Assessing the "Short Mental Distance" in Eco-Industrial Networks

Weslynne S. Ashton and Ariana C. Bain

Keywords:

eco-industrial development
industrial ecology
industrial symbiosis (IS)
industrial waste
social capital
social network analysis

Supplementary material is available on the *JIE* Web site

Summary

Like many economic exchanges, industrial symbiosis (IS) is thought to be influenced by social relationships and shared norms among actors in a network. While many implicit references to social characteristics exist throughout the literature, there have been few explicit attempts to operationalize and measure the concepts. The "short mental distance," "trust," "openness," and "communication" recorded among managers in Kalundborg, Denmark, set a precedent for examining and encouraging social interactions among key personnel in the dozens of eco-industrial networks around the world. In this article we explore the relationships among various aspects of social embeddedness, social capital, and IS. We develop a conceptual framework and an approach using quantitative and qualitative methods to identify and measure these social characteristics, including social network structure, communication, and similarities in norms and conceptions of waste, and apply them in an industrial network in Nanjangud, South India. The findings suggest that there is a fairly high level of shared norms about dealing with waste—the "short mental distance"—in this network, but by-product transactions are only weakly correlated with the structure and content of communication among managers. Replication of this approach can increase the understanding and comparability of the role of social characteristics in eco-industrial activities around the world.

Introduction

Industrial ecology offers a vision for sustainable operation of industrial systems based on insights from the organization of biological ecosystems. Kalundborg, Denmark, was celebrated in the early 1990s as the first "industrial ecosystem" embodying this vision with companies minimizing waste output and reusing by-products from different industries. Since its "uncovering," Kalundborg's self-organized eco-industrial network (EIN) continues to adapt to changing conditions while contributing to the economic and environmental viability of the region. Many analyses of the region's successful industrial symbiosis (IS) have placed significant emphasis on the importance of "short mental distance," "trust," "openness," and "communication" among company managers (Chertow 2000; Ehrenfeld and Gertler 1997; Gertler 1995; Jacobsen and Anderberg 2005). The experience in Kalundborg set a precedent for examining and encouraging social interactions among key personnel in the dozens of eco-industrial networks that have since developed around the world. The IS literature is peppered with terms that implicitly refer to the characteristics of the social system underlying symbiotic activities. This article builds on this body of work and addresses the question, "how do the social relationships among managers (social embeddedness) relate to the presence of IS and other inter-firm relationships in an industrial network?"

Several authors emphasize social embeddedness and social capital as key constituents of the characteristics of industrial networks. Social embeddedness formalizes how recurring

Address correspondence to: Weslynne Ashton, Illinois Institute of Technology, Stuart School of Business, 565 W. Adams St., Chicago, IL 60661, USA.
Email: washton@stuart.iit.edu

DOI: 10.1111/j.1530-9290.2011.00453.x

Volume 16, Number 1

social interactions among actors shape economic activities (Granovetter 1985). An actor becomes embedded within a group through multiple types of repeated interaction with others in that group. These repeated interactions lead to the creation of shared norms influencing behavior as well as patterns of relationships that are referred to as social structure or social networks. Besides connecting individual actors, social networks are also repositories of culture, including information, norms, and pressures, as well as fungible resources. Individuals within the networks have variable access to these resources depending on to whom they are connected, and others' perceptions of them. Actors are said to possess social capital if they can utilize the network to access these resources (Finsveen and Van Oorschot 2008).

This article conceptualizes and develops an approach for measuring the social characteristics in eco-industrial networks (a subset of industrial networks in which IS is found), using a single case study to test its applicability. Initially, we review the relevant literature from the fields of IS, social embeddedness, and social capital. We draw connections among these fields to operationalize aspects of social embeddedness and social capital that are pertinent to eco-industrial networks and propose how they can be measured. Subsequently, we develop a methodological approach for assessing social embeddedness and social capital and how they relate to IS, and then measure these characteristics in a case study in an industrial area around Nanjangud, India.

Literature Review

Social Embeddedness and Social Capital

Sociologists have long argued that there is an important social dimension influencing economic behavior, which is termed social embeddedness (Granovetter 1985). The concept places individual and organizational actions within the context of social relationships as well as market rationality. An actor is said to be socially embedded in a particular group if that actor's behavior is influenced by relationships with others and the norms that are shared by the group. Repeated interactions and multiple relationships give rise to what is termed social structure or social networks. The social structure and the repeated interactions of individuals or organizations within those structures constitute social embeddedness (Gulati and Gargiulo 1999; Kilduff et al. 2006; Uzzi 1996). An actor may be embedded through multiple dimensions (Zukin and DiMaggio 1990):

- Structural: morphology of the social network and position of the actor in it;
- Political: influence of the political system, and distribution of power among actors;
- Cultural or relational: trust, shared norms, and expected behaviors influencing actors in the network; and
- Cognitive: shared mental models for decision-making and systems of meaning.

Socially embedded firms engage in relationships that emphasize trust, cooperation, and repeated interactions on multiple issues (Uzzi 1997). These interactions can contribute to both long-term and immediate profitability, as socially embedded actors may have differentiated access to tangible or intangible resources and lowered transaction costs for establishing and enforcing contracts. Bourdieu (1986, 248–249) describes social capital as "the sum of the resources, actual or virtual, that accrue to an individual or group by virtue of possessing a durable network of more or less institutionalized relationships of mutual acquaintance and recognition." Nahapiet and Ghoshal (1998, 243) extend this definition to "resources embedded within, available through, and derived from the network of relationships." Social capital thus arises from social embeddedness, and is often characterized along similar dimensions: structural, relational/cultural, and cognitive (Nahapiet and Ghoshal 1998; Portes 1998). We follow this logic and conceptualize social capital as resulting from the process of social embeddedness among individual human actors (i.e., repeated interactions that create shared culture, norms, and a social network structure). Either the whole network or individuals within the network can possess or benefit from social capital (Brondizio et al. 2009; Uzzi 1997). Here, we focus on the individual level, as we are interested in how distinct managers utilize their relationships to access key resources for their firms.

In India, social capital and interfirm information and resource sharing are noted to be important contributors to the economy's rapid growth (D'Costa 1998; Tewari 1998). Tewari (1998) examined the success of small-scale industries in Ludhiana and found that interfirm cooperation can "defray costs, spread or share risks and hence cope with uncertainty in product and input markets" (p. 1391). Other studies find that a history of collective action builds social capital and facilitates continuing cooperation, but that this alone is insufficient to ensure success (Krishna 2004; Narayanan and Livermore 2007).

Social network analysis (SNA) has emerged as the preferred method for measuring social embeddedness and social capital by counting the number and types of relationships (or ties) among individuals and the possession of individual attributes or collective goods within networks. Research on social capital most often aims to capture the extent to which actors can obtain desired outcomes or resources through network connections (Van Deth 2003). However, recent work highlights the importance of identifying what actual resources a network transmits and the cultural context that frames the transfer, rather than simple structural connectivity among actors (Finsveen and Van Oorschot 2008; Nahapiet and Ghoshal 1998; Portes 1998). Researchers emphasize that ignoring cultural and cognitive aspects of embeddedness misses the full range of social effects on the group's activities (Finsveen and Van Oorschot 2008).

Industrial Symbiosis

Industrial symbiosis refers to the shared management of physical resources for individual and collective advantage of distinct firms in relative geographic proximity (Chertow 2000). The

term EIN refers to a group of companies engaged in IS (and other sustainable practices) either colocated in an industrial park or across a larger region. EINs may simply be considered as a subset of industrial networks, where IS is practiced. IS can emerge in industrial clusters, especially those where natural resources are constrained, where regulations encourage resource conservation, or where the costs of residual (waste or by-products) reuse and recycling are lower than disposal (Chertow et al. 2008; Van Berkel 2006). Resource sharing within EINs may include selling residuals for reuse, shared utilities such as energy or water, informal raw material sharing, and product and raw material sales through traditional supply chain market transactions. In the last decade, various initiatives around the world have had success in facilitating IS among organizations, but this article focuses on "self-organized" EINs.

While firms commonly pursue IS for economic reasons, positive environmental externalities typically accompany the interfirm synergies. Companies engaging in by-product synergies often enter into contracts to formalize the rules of their relationship, such as the price, quantity, frequency, and quality of residual materials that are to be traded over a particular time period. Some arrangements are less formal, and may occur on an ad hoc basis. Interfirm cooperation appears to be embedded within a history of personal relationships among managers and successful collective action, beyond the technical compatibility of material inputs and outputs, economic feasibility of exchanges, and facilitative regulatory climate (Ashton 2008; Baas and Boons 2004; Jacobsen and Anderberg 2005).

Measuring Social Characteristics in Eco-Industrial Networks

A growing number of researchers have examined the social characteristics related to IS (Baas and Boons 2004; Boons and Howard-Grenville 2009; Chertow and Ashton 2009; Cohen-Rosenthal 2000; Hoffman 2003; Jacobsen 2005; Tilleman et al. 2009). In applying the concept of embeddedness to industrial ecology, Boons and Howard-Grenville (2009, 15–18) note, "at the core of industrial ecology is its focus on energy and material flows in industrial processes. For a social scientist, the immediate question is: how are these flows shaped through human interaction?" They suggest two other dimensions of embeddedness that ought to be considered: spatial embeddedness, which emphasizes geographic proximity, and temporal embeddedness, which situates actions within a historical context (Boons and Howard-Grenville 2009). In this article we focus on structural, cultural, and cognitive dimensions of embeddedness.

Several authors have drawn on SNA to quantify the types and extent of material synergies and information flows in these systems (Ashton 2008; Domenech and Davies 2009, 2011; Paquin and Howard-Grenville 2009). Ashton (2008) found significant correlations among personal relations, social network position, and synergies among pharmaceutical manufacturers in Puerto Rico. Domenech and Davies (2011) highlight the importance of treating knowledge and information flows as distinct from material flows, as the former are much more prevalent than the latter in EINs.

Communication in an EIN occurs for reasons ranging from social engagements to discussing labor practices and safety at different facilities, or contracting the sale of products or by-products. Cultural practices, expectations, and norms may coevolve with the system's social network structures. Previous work suggests that shared norms related to conceptions of waste and what to do with it, as well as communication across diverse industrial sectors, increase as EINs evolve (Ashton 2008; Chertow and Ashton 2009; Hoffman 2003; Howard-Grenville and Paquin 2008; Jacobsen 2005). We characterize these aspects as the cultural and cognitive dimensions of embeddedness, in addition to examining the social network structure for this study.

Conceptual Framework

Our conceptual framework describes the social characteristics in an EIN and the methodological approach suggests a means to measure these characteristics alongside a more typical material flow analysis. The social characterization examines the physical and information exchanges at the firm level and social interactions at the manager level, and builds upon the methodology of Ashton (2008). Our research focuses on the question: How do the social relationships among managers (social embeddedness) relate to the presence of IS and other interfirm relationships in an EIN?

A precursor to this question requires an understanding of how social embeddedness and social capital manifest in EINs. Figure 1 illustrates the relationship between the concepts described below.

As a first step, we conceptualize interfirm resource synergies—specifically product sales, by-product synergies, and informal exchanges—as outcomes of social and economic decision making, including considerations of resource availability from the ecosphere and regulations imposed by society. These synergies exist along a theoretical continuum from purely arms-length transactions, based on price and market conditions, to purely socially embedded, based on the relationships among managers and their individual possession of social capital, or access to resources in the network. Arms-length transactions include trading of resources for which there is a well-established market value, such as products. Socially embedded interactions include sharing resources that are less fungible, such as asking for advice, and are highly dependent on the possession of social capital. We treat interfirm relations as outcomes that may or may not be influenced by social embeddedness measures.

Second, we assert that relationships among the managers, rather than among the firms, provide the most appropriate level for measuring the presence of the three dimensions of social embeddedness covered in this article—structural, cultural, and cognitive. They span different levels of organization: individual managers and firms. Each dimension has multiple explanatory variables, or components, for the observed outcomes of interfirm resource synergies. We measure these dimensions and explanatory variables by combining social network data with qualitative data about communication and managers' relationships. The

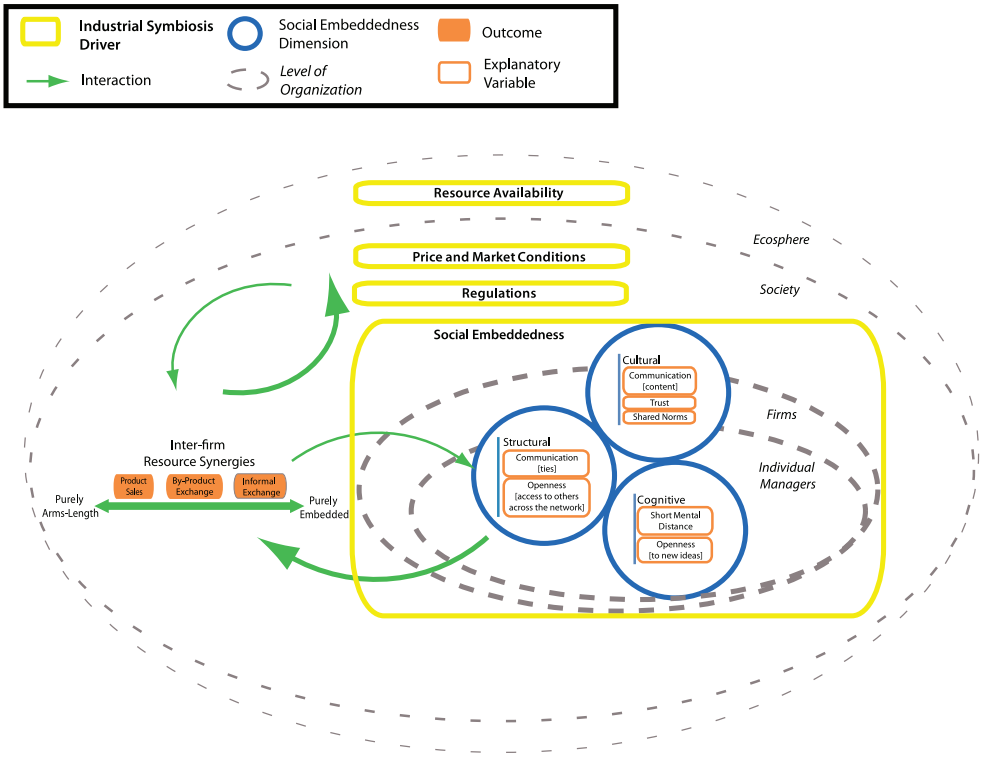

Figure 1 Industrial symbiosis and social embeddedness conceptual framework. The graphic illustrates how interfirm relations are influenced by the forces of price and market conditions, regulations, resource availability, and social embeddedness. The explanatory variables used in this study are positioned within three dimensions of social embeddedness (structural, cultural, and cognitive), which are possessed by individual managers, firms, and society. Note: Political, spatial and temporal aspects of embeddedness are not represented. A manager's ability to utilize social embeddedness factors for accessing resources through the network constitute social capital. Thus the interfirm relations may be more or less dependent on each individual's social capital.

role of IS drivers other than social embeddedness—regulations, price and market conditions, and resource availability—is acknowledged, but treated as exogenous and occurring at levels of organization not covered in this study. Therefore, other IS drivers are not explicitly quantified as explanatory variables in this framework.

Finally, we hypothesize that the trade of resources with less established market value, such as by-products, would be more closely correlated with measures of social embeddedness at the managerial level than product sales, but less than informal exchanges. That is, they occur somewhere in the middle of this continuum, with social factors mediating economic and technical considerations. Social capital and social embeddedness are iteratively related (Giddens 1979). So while we treat interfirm relations as potential outcomes from managers' social ties and possessing social capital, firm relations also contribute to the embeddedness of managers who continually interact because of and through their business relationships, through the process of structuration.

We align terms that the IS literature often uses to describe social characteristics in networks with social embeddedness terms at the managerial level (table 1), but acknowledge that there could be other ways to define and align these terms. We place "short mental distance" in the category of cognitive embeddedness after Chertow and Ashton (2009), who defined the latter as "mental distance between firm managers to perceive opportunities for collaboration and material reuse/exchange." In some cases we decompose terms commonly used in the IS literature into different social embeddedness dimensions. For example, cognitive and structural dimensions could define "openness." The former refers to the shared mindset of actors and whether they are open to new ideas, and could more accurately be termed "open-mindedness." The latter, structural openness, addresses the actual structure of relationships, describing how much actors interact with those to whom they are directly connected versus accessing others outside their core group. We then align these terms with social network indicators for the structural dimension and code responses for cultural and cognitive dimensions.

Methodology

Data Collection and Analysis

The research team conducted field surveys in June–July 2008 in two adjacent industrial estates in Nanjangud, South India.

Table 1 Framework for measuring social characteristics related to industrial symbiosis in this study

Social embeddedness dimension	Industrial symbiosis term	Measures
Cognitive	Short mental distance	Factors in managers' decision making on issues such as what to do with waste, where to get advice
	Openness	Open-mindedness to new ideas and innovations
Cultural	Communication	Content of communication, such as how often managers communicate, what they talk about
	Trust	Willingness to work with others
Structural	Communication	Overall network structure and connectivity regarding information flow within individual's ego-network
	Openness	Degree of structural openness to access others beyond immediate neighbors in network

Nanjangud is approximately 20 kilometers (km) from Mysore in the Indian state of Karnataka, with a population of about 50,000. The Nanjangud Industrial Area (NIA) contains two adjacent industrial estates—Karnataka Industrial Area Development Board Estate (KIADB) and Thandya—populated by a diverse mix of more than 60 independent enterprises[1] spanning a size range from microscale one-person informal enterprises to large, domestically owned companies and subsidiaries of multinational corporations. Most of the companies in the NIA are also members of the Nanjangud Industrial Association, and initial surveys were done with association members.

We followed a structured interview format with managers of 42 facilities who provided annual material flow analysis (MFA) data for their facilities from 2007 and information about their relationships with others in the network (see Supporting Information S1 on the Journal's Web site for the survey instrument). Interviewees were presented with a list of names of companies and managers in the NIA and were asked a series of questions about their interactions with those on the list (a whole network approach). In two instances, facilities had the same management, so the social characteristics data for each have been included as one facility; one facility surveyed had no inputs or outputs and was subsequently determined to be nonoperational, lowering the number of respondents to 39.

A detailed description of the MFA methods and results was previously published (Bain et al. 2010). Material flow data consisted of quantities of raw materials, water, and energy consumed and the quantities of products, waste, and energy generated by each of the industrial facilities.

The social network data identified relationships amongst firms and relationships amongst managers in those companies. At the firm level, we focused on relationships that indicate the trade of physical resources and informal interactions; these constituted our dependent variables that were hypothetically the outcome of the respective manager's social embeddedness. Specific variables were any relationship (any business or nonbusiness relationship), formal (contractual relationship), informal (relationship without a contract, such as giving or receiving advice and borrowing equipment or raw materials), by-product exchange (sale or donation of a by-product), and product sales (sale of a product). For individuals, survey questions focused on the types of relationships, frequency, and nature of communication among managers in the NIA and decision making regarding what to do with waste materials; these were our explanatory variables. Specific variables included recognition (interviewee recognizes the name of other managers), know personally (interviewee has met and interacted with another manager in the network), any communication (interviewee has some communication on an ongoing basis with another), communication frequency (more than once per week, more than once per month, less than once per month), and communication content (interviewee discusses business, personal, or both with another).

For the majority of relationships binary coding (0, 1) indicated the absence or presence of a particular tie among each pair of actors. Some ties, such as communication frequency and means of communication, were coded as ordinal values (0, 1, 2, 3) to indicate the strength of those ties. The interfirm and interpersonal data for each type of relationship were entered as two-dimensional tables or sociomatrices on separate worksheets in Microsoft Excel. Rows represented respondents and columns represented the person or firm the respondent was reporting on. Ties are directional. For example, one actor might claim to know another actor, but the latter might not acknowledge the former. As a result, some sociomatrices were asymmetrical because of differences in each actor's reported ties. In keeping with the definition of social capital as "access to resources," we based the analyses on "in-degree" ties, or responses received about each actor, rather than claims made by the actors about others ("out-degree"). In-degree represents how others perceive an actor in the network, thus persons and companies perceived as more "worth knowing" received more claims from others and would be expected to possess higher levels of social capital that enable them to obtain resources from others. The sociomatrices were transferred to UCINET (Borgatti et al. 2002) to calculate various SNA metrics, and to NetDraw for visualization of the network structure and connectivity (Borgatti 2002) (see Supporting Information S2 on the Web for SNA results).

Cultural embeddedness was recorded as the content of communication among managers in the network. Managers were

asked to detail how often they communicated with others in the network (more than once per week, more than once per month, less than once per month), what they spoke about (business, personal, both), and how they communicated (in person, by phone, at meetings). Their responses were coded with ordinal values where higher numbers indicated greater frequency or intensity.

As we related cognitive embeddedness to the terms "short mental distance" and "open-mindedness" in IS networks, we were interested in whether managers shared conceptions about what to do with residual materials and how they would seek out information about the reuse potential of these materials. In order to assess shared conceptions of what is a waste versus a residual material with value, managers were asked to rank the factors they consider important in making decisions about to whom they will sell or give their residuals. Their responses were manually coded as "arms-length" or "embedded," based on the degree of economic or formal emphasis in the responses. We treated the frequency of similar responses as indicative of the level of cognitive embeddedness in the network.

Results

The results for the MFA and firm-level relationships are presented first, followed by the cognitive, cultural, and social embeddedness at the manager level, and finally the statistical network correlation analyses.

Measuring Material Flows and Other Relationships Among Firms

The 39 facilities in the study generated 897,210 metric tons (t) of nonhazardous industrial residuals in 2007.[2] The companies reported recovering or sending 893,120 t (99.5%) for reuse or recycling, and disposing of 4,090 t either at the generating facilities or off-site. Of the 893,120 t of recovered residuals, the generating facilities reused 81% (724,630 t) on-site, while 19% left the gates of generating facilities. Of the materials sent off-site, the NIA generating facilities directly transferred 67% of the materials (113,650 t) to other parties who utilized the residual as is. However, 45,260 t (27%) of nonhazardous ash reported as transferred for direct reuse could not be verified. The informal recycling market received 9,580 t (6%) of the balance (Bain et al. 2010).

By-Product Synergies

Eleven symbiotic interactions were uncovered and verified as occurring within the boundaries of the study area (figure 2). Ten of these were by-product synergies between pairs of facilities, and one involved the supply of electricity from one company to another on an as-needed basis. Looking beyond the estate boundaries, a further 17 instances were recorded of by-product transfers from facilities within the NIA to others outside the NIA for reuse. Additionally, 17 NIA facilities use by-products from other facilities, such as agricultural residues

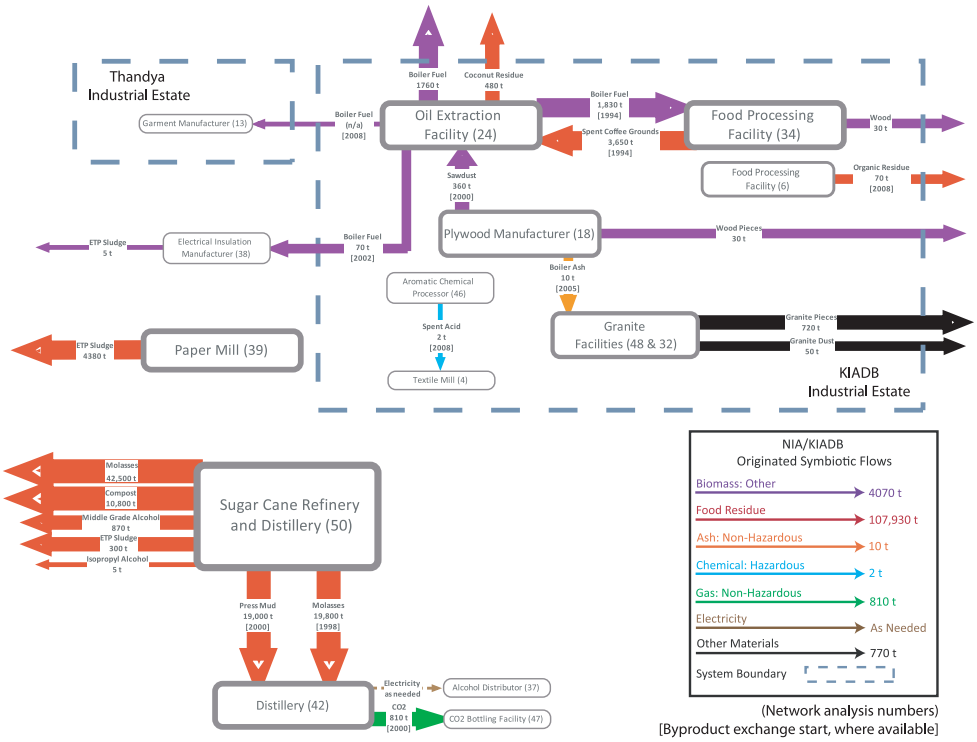

Figure 2 By-product synergies originating from Nanjangud Industrial Area companies (2007). Arrows connecting companies indicate the quantity and direction of the material flow and the year the synergy was started (where available). Node positions reflect approximate geographical locations in Nanjangud.

Table 2 Network characteristics for interfirm relationships

Metrics	Any relationship	Informal exchange	Product sale	By-product exchange
Number of firms with tie	32	29	25	12
Average degree (number of ties per firm) (standard deviation in parentheses)	5.31 (5.44)	2.49 (3.01)	1.0 (1.34)	0.46 (0.87)
Density (ratio of actual ties to all possible ties)	0.14	0.07	0.04	0.01
Compactness (measures connectedness of network: value is 1 when all are connected, and 0 when all are isolated)	0.315	0.183	0.097	0.02
Average constraint (measures how constrained each node is by neighbors: value is 1 when completely constrained, low when more open, and 0 when isolated)	0.314	0.373	0.425	0.259

Note: All calculations were conducted in UCINET.

compressed into briquettes, as raw material inputs. In total, 9.9% (288,714 t) of the total 2,910,169 t of inputs from outside the NIA come from residuals. However, these input numbers do not count by-products generated by NIA companies that serve as raw materials for other processes, either within their own facilities or to others.

Interfirm Relations

Interviewees reported on the relationships that their company had with others in the study. Of the 39 interviewed, 32 were members of the Nanjangud Industrial Association and 7 were not. Notable relationships are reported here (see table 2) along with network statistics for each of these ties:

- Any relation: having any business or nonbusiness relationship with another in the network.
- Informal exchange: providing or receiving technical advice or raw materials at no cost.
- Product sale: selling products to another company.
- By-product synergy: selling or donating by-products to another.

With the exception of "any relationship," these are distinct ties that may have little to do with each other. Almost all (32 of 39) companies reported having a relationship with other firms in the network, slightly fewer (29 and 25, respectively) have at least one informal or product sales relation, and few (12) trade by-products with others in the network. Compactness measures how tightly actors connect to each other, and is very low for all except "any" relationship, suggesting that firms are not closely bonded to each other for these exchanges. The constraint values, or how dependent an actor is on its immediate connections for accessing the rest of the network, are fairly low, suggesting that actors are open to others beyond their immediate neighbors. Figure 3 illustrates the ties for by-product synergies and informal exchanges. The latter appears much more prevalent. Interestingly only three (of the eight) pairs reporting by-product synergies also report informal exchanges, suggesting that most do not consider these synergies to be an informal relationship.

Measuring Social Characteristics among Managers

Cognitive Embeddedness

We asked questions to determine whether managers shared conceptions about what to do with waste materials. When asked what drives reuse decisions for a new residual material, 14 of the 39 managers ranked "legal liability" as their top consideration, 13 ranked "cost," and 2 ranked both of these equally. Three respondents ranked "location," two ranked "simple processing," and two ranked "personal reference," while three did not respond. We coded both of the top responses as "arm's-length," as they suggest a high priority on formal regulatory or market-driven viability of disposal or reuse options.

Another question asked how managers would find potential buyers for a new residual. Responses were coded to indicate either "arms-length" or market-based, "embedded" or personal communication-based, or "hybrid" approaches that combined the two. Thirteen of the managers indicated a preference for an arms-length approach, with illustrative responses like:

- "We would issue a call for tenders or put an advertisement in the newspaper."
- "We would ask the Pollution Control Board what to do with it."

Eleven indicated "embedded" preferences and 11 indicated "hybrid" approaches combining the two. Four companies did not respond. Typical embedded responses were

- "We identify the potential value of a by-product and try to find a buyer directly."
- "We go through personal references and then base our decision on cost."

Hybrid responses included

- "We would use our current scrap dealers to distribute information and advertise it in the newspapers."
- "We would first look within the company for a solution, then approach the Confederation of Indian Industry or

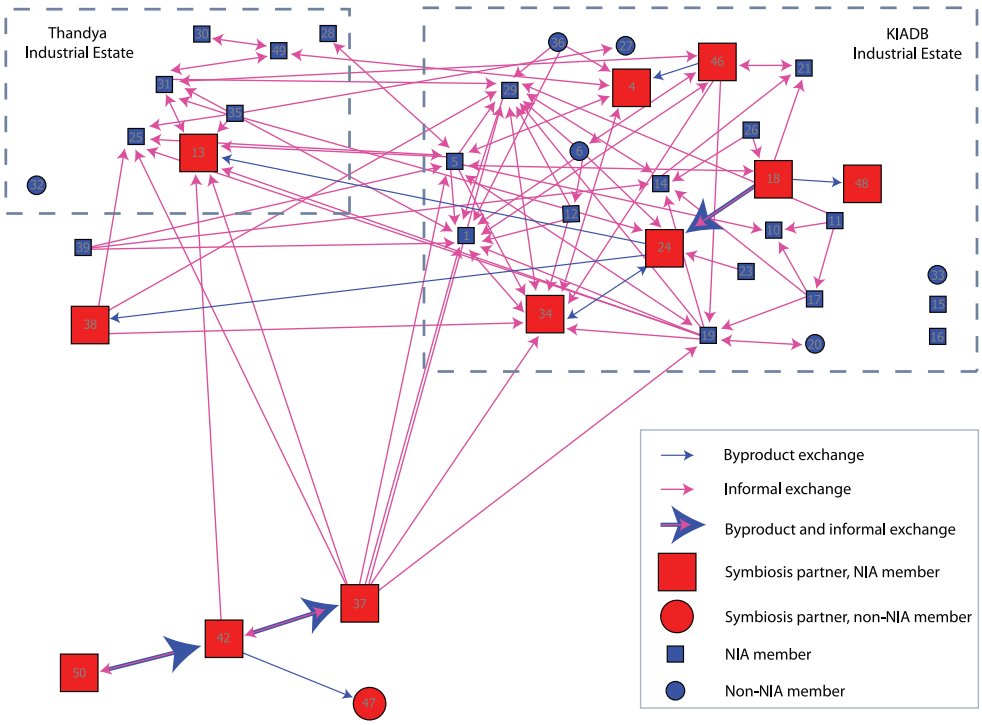

Figure 3 Network structure for informal and by-product exchanges among Nanjangud Industrial Area companies. Arrows connecting company nodes indicate the type of relationship (informal or by-product exchange) and the reported direction. Node positions reflect approximate geographical locations in Nanjangud.

another association to help us find a buyer, then we might approach the Pollution Control Board to see what to do with it."

These responses indicate that while economics and liability are the primary drivers, almost 60% of the managers in this network would use an "embedded" approach, on its own or in combination with market approaches, to deal with a new residual stream. These results suggest that there is a shared conception of the high value of residual materials, and that leveraging social capital is an appropriate means by which to find buyers for these materials.

Cultural Embeddedness

We asked questions to understand the strength and intricacies of communication among those who report knowing each other to determine cultural embeddedness, defined above as the content of communications. In communities with high levels of social capital, one would expect frequent communication on multiple issues via various means.

Amongst the managers of companies engaging in synergies, there was curiously a low level of reported communication (see table 3). Of the 11 synergies, 3 reportedly had no communication; communication was reported by only one of the actors in each of six pairs, and in only one pair (in which there was a two-way exchange) did both report communicating with each other frequently. In hindsight, we believe this may have been due to interviewing persons who may not have been responsible for the synergy, and therefore would not have communicated with the identified persons. We adjusted the communication data for logical consistency by including 1s where interviewees had indicated a synergy because it requires communication between partners. We feel justified in this approach, as even with the reported bidirectional exchange, confirmation from one of the actors occurred only after a return visit and follow-up question to verify that synergies actually took place. We were unable to return to all the actors for this additional verification. Descriptive statistics about cultural embeddedness for the whole network are also included in table 3, and are based on the responses about each manager (in-degree) rather than interviewee responses (out-degree).

Structural Embeddedness

We also used the communications questions to quantify the structural embeddedness based on the premise that repeated interactions create the network morphology. Figure 4 illustrates the communication frequency tie. Very few managers (seven) have frequent communication with more than two others. Communication also appears to be more frequent among those who are members of the NIA than among those who are not. There also appears to be strong spatial orientation regarding communication. Managers have numerous ties with managers whose companies are located close to theirs, and a few have ties with actors in other parts of the region. Communication

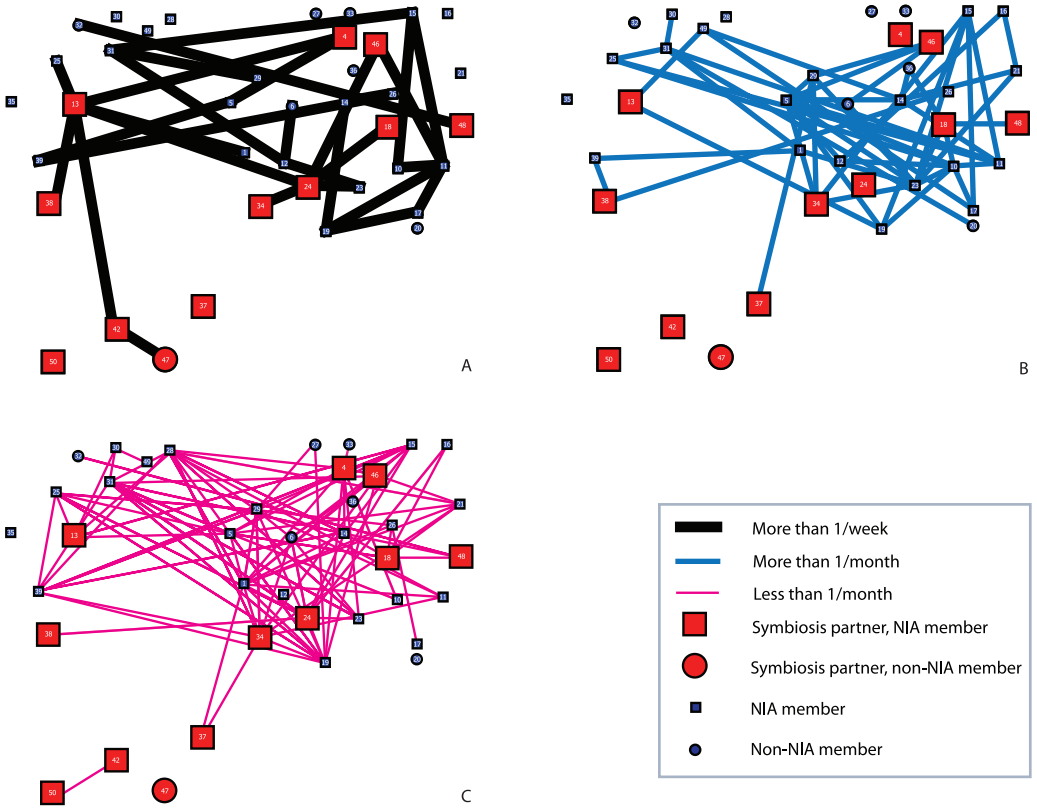

Figure 4 Communication frequency among company managers in the Nanjangud Industrial Area - A: more than once per week, B: more than once per month, C: less than once per month. The thickness of lines connecting nodes indicates the frequency of communication among managers. Node positions reflect approximate geographical locations in Nanjangud.

Table 3 Communication among managers of firms with synergies, and descriptive statistics for communication for the whole network

Pair	Material traded	Years trading	Years known	Communication content	Communication frequency	Communication means
46→4	Spent acid	<1	4	Business	<1/month	Telephone
18→48	Boiler ash	3	1	Personal	<1/month	In person, telephone
18→24	Sawdust	8	10	Business	>1/week	In person
34→24	Coffee grounds	14	4	Business	>1/week	In person
24→34	Boiler fuel	14	4	Business	>1/week	In person
24→38	Boiler fuel	6	NR	NR	NR	NR
24→13	Boiler fuel	<1	1	Business	>1/week	In person
50→42	Molasses	10	NR	NR	NR	NR
50→42	Press mud	8	NR	NR	NR	NR
42→47	Carbon dioxide	6	8	Business and personal	>1/week	In person, telephone
42→37	Electricity, as needed	NR	NR	Business and personal	>1/week	In person, telephone
Whole network statistics			<1 year = 15%; <5 years = 56%; >5 years = 29%	Business = 72%; Personal = 12%; Business and personal = 16%	>1/week = 19%; >1/month = 27%; <1/month = 54%	Telephone = 22%; NIA = 16%; In person = 43%; All of the above = 19%

Note: NR = not reported.

Table 4 Network metrics for any communication among actors engaged in synergies

Interviewee	Degree (in)	Degree (out)	Constraint
#4	7	6	0.345
#13	3	11	0.254
#18	9	3	0.334
#24	9	13	0.761
#34	13	4	0.273
#37	1	4	0.549
#38	4	1	0.541
#42	4	3	0.265
#46	6	8	0.311
#47	1	0	1.00
#48	2	3	0.462
#50	1	1	1.00

frequency does not appear to follow this pattern, with frequent communication among actors not spatially colocated. Table 4 shows structural metrics at the actor level for communication of only the 12 actors engaged in synergies.

The difference between in-degree (ties claimed by others about the actor) and out-degree (ties claimed by the actor about others) is indicative of the perceived reputation and social capital of the actors, with those perceived more highly receiving more claims than were given out. For example, #34, the manager of a large and well-respected company, said he communicated with 4 others, but 13 claimed to have regular communication with him. The actors with the highest constraint (1.00) are only connected to a single other actor, therefore their access to communication with others would be mediated through their one connection and their structural openness would be very low. Conversely, those with low constraint have access to information from multiple others in their network and are more open structurally.

Measuring Relationships among Social Embeddedness, Social Capital, and Industrial Symbiosis

The final step in the analysis compared the network structures at the firm and managerial levels for correlations. Correlation analyses in UCINET measured the similarity in network structures for different types of interfirm relationships. For firms, matrix correlation tests for informal exchanges, product sales, and by-product synergy ties measure the level of similarity among them. Informal relations and product sales correlated strongly and significantly with each other, but neither had significant correlation with the synergy ties. The lack of correlation may have resulted from the small number of intranetwork synergies and relatively larger number of informal exchanges and product sales.

Analyzing the interfirm ties against the individual-level managerial ties, informal firm relationships showed the strongest correlations. Both product and by-product transfers showed lower, but significant, correlation at a $p < 0.05$ level (table 5). As we have just a snapshot in time, it is impossible to say whether one type of relationship may precede another. The significantly stronger correlation between the managerial and informal relations suggests that this relationship is more heavily reliant on social capital than the others.

By-product synergies appear to be more closely related to product sales from the perspective of personal communication, indicating that economic value influences transactions more than the social structure. This contradicts our hypothesis that it would be more closely related to social characteristics. Logistic regressions between the presence of symbiotic ties and individual managerial (ego) characteristics, such as constraint, did not reveal any definitive correlations. This suggests that individual social structural attributes may not be good predictors of engaging in self-organized symbiosis, at least in this case or possibly because of the small sample size.

Discussion

Social Embeddedness, Social Capital, and Industrial Symbiosis in Nanjangud

Measuring different components of embeddedness using individual managerial relationships, and how they correlate with the presence of interfirm relations enables a deeper understanding of the role of social factors in the Nanjangud EIN. By focusing on the firm-level structural relations, we observe that by-product synergies resemble product sales more closely than informal relations. Measures of social embeddedness (personal interaction and communication) among managers correlate much more strongly with informal exchanges than either product sales or synergies. Informal relationships, such as giving advice or borrowing equipment, present values that are not easily

Table 5 Correlations between "informal exchange," "product sales," and "by-product synergy" and interpersonal relational ties

Interfirm tie	Informal	Product	By-product
Know personally	0.314 ($p = 0$)	0.164 ($p = 0$)	0.165 ($p = 0$)
Years known	0.262 ($p = 0$)	0.166 ($p = 0$)	0.066 ($p = 0.042$)
Any communication (adjusted)	0.324 ($p = 0$)	0.205 ($p = 0$)	0.243 ($p = 0$)
Communication frequency (adjusted)	0.307 ($p = 0$)	0.168 ($p = 0.005$)	0.340 ($p = 0$)
Any communication	0.313 ($p = 0$)	0.201 ($p = 0$)	0.086 ($p = 0.017$)
Communication frequency	0.291 ($p = 0$)	0.156 ($p = 0.005$)	0.162 ($p = 0$)

captured and are much more embedded in the social structure. The small, though positive and significant, correlations between both product and by-product sales, and interpersonal ties suggests that these are primarily economic transactions, and are embedded within social relations to a lesser degree. By just looking at the structural dimension of embeddedness, it would appear that synergies are not very socially embedded.

However, attention to the cognitive dimension indicates that managers universally seek remunerative uses for their residuals and therefore share the cognitive frame that residuals are potential resources. Economic and liability concerns are foremost in selecting reuse opportunities, but more than half the managers indicate they would also utilize personal contacts to find buyers for future residuals. This indicates a fairly high level of shared norms regarding waste issues and thus what is termed "short mental distance" in the IS literature. These shared norms were likely to have become more embedded over time as managers shared information about residual reuse through the network.

"Communication" patterns govern the flow of information and are indicative of cultural embeddedness and trends in the quality of relationships. Communication is spatially embedded, with the most reported number of contacts with other managers in close proximity to each other. The high prevalence of informal arrangements suggests a willingness to work with others on matters that may not have immediate fungible outcomes, which indicates strong social capital. Almost one-third of the managers reported knowing others in the network for more than five years, thus there has been adequate time to build familiarity, trust, and "quality" in relationships through repeated interactions.

Within the analysis, statistical measures such as constraint describe the relative structural "openness" of this network. The present survey did not adequately capture cognitive attitudes regarding "open-mindedness" or "trust," despite having a local researcher explain the intention of the question. Ashton's (2008) study in Puerto Rico demonstrates a significant correlation between trust and symbiosis ties, but not between trust and product sales. She suggests "familiarity and trust are 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 rather than social forces" (Ashton 2008, 48). While we do not have the data to make a comparable statement about actors in Nanjangud, such questions are important to include in culturally appropriate ways for understanding this particular social characteristic.

There are several factors that might make the NIA unique in terms of material reuse and social embeddedness: (1) a high proportion of organic, agricultural feedstocks, which makes waste reuse technically feasible because the materials are largely nonhazardous; (2) the semirural location of the industrial estates, which limits access to market resources, makes company managers remain in the same jobs longer and more reliant on each other; and (3) a strong preference for resource conservation and reuse throughout India (Bain et al. 2010). It is only through comparison with other EINs using similar methodological approaches that we may begin to understand how social characteristics affect symbiosis in different contexts.

Recommendations for Future Research on Social Characteristics of Eco-Industrial Networks

This study's approach revealed the importance of including multiple dimensions of embeddedness and not just focusing on social network connectivity. However, it was an early exploration to conceptualize and measure these factors. Future research could significantly improve the methodology:

1. Parallel analysis of interfirm and managerial network ties provides a granular perspective of the EIN by identifying the manager's network positions and relations. One challenge that this presents is that the senior people interviewed from each company may not know everything about the company's material flows or the people in other companies responsible for buying or selling residuals. In India, specifically, handling waste has cultural and class associations that influence which people manage it. This suggests a need to either interview multiple persons in a company or target the person(s) most likely to manage by-product exchanges or waste sales/purchases.
2. Interviews became lengthy, and can be shortened by emphasizing certain ties that are essential for understanding "access to resources," such as a limited number of types of interfirm relationships representing different resource transfers and emphasizing various aspects of communication among managers. The interviews included direct questions about leadership, trust, and respect that may be better captured by indirect questions that are more sensitive to cultural norms.
3. We found that aggregate network measures have limited use for understanding who has access to resources because the distribution of access among actors is important (Finsveen and Van Oorschot 2008). For example, while average degree is a standard network statistic for structural analysis, it is not particularly relevant within this context because it does not distinguish the individual connectivity of actors. Constraint measures are more meaningful at the node level rather than aggregated over the whole network, as it is each individual's own links with others that determines their access to resources. However, whole network measures are important for understanding how symbiotic ties are distributed relative to other types of interfirm relationships.
4. We suggest including data from snowball sampling that investigates actors outside of the network. Such analyses would have to focus on ego-network measures since no one actor is likely to know all those who have been identified by others.
5. In order to incorporate spatial and temporal aspects of embeddedness (Boons and Howard-Grenville 2009), data should be gathered to cover the locations of facilities, venues for common activities, and the timing of

the establishment and duration of existing and failed exchanges.

As researchers are still in the early stages of understanding how social characteristics are important, we will need to measure all aspects of embeddedness. Once we have developed a simplified methodology, we can then focus attention on teasing apart the contributions of technical feasibility, economic viability, government policies, and social characteristics in the development and continued management of symbiotic networks.

Measuring social embeddedness and social capital in EINs can inform the facilitation of network growth and sustainability in self-organized EINs. Researchers and practitioners can assess existing levels of social embeddedness by asking questions about shared norms and the structure of communication. This can determine whether there is enough fertile ground for symbiotic activities to be promoted through the existing network, as well as identify key players who are information brokers among peers or have high levels of social capital, and can be recruited to lead such efforts. In the absence of social capital in a small, spatially proximate network, effort can focus on increasing face-to-face interaction, perhaps including simple collective actions (De Groot and Tadepally 2008), which can be enough to increase bonding and information sharing. In larger facilitated networks, the work of National Industrial Security Program (NISP) practitioners demonstrates how brokers can provide a crucial link in building trust between companies that lack spatial, cultural, or structural connection (Paquin and Howard-Grenville 2009).

Conclusion

Much of the IS literature implicitly acknowledges that social factors affect the development of symbiosis. While researchers cannot yet explicitly detail the causal relationship among social factors like embeddedness and social capital and IS, our work advances the discussion by conceptualizing and developing an approach to quantify the presence of these factors and their correlation with IS. We combined quantitative and qualitative measures for structural, cultural, cognitive, temporal, and spatial aspects of social embeddedness. The results from this case study, along with a review of existing literature, suggest that the different dimensions of social embeddedness may vary in importance in different networks, and that the various forms must be considered in studies of this kind. The NIA has a fairly high level of shared cognitive framing and norms about dealing with residuals; a "short mental distance" is indeed present. Synergies were only weakly correlated with "communication" among managers, suggesting that actors in the network favor economic over social forces in their decision making about reusing residuals. The significant correlations among managers' communication and interfirm ties reinforce the iterative concept of network evolution. Our research framework can be applied to other sites in order to increase the understanding and comparability of the role of social characteristics in eco-industrial activities around the world.

Acknowledgments

The authors wish to thank Marian Chertow and Megha Shenoy for their contributions to the research project through the Yale Program on Industrial Ecology in Developing Countries. We also wish to thank the anonymous reviewers and editors for their fastidiousness in helping us to greatly improve the quality of the manuscript.

Notes

1. Even park administrators do not know the precise number of enterprises. There are many informal enterprises often with a single owner or employee. At least 12 of the enterprises are semiformal granite-cutting facilities. The field study included two of the granite facilities.
2. One metric ton $= 10^3$ kg (SI) ≈ 1.1 short tons.

References

Ashton, W. 2008. Understanding the organization of industrial ecosystems: A social network approach. *Journal of Industrial Ecology* 12(1): 34–51.

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.

Bain, A., M. Shenoy, W. Ashton, and M. Chertow. 2010. Industrial symbiosis and waste recovery in an Indian industrial area. *Resources, Conservation and Recycling* 54(12): 1278–1287.

Boons, F. and J. Howard-Grenville, eds. 2009. *The social embeddedness of industrial ecology*. Cheltenham, UK: Edward Elgar.

Borgatti, S. P. 2002. *NetDraw: Graph visualization software*. Cambridge, MA, USA: Analytic Technologies.

Borgatti, S. P., M. G. Everett, and L. C. Freeman. 2002. *Ucinet for Windows: Software for social network analysis*. Cambridge, MA, USA: Analytic Technologies.

Bourdieu, P. 1986. The forms of capital. In *Handbook of theory and research for the sociology of education*, edited by J. Richardson. New York: Greenwood.

Brondizio, E. S., E. Ostrom, and O. R. Young. 2009. Connectivity and the governance of multilevel social-ecological systems: The role of social capital. *Annual Review of Environment & Resources* 34: 253–278.

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

Chertow, M. R. and W. S. Ashton. 2009. The social embeddedness of industrial symbiosis linkages in Puerto Rican industrial regions. In *The social embeddedness of industrial ecology*, edited by F. Boons and J. Howard-Grenville. Cheltenham, UK: Edward Elgar.

Chertow, M. R., W. S. Ashton, and J. C. Espinosa. 2008. Industrial symbiosis in Puerto Rico: Environmentally-related agglomeration economies. *Regional Studies* 42(10): 1299–1312.

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

De Groot, W. T. and H. Tadepally. 2008. Community action for environmental restoration: A case study on collective social capital in India. *Environment, Development and Sustainability* 10(4): 519–536.

Domenech, T. and M. Davies. 2009. The social aspects of industrial symbiosis: The application of social network analysis to industrial symbiosis networks. *Progress in Industrial Ecology* 6(1): 68–99.

Domenech, T. and M. Davies. 2011. Structure and morphology of industrial symbiosis networks: The case of Kalundborg. *Procedia Social and Behavioral Sciences* 10: 79–89.

D'Costa, A. P. 1998. An alternative model of development? Cooperation and flexible industrial practice in India. *Journal of International Development* 10(3): 301–321.

Ehrenfeld, J. and N. Gertler. 1997. Industrial ecology in practice: The evolution of interdependence at Kalundborg. *Journal of Industrial Ecology* 1(1): 67–79.

Finsveen, E. and W. van Oorschot. 2008. Access to resources in networks: A theoretical and empirical critique of networks as a proxy for social capital. *Acta Sociologica* 51(4): 293–307.

Gertler, N. 1995. *Industrial ecosystems: Developing sustainable industrial systems*. Masters thesis, Technology & Policy Program, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA.

Giddens, A. 1979. *Central problems in social theory*. Berkeley: University of California Press.

Granovetter, M. 1985. Economic action and social structure: The problem of embeddedness. *American Journal of Sociology* 91(3): 481–510.

Gulati, R. and M. Gargiulo. 1999. Where do interorganizational networks come from? *American Journal of Sociology* 104(5): 1439–1493.

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

Howard-Grenville, J. and R. Paquin. 2008. Organizational dynamics in industrial ecosystems: Insights from organizational behavior theory. In *Changing stocks, flows and behaviors in industrial ecosystems*, edited by M. Ruth and B. Davidsdottir. Northampton, MA: Edward Elgar.

Jacobsen, N. 2005. Industrial symbiosis in the making: Bridging social and technical explanations—The case of Kalundborg, Denmark. Paper presented at the *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, USA: MIT Press.

Kilduff, M., W. Tsai, and R. Hanke. 2006. A paradigm too far? A dynamic stability reconsideration of the social network research program. *Academy of Management Review* 31(4): 1031–1048.

Krishna, A. 2004. Understanding, measuring and utilizing social capital: Clarifying concepts and presenting a field application from India. *Agricultural Systems* 82: 291–305.

Nahapiet, J. and S. Ghoshal. 1998. Social capital, intellectual capital, and the organizational advantage. *Academy of Management Review* 23(2): 242–266.

Narayanan, L. and M. Livermore. 2007. Social capital and minor irrigation projects in Tamil Nadu, India: The role of community organization in common pool resource management. *Social Development Issues* 29(2): 45–60.

Paquin, R. and J. Howard-Grenville. 2009. Facilitating regional industrial symbiosis: Network growth in the UK's National Industrial Symbiosis Programme. In *The social embeddedness of industrial ecology*, edited by F. Boons and J. Howard-Grenville. Cheltenham, UK: Edward Elgar.

Portes, A. 1998. Social capital: Its origins and applications in modern sociology. *Annual Review of Sociology* 24: 1–24.

Tewari, M. 1998. Intersectoral linkages and the role of the state in shaping the conditions of industrial accumulation: A study of Ludhiana's manufacturing industry. *World Development* 26(8): 1387–1411.

Tilleman, S., R. Paquin, and J. Howard-Grenville. 2009. Is there cash in that trash? Exploring industrial symbiosis through the resource based view of the firm. Paper presented at the *International Society for Industrial Ecology Fourth Biennial International Conference*, 21–24 June, Lisbon, Portugal.

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.

Uzzi, B. 1997. Social structure in interfirm networks: The paradox of embeddedness. *Administrative Science Quarterly* 42(1): 35–67.

Van Berkel, R. 2006. *Regional resource synergies for sustainable development in heavy industrial areas: An overview of opportunities and experiences*. Perth, Australia: Centre of Excellence in Cleaner Production, Curtain University of Technology.

Van Deth, J. W. 2003. Measuring social capital: orthodoxies and continuing controversies. *International Journal of Social Research Methodology* 6(1): 79–92.

Zukin, S. and P. DiMaggio. 1990. *Structures of capital: The social organization of the economy*. Cambridge, UK: Cambridge University Press.

About the Authors

Weslynne Ashton is an assistant professor at the Illinois Institute of Technology, Stuart School of Business, Chicago, Illinois, USA. **Ariana Bain** is a senior associate at Except Integrated Sustainability, New Haven, Connecticut, USA. The field research was conducted while both were affiliated with the Yale School of Forestry and Environmental Studies, New Haven, Connecticut, USA.

Supporting Information

Additional supporting information may be found in the online version of this article.

Supporting Information S1: This supporting information provides the survey instrument used in this study.

Supporting Information S2: This supporting information contains additional details on and results of the social network analysis for this study.

Please note: Wiley-Blackwell is not responsible for the content or functionality of any supporting information supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.