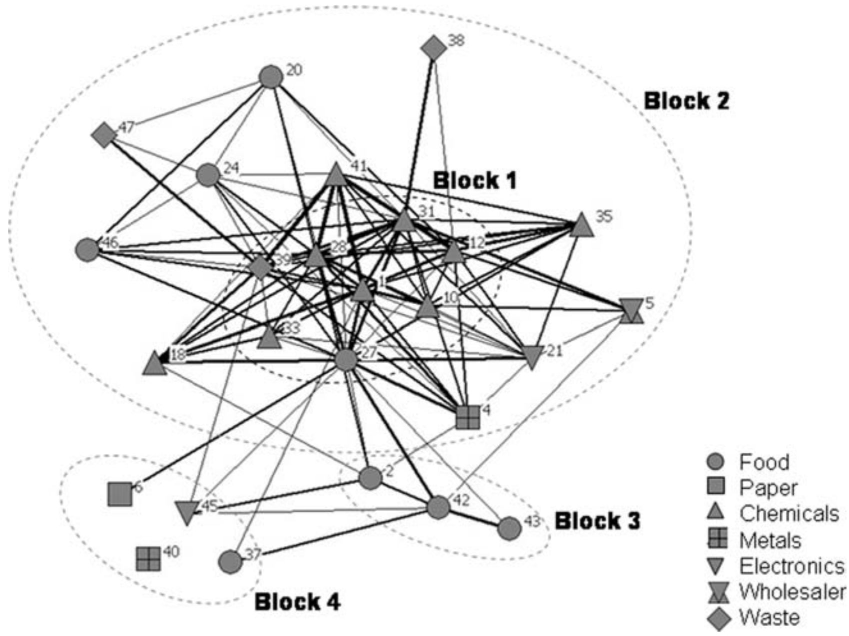

Figure 5 Managerial social network showing strength of ties and block groups. Each node represents a manager (labels correspond to company numbers as above), and each line represents a personal relationship between a pair of managers. The weight of the line is proportional to how well the managers reported knowing each other. The nodes are positioned according to their block groups.

Identifying characteristics of block members adds meaning to the social structure obtained through the CONCOR procedure. Block 1 was populated primarily by managers in the pharmaceutical industry, with two managers from other industry sectors (one food and one waste). It is interesting that the managers of Trader#5 and Pharma#35, which were in the core of the interfirm network, were members of Block 2 rather than Block 1. The members of Block 2 and 4 worked in different industrial sectors. Block 3 was populated by three food company managers; their relatively higher awareness of each other and low awareness of and by all others suggests that this block can be considered a distinct subgroup. Block 4's complete lack of recognition of anyone suggests that these managers did not consider themselves part of any social network in the region, even though several managers from other blocks recognized them.

Figure 5 graphically presents data on the managerial relationships in the network.

Respondents were asked to categorize the managers they recognized as (1) those they knew only by name, (2) those they knew personally, and (3) those they knew very well. Actors Pharma#1, Food#27, and Pharma#28 had more strong ties than any other actors and were thus in the center, whereas actor Metal#40 had no ties and was considered isolated from others in the network. The members of Block 1 were located in the center of the network and were surrounded by members of Block 2. Members of Blocks 3 and 4 had fewer ties with the others and were peripheral to the core network. The center of figure 5 is characterized by a dense network of strong and weak ties. The outer part of the figure is considerably sparser, with fewer and weaker ties among managers in different industries. This social structure suggests that cooperation was more likely to be seen within the established pharmaceutical manufacturing organizational field, as ties were more numerous and stronger among those managers.

As a proxy for trust, respondents were asked to indicate which of the other managers they would be willing to do business with personally, regardless of industry affiliation. Trust was assumed

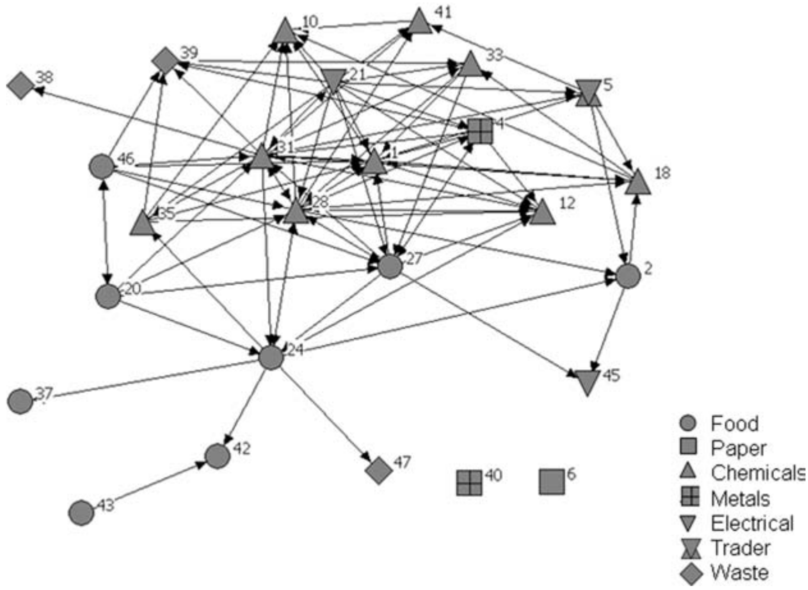

Figure 6 Managerial social network showing allocation of trust. Each node represents a manager, and each line represents a vote of trust (arrows point to recipient).

necessary to enter into a business relationship based on the respondent's prior interaction with or knowledge of the subject. Figure 6 shows the network structure for this tie.

As would be expected, actors who were members of the core block were allocated the highest votes for trust. Trust was not restricted by industry, as respondents gave votes to others from a variety of sectors. Two managers neither gave nor received trust votes (Paper#6 and Metal#40); they were both members of Block Group 4, the least connected socially.

Network Correlations

Correlation analyses were performed to measure the similarity in network structures for different types of interfirm relationships and determine whether these were correlated with IS relationships. Linear and nonlinear regressions used in statistics are not appropriate for examining social networks, as there is a high degree of autocorrelation among matrix cells, because, by definition, the cells represent a possible connection between actors (Dekker et al. 2005). Instead, quadratic assignment procedure analysis was performed in UCINET to test the similarities among matrices for different relationships. In this procedure, the Pearson's correlation coefficient, a measure of the level of similarity between the two matrices, is first calculated on the basis of corresponding cells of the matrices. Rows and columns of one matrix are then randomly permutated, and correlations with the fixed matrix are recomputed hundreds of times to determine the proportion of times that the random measure is greater than or equal to the coefficient calculated in the first step. A low proportion ($p < 0.05$) suggests a strong relationship between the matrices that is unlikely to be random (Borgatti et al. 2002).

The "IS" matrix was analyzed for correlation with several other interfirm relations. Results are listed in table 6, along with those of the supply chain matrix for comparison.

In general, the correlation coefficients were low, because of the low presence of IS among the firms, but ties were significantly correlated. The IS and supply chain matrices were correlated with each other and with firm recognition, formal and informal relations, and comembership in the Puerto Rico Manufacturers' Association.

The correlations between various interpersonal ties and the presence of IS among firms were then computed. For comparison, the correlations

Table 6 Correlations between interfirm relations

Interfirm relation	*Industrial symbiosis*		*Supply chain*	
	Pearson coefficient	*p*	*Pearson coefficient*	*p*
Recognition of firms	0.218	0.000	0.414	0.000
Formal relations between firms	0.333	0.000	0.404	0.000
Informal relations between firms	0.330	0.000	0.321	0.000
Product sales between firms	0.148	0.010	-	-
PRMA comembership	0.246	0.006	0.163	0.004

Note: PRMA = Puerto Rico Manufacturers' Association; p = the proportion of times that the random measure is greater than or equal to the coefficient calculated in the first step.

Table 7 Correlations between interpersonal and interfirm relations

Interpersonal relation	*Industrial symbiosis*		*Supply chain*	
	Pearson coefficient	*p*	*Pearson coefficient*	*p*
Recognition of managers of other firms	0.273	0.003	0.192	0.006
Respect for managers of other firms	0.299	0.001	0.157	0.033
Trust (willingness to do business with managers of other firms)	0.129	0.047	0.086	0.140
CONCOR block group comembership	0.358	0.001	0.075	0.075

Note: CONCOR = convergence of iterated correlations; p = the proportion of times that the random measure is greater than or equal to the coefficient calculated in the first step.

between managerial ties and the IS and supply chain matrices are presented in table 7.

Two of the observed ties—knowing other managers and respecting them—appeared to be significant for both IS and supply chain relations. The trust ("willingness to do business with") tie and block group were significant for IS but not for the supply chain. Binary logistic regression models relating the presence of IS to selected firm- and managerial-level attributes, organizational affiliations, and network positions are discussed in the second supplement contained in the Supplementary Material for this article available on the *JIE* Web site.

Discussion

Comparing network structures of IS ties with other business relations revealed their similarities and differences. Supply chain relations were most prevalent as each firm bought a product from or sold one to at least one other firm. IS activities, by comparison, were undertaken by only 39% of the firms. IS relations were sparser and less centralized than the other interfirm relationships but were common in the core of the network.

Different IS activities displayed distinctive network topologies—by-product exchanges appeared as several unconnected dyads, solvent recovery followed a star network formation, and utility sharing took the form of a fully connected network. These network configurations suggest differences in the resilience of the relationships. The loss of one by-product flow or exchange partner would not likely affect any of the other exchanges. The loss of a single chemical company probably would not alter the solvent recovery loop, but loss of the solvent recovery service provider would collapse this relation. Loss of one or a few chemical companies would not likely affect the continued participation of others in the utility sharing arrangement; however, a change in the agreement would impact all the participants.

Although several interfirm and interpersonal relationships appeared to be significantly correlated with participation in IS, many of these are intuitively obvious, such as recognizing a firm. Some interesting correlations are worthy of discussion. Membership in the Puerto Rico Manufacturers' Association was correlated with IS, which indicates that professional associations provided a venue for managers in different sectors to interact, much like the Rotary Club and Environment Club in Kalundborg (Jacobsen 2005). See the third supplement in the Supplementary Material for this article on the *JIE* Web site for an examination of how managers met and interacted. Among managers, trust (or willingness to do business) and block group ties were significant for IS but not for product sales. This suggests that familiarity and trust were more important in the observed IS activities than in supply chain relations, which makes sense, as one would expect the latter to be governed by impersonal market forces rather than social forces. Additionally, as subsidiaries of multinational firms, many organizations were restricted by corporate decisions that set contracts with particular vendors at a global or national level.

Although there was a correlation between knowing other managers and the presence of IS, very few of today's managers were employed when interfirm cooperation began, so it is not possible to know how social relationships influenced the adoption of IS. Nonetheless, it is interesting to note that the Wastewater Advisory Council—a symbiosis initiative—now facilitates interaction around issues besides management of the wastewater plant. For many of the more junior managers in the pharmaceutical industry, their main place of interaction with each other and their superiors is through the Council. Thus, the Council acts as an institutionalization mechanism for IS by creating familiarity, increasing trust through repeated interaction, and establishing by-product reuse and cooperative resource management as norms.

Some authors have suggested that when IS becomes established in a region, firms should increase interaction with others across industries and form their own organization field (Howard-Grenville and Paquin 2006). This may be more relevant for mixed industry clusters, in which by-product exchanges across sectors are more prevalent. In regions dominated by firms in a single industry, opportunities for utility and service sharing may overshadow (but not eliminate) opportunities for by-product exchanges because of the similarity of resources and needs (Chertow et al. 2008). In Barceloneta, there is frequent interaction within the pharmaceutical industry, and IS activities are commonplace, but communication across industries is not happening on a significant basis. An IS organizational field has emerged locally, in which there are shared norms regarding wastes and resource management and a mechanism for institutionalizing these norms, but it is still very much centered on the main industrial sector.

Conclusions

IS practices were less prevalent than other types of business relations but were common in the core of the manufacturing industry network in Barceloneta. Different IS activities—by-product exchanges, service sharing, and utility sharing—each had different organizational configurations—unrelated dyads, star networks, and fully connected network forms, respectively. IS was found to be correlated with firm recognition, formal and informal relations, and membership in the island manufacturers' association. Several interpersonal ties—trust and a high position in the social hierarchy—were found to be correlated with IS participation but not with the sale of products or services. As the study took place decades after IS practices were instituted, not much can be said with respect to how personal ties might have influenced the adoption of IS. However, one local organization—the Wastewater Advisory Council—acts to institutionalize IS practices by providing a forum for regular interaction around resource management issues.

This study was an exploration of how SNA can be used to study industrial ecosystems. The whole-network approach was suitable for understanding how IS compares with different interfirm and interpersonal relations within a defined system. Exploratory SNA can be used to identify the most important actors in the network, with whom in-depth interviews can be conducted to gain a greater appreciation for how information and influence flow through the network. Additional SNA studies might involve examining how symbiosis evolved over time, delving deeper into the role of trust, and comparing network configurations in industrial ecosystems around the world. SNA is limited by the fact that it captures a snapshot of the relationships in a system, but repeated studies can be used to create time-series data to examine how a system changes. Currently, new modeling and analytical approaches are being developed to examine the dynamic interaction between social and other types of relationships (Brieger et al. 2002). On its own, SNA can only show how different ties are organized and related, which is useful for understanding how symbiosis is organized within a system. Contextual information is still needed to understand the importance of particular ties relative to others and to put meaning behind the observed relationships.

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Notes

1. The pharmaceutical firms typically contract waste brokers to find buyers for these by-products.
2. The largest effluent flows were from facilities producing active pharmaceutical ingredients via fermentation. These flows typically had high organic loads and low concentrations of metals and volatile organic compounds.
3. The 2002 U.S. Economic Census of Island Areas for Puerto Rico (Manufacturing) counted 94 manufacturing establishments in these municipalities, of which 55 firms employed 10 or more persons. The 2004 Puerto Rico Industrial Development Company Manufacturing Directory, which excludes manufacturers with fewer than 10 employees, listed a comparable number of manufacturers (59) for this region. I excluded smaller enterprises. Only 39 firms were contacted for interviews, as some companies were listed under multiple names, whereas others were no longer in operation.
4. When the position existed, typically in larger companies, I interviewed environmental managers along with general managers to obtain more detailed information on utilities, waste management, and by-product exchanges.
5. Although representatives from 15 of the companies were not interviewed, their relationships with other companies are included, from the perspective of the interviewees. However, some network measures are undercounted because these firms did not provide information themselves.
6. It was not expected that pharmaceutical firms would sell products to each other; however, a few pharmaceutical respondents indicated that their firms contracted with some of the other pharmaceuticals to manufacture some of their products for them.
7. It should be noted that these three firms were located in Manatí, away from the main cluster of firms; manufactured finished pharmaceutical products rather than performing chemical or biological synthesis; and were smaller than most of the others in this study.
8. Results of managerial relationships are shown for general managers only. This was done to simplify the presentation of data, as persons from the same firm tended to have similar relationships with others, as well as to perform comparisons on interpersonal and interfirm relationships so that each firm would have a single respondent. In two cases in which a general manager was not interviewed, responses from the environmental managers were used.

References

Ashton, W. S. 2003. Inter-firm collaboration in eco-industrial networks with a case study of Puerto Rico's pharmaceutical manufacturing cluster. Master's thesis, School of Forestry & Environmental Studies, Yale University, New Haven, CT.

Baas, L. W. and F. A. Boons. 2004. An industrial ecology project in practice: Exploring the boundaries of decision-making levels in regional industrial systems. *Journal of Cleaner Production* 12(8-10): 1073–1085.

Borgatti, S. P. 2002. NetDraw: Graph Visualization Software 2.41. Harvard, MA: Analytic Technologies.

Borgatti, S. P., M. G. Everett, and L. C. Freeman. 2002. Ucinet for Windows: Software for Social Network Analysis 6. Harvard, MA: Analytic Technologies.

Brieger, R. L., K. Carley, and P. Pattison. 2002. *Dynamic social network modeling and analysis: Workshop summary and papers*. Washington, DC: National Academies Press.

Chertow, M. R. 2000. Industrial symbiosis: Literature and taxonomy. *Annual Review of Energy & Environment* 25(1): 313–337.

Chertow, M. R. 2007. "Uncovering" industrial symbiosis. *Journal of Industrial Ecology* 11(1): 11–30.

Chertow, M. R., W. S. Ashton, and J. C. Espinosa. 2008. Industrial symbiosis in Puerto Rico: Environmentally-related agglomeration economies. *Regional Studies*. Forthcoming.

Cohen-Rosenthal, E. 2000. A walk on the human side of industrial ecology. *American Behavioral Scientist* 44(2): 245–264.

Dekker, D., D. Krackhardt, and T. Snijders. 2005. Sensitivity of MRQAP tests to collinearity and autocorrelation. In *Working Paper Series on Research in Relationship Management*. Nijmegen, Netherlands: Nijmegen School of Management.

Desrochers, P. 2001. Cities and industrial symbiosis: Some historical perspectives and policy implications. *Journal of Industrial Ecology* 5(4): 29–34.

Ehrenfeld, J. and M. R. Chertow. 2002. Industrial symbiosis: the legacy of Kalundborg. In *A Handbook of Industrial Ecology*, edited by R. U. Ayres and L. W. Ayres. Cheltenham, UK: Edward Elgar.

Frosch, R. A. and N. E. Gallopoulos. 1989. Strategies for manufacturing. *Scientific American* 266: 144–152.

Gibbs, D. 2003. Trust and networking in inter-firm relations: The case of eco-industrial development. *Local Economy* 18(3): 222–236.

Gibbs, D., P. Deutz, and A. Proctor. 2005. Industrial ecology and eco-industrial development: A new paradigm for local and regional development? *Regional Studies* 39(2): 171–183.

Gordon, I. R. and P. McCann. 2000. Industrial clusters: Complexes, agglomeration and/or social networks. *Urban Studies* 37(3): 513–532.

Hanneman, R. A. and M. Riddle. 2005. *Introduction to social network methods*. Riverside, CA: University of California.

Harrison, B., M. R. Kelley, and J. Gant. 1996. Innovative firm behavior and local milieu: Exploring the intersection of agglomeration, firm effects, and technological change. *Economic Geography* 72(3): 233–258.

Hoffman, A. 2003. Linking social systems analysis to the industrial ecology framework. *Organization & Environment* 16(1): 66–86.

Howard-Grenville, J. and R. Paquin. 2006. Organizational dynamics in industrial ecosystems: Insights from organizational behavior theory. In *Dynamics of industrial ecosystems*, edited by M. Ruth and B. Davidsdottir. Forthcoming.

Inland Chemical. 1973. *Final environmental impact statement for Inland Chemical Project, Manati, Puerto Rico*. San Juan, Puerto Rico: Administracion de Fomento Economico.

Jacobsen, N. 2005. Industrial symbiosis in the making: Bridging social and technical explanations—The case of Kalundborg, Denmark. Paper presented at 11th Annual International Sustainable Development Research Conference, 6–8 June, Helsinki, Finland.

Jacobsen, N. and S. Anderberg. 2005. Understanding the evolution of industrial symbiotic networks: The case of Kalundborg. In *Economics of industrial ecology: Materials, structural change, and spatial scales*, edited by J. C. J. M. van den Bergh and M. Janssen. Cambridge, MA: MIT Press.

Markusen, A. 1996. Sticky places in slippery space: A typology of industrial districts. *Economic Geography* 72(3): 293–313.

McMahon, S. M., K. H. Miller, and J. Drake. 2001. Networking tips for social scientists and ecologists. *Science* 293: 1604–1605.

Microsoft Corporation. 2002. Microsoft Access 10.2627.2625. Redmond, WA: Microsoft Corporation.

Porter, M. E. 1998. *On competition*. Cambridge, MA: Harvard Business School.

Scott, A. J. 2004a. A perspective of economic geography. *Journal of Economic Geography* 4(5): 479–499.

Scott, W. R. 2004b. Reflections on a half-century of organizational sociology. *Annual Review of Sociology* 30(1): 1–21.

SPSS Inc. 2005. SPSS 14.0 for Windows—Graduate student edition. Chicago: SPSS Inc.

Stevenson, W. B. and D. Greenberg. 2000. Agency and social networks: Strategies of action in a social structure of position, opposition, and opportunity. *Administrative Science Quarterly* 45(4): 651–678.

US Census Bureau. 2005. 2002 economic census of island areas: Puerto Rico manufacturing. Washington, DC: US Census Bureau.

Uzzi, B. 1996. The sources and consequences of embeddedness for the economic performance of organizations: the network effect. *American Sociological Review* 61(4): 674–698.

Van Beers, D., G. Corder, A. Bossilkov, and R. Van Berkel. 2007. Industrial symbiosis in the Australian minerals industry. *Journal of Industrial Ecology* 11(1): 55–72.

Van Berkel, R. 2004. Industrial symbiosis in Australia: An update on some developments and research initiatives. In *The Industrial Symbiosis Research Symposium at Yale: Advancing the study of industry* *and environment*. New Haven, CT: Yale School of Forestry & Environmental Studies.

Wasserman, S. and K. Faust. 1994. *Social network analysis: Methods and applications*. Cambridge, UK: Cambridge University Press.

Wellman, B. 1988. Structural analysis: From method and metaphor to theory and substance. In *Social Structures: A Network Approach*, edited by B. Wellman and S. D. Berkowitz. Cambridge, UK: Cambridge University Press.

White, H. C., S. A. Boorman, and R. L. Brieger. 1976. Social structure from multiple networks: I. Blockmodels of roles and positions. *American Journal of Sociology* 81(4): 738–780.

Zero Emissions Research and Initiatives. 2005. ZERI case studies. Montfort Boys Town, Fiji: Zero Emissions Research and Initiatives. http://www.zeri.org/index.cfm?id=projectFiji. Accessed 2005.

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