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RESEARCH ARTICLE

Network analysis of eight industrial symbiosis systems

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Abstract Industrial symbiosis is the quintessential characteristic of an eco-industrial park. To divide parks into different types, previous studies mostly focused on qualitative judgments, and failed to use metrics to conduct quantitative research on the internal structural or functional characteristics of a park. To analyze a park's structural attributes, a range of metrics from network analysis have been applied, but few researchers have compared two or more symbioses using multiple metrics. In this study, we used two metrics (density and network degree centralization) to compare the degrees of completeness and dependence of eight diverse but representative industrial symbiosis networks. Through the combination of the two metrics, we divided the networks into three types: weak completeness, and two forms of strong completeness, namely "anchor tenant" mutualism and "equality-oriented" mutualism. The results showed that the networks with a weak degree of completeness were sparse and had few connections among nodes; for "anchor tenant" mutualism, the degree of completeness was relatively high, but the affiliated members were too dependent on core members; and the members in "equality-oriented" mutualism had equal roles, with diverse and flexible symbiotic paths. These results revealed some of the systems' internal structure and how different structures influenced the exchanges of materials, energy, and knowledge among members of a system, thereby providing insights into threats that may destabilize the network. Based on this analysis, we provide examples of the advantages and effectiveness of recent improvement projects in a typical Chinese eco-industrial park (Shandong Lubei).

Keywords industrial ecology, network analysis, density, network degree centralization, eco-industrial park

1 Introduction

Industrial symbiosis can be defined as a network in which enterprises cooperate by using each other's by-products and wastes, thereby forming the industrial equivalent of a biological symbiotic network (Chertow, 2000; Lowe, 2001; Chertow and Lombardi, 2005; van Beers et al., 2007). With the discovery of the Kalundborg industrial symbiosis in 1989 (Ehrenfeld and Gertler, 1997; Jacobsen, 2006; Chertow, 2007), researchers began describing "an epic example of industrial symbiosis" and Kalundborg gained worldwide attention, prompting many studies (Engberg, 1992; Gertler and Ehrenfeld, 1996; Schwarz and Steininger, 1997; Ehrenfeld and Chertow, 2002). Eco-industrial parks can be described as a specific form of industrial symbiosis in which a community of enterprises are located sufficiently close together that they can exchange materials, energy, and information, with the goal of improving their individual and overall environmental and socioeconomic performance by developing a complex network of flows among the members (Lowe, 2001).

Categorizing industrial symbioses into different types is an important way to reveal the similarities and differences in the symbioses. Scholars have categorized industrial symbioses into multiple types based on different perspectives. Lowe (1997) divided them into co-located eco-industrial parks and virtual eco-industrial parks based on the physical locations of the component industries. Lambert and Boons (2002) further divided co-located eco-industrial parks into industrial symbiosis complexes (parks consisting of concentrations of materials and energy

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intensive and interrelated industries) and mixed industrial parks (more diverse parks consisting of a variety of small and medium sized enterprises). Chertow (2007) identified whether the symbiosis had emerged spontaneously or had been planned, and on this basis, divided parks into planned and self-organizing symbiosis models. Fichtner et al. (2004) divided industrial symbiosis into industrial supplier parks and resource recovery networks. However, these categorizations mainly focused on qualitative assessments rather than on using metrics to quantitatively analyze the internal structural or functional characteristics of the park.

Qualitative analysis of these internal characteristics of a system can provide a basis for further quantitative study. Ashton (2009) established a framework to qualitatively assess the structure, function, and evolution of a regional industrial ecosystem. This framework included material or energy flows, competition, resilience, succession, and social capital, and helped to reveal the social and economic aspects of an industrial system. Nonetheless, this integrated analysis of industrial systems remained mostly limited to qualitative analysis. Because ecology is a quantitative science (Wright et al., 2009), drawing on the analytical techniques developed in ecology can broaden and deepen our understanding of industrial systems and the sustainability of an industrial ecology (Wells and Darby, 2006). Wright et al. (2009) tried to quantitatively integrate ecosystem theories into the study of industrial systems, and found that this analysis provided meaningful insights and a theoretical platform for future studies.

Quantitative analysis can be developed by abstracting industrial symbiosis systems into networks that describe their internal characteristics using the techniques of structural and functional analysis. Network analysis offers certain advantages in determining the functional properties of a network and its structural attributes (Fath and Patten, 1999; Doménech and Davies, 2009; Zhang et al., 2010). To examine the functional characteristics of an industrial symbiosis, Chen (2003) analyzed the average path length and cycling index for sulfur utilization in the Shandong Lubei Eco-industrial Park. In community ecology, species are the functional units. The enterprises in an industrial system also take on functional roles. Seeing enterprises as organisms that function within an ecosystem can provide important insights into an industrial system (Wright et al., 2009). Similarly, the interactions or exchanges among enterprises are analogous to the paths among species in an ecosystem. Therefore, by analogy with the food webs in natural systems, industrial systems can be abstracted as industrial networks (i.e., webs of interactions).

In research on the structural characteristics of an industrial symbiosis, scholars began by using metrics developed for natural ecosystems. For example, connectance (Graedel and Allenby, 1995; Hardy and Graedel, 2002; van Berkel et al., 2009; Dai, 2010) can be useful in analyzing the completeness of the network and can also reflect the degree of interaction among members and whether generalists and specialists exist in the system (Wright et al., 2009). However, to quantify other structural attributes, it is useful to introduce additional metrics from network analysis.

Ashton (2008) chose network density, network degree centralization, and nodal average (average degree for all nodes in the network) as the metrics in network analysis. She extended the analysis by examining the correlation and centralization among the formal relationships through supply chains and informal relationships through interpersonal interactions. Doménech and Davies (2011) introduced several potentially useful metrics from network analysis, such as the core–periphery structure, reciprocity, and multiplexity, and used them to define the different structural characteristics of a single network. They examined the Kalundborg symbiotic network and concluded that their approach provided a comprehensive methodological and analytical framework that could reveal the structural elements of an industrial symbiotic network. Some Chinese scholars have also used metrics from network analysis to identify central nodes, weak nodes, and independent nodes in a network or to define how their roles have changed over time (Zhong et al., 2010; Zhang et al., 2013). In such research, various network analysis metrics have been used to analyze the structural attributes of a single network or a single metric has been used to compare multiple networks, but few researchers (e.g., Zhang et al., 2013) have compared two or more industrial symbioses in different countries (or regions) using more than one metric to identify differences in their structural attributes, and the systems have often not been quantitatively categorized in those studies.

In this paper, we aimed to analyze the structural attributes of several industrial symbiotic networks and describe how the different structures influenced the exchanges of materials, energy, or knowledge among members of the networks. To support this analysis, we chose two metrics: the network density and network degree centralization, which we will define in the next section. By comparing these two metrics for eight diverse but broadly representative industrial symbiosis systems from China and abroad, we were able to quantitatively divide these parks into three different types and summarize the similarities and differences in the structural attributes of each type. On this basis, we identified how the different structures influence the exchanges of resources and the threats to stability of these networks. (In the context of the present paper, “threat” refers to the adverse consequences that would result from the elimination of a key node or impairment of its functioning.) Finally, we chose a typical eco-industrial park in China (the Shandong Lubei park) and describe the advantages obtained from the projects that have been implemented by its managers in recent years to increase the degree of symbiosis.

Table 1 Characteristics of the eight typical industrial symbiosis systems

Type	Name of park	Construction date	Location	Characteristics	Data sources
Co-located eco-industrial parks	Kalundborg	1960s	Denmark	It formed spontaneously through promotion of the economic benefits of its members	Ehrenfeld and Gertler (1997), Chertow (2007), Mihelcic and Zimmerman (2010)
	Tianjin TEDA	2005	Eastern China	It was one of the first 14 national economic development zones in China, and was planned by governmental officials and researchers	Shi et al. (2010), TEDA Trade Promotion Centre (2012)
	Shandong Lubei	2003	Eastern China	It was the biggest ammonium phosphate, sulfate, and cement manufacturing enterprise in China, and was owned by the Lubei Chemical Company Ltd.	Feng (2003), Yang et al. (2004), Fang et al. (2007)
	Xinjiang Shihezi	2002	Western China	It was located in an arid region of northern China	Wu et al. (2004)
	Guangxi Guigang	2001	Western China	It resulted from efforts to improve an existing park to reduce its high levels of emissions	Zhu et al. (2007)
	Choctaw	1995	Central U.S.A.	It was developed based on a master plan, and its aim was to solve the significant problem of storing and utilizing shredded tires	Potts Carr (1998)
	Kitakyushu	1997	Japan	It was the first eco-industrial park in Japan to recycle and reuse wastes	Muto (2004), Kitakyushu Eco-Town Project (2005), Kitakyushu Eco-Town Plan by the City of Kitakyushu (2012)
Virtual eco-industrial park	Styria	1992	Austria	It includes paper-production industries, power plants, cement plants, iron scrap dealers, and a wastewater treatment plant	Schwarz and Steininger (1997)

2 Methods and materials

2.1 Criteria for choosing the eco-industrial parks

Lowe (1997) divided eco-industrial parks into two kinds: co-located and virtual eco-industrial parks. Co-located eco-industrial parks are systems in which the enterprises are gathered at the same site or in the same region; virtual eco-industrial parks do not require the enterprises to be in the same region, but the parks are nonetheless built around the exchanges of by-products and wastes among enterprises (Lambert and Boons, 2002). In co-located eco-industrial parks, the proximity of the enterprises makes it easier to optimize the environmental and economic benefits (Martin et al., 1996; Heeres et al., 2004). Kalundborg is an example of this type. Virtual eco-industrial parks, by enabling the exchanges of waste materials and energy within a larger region or between regions, offer the potential for substantial environmental benefits (Schwarz and Steininger, 1997; Côté and Cohen-Rosenthal, 1998). The Brownsville industrial symbiosis in the United States is a typical virtual park (Martin et al., 1996). In this study, we choose seven co-located parks and one virtual eco-industrial park to obtain a group with a wide range of characteristics. Table 1 summarizes their construction dates, locations, and some basic characteristics.

2.2 Graphical representation

In this paper, we used principles from social network analysis to establish graphical representations of the industrial symbiotic networks of the eight parks. To do so, we used data obtained from previous studies (which are cited in Table 1). Online Supplemental Figures S1 to S8 illustrate the key members of these industrial symbioses and the connections among them.

The network illustrations are composed of nodes and paths. In network analysis, the nodes represent enterprises with active behavior, such as members that are engaged in production, circulation, and service activities. It’s important to note that industrial symbioses are not isolated from their surrounding environment, as they are inevitably connected with rivers, bodies of water, the atmosphere, and soil. We have indicated the most important of these elements in the online supplemental figures using dashed rectangular boxes or ellipses. Since some members of the network (i.e., members that provide crucial inputs to the network or receive its outputs) are often located outside its administrative boundary, even in co-located parks, the network includes both members inside the park and the members outside of the park.

The paths between nodes are necessary, as these paths represent the exchanges of tangible flows such as by-products and wastes, the sharing of infrastructure, and the exchanges of intangible flows such as knowledge (Chertow, 2000; Harper and Graedel, 2004; Chertow and Lombardi, 2005; Mirata and Emtairah, 2005; Doménech and Davies, 2011). The exchanges of knowledge ("information exchanges") exist in the form of exchanges of know-how and technology, potentially leading to innovations.

Finally, based on the list of members of each system and the exchanges between them, we established the adjacency matrix ***A***. In this matrix, rows (i) represent the providers of a resource, and columns (j) represent the receivers of the resource. If any two enterprises (nodes) in the same system exchange resources, we concluded that the two enterprises were connected by a path. In adjacency matrix ***A***, the value of the corresponding element for the connected enterprises is 1. If there are no exchanges between two enterprises, the value of the corresponding element in adjacency matrix ***A*** is 0. These relationships between two enterprises are directional. For example, in Fig. 1, Member 1 delivers resources to Member 2, so the value of the corresponding element (a_{12}) is 1; conversely, Member 2 does not deliver resources to Member 1, so the value of the corresponding element (a_{21}) is 0. For simplicity, we have assumed there were no flows within the same node (e.g., $a_{11} = 0$), but a more complex analysis could account for the difference between nodes with and without internal flows (i.e., values of 1 and 0, respectively).

The symbiotic network comprises a series of nodes and the paths between them. Using the data in adjacency matrix ***A*** and version 6 of the UCINET software (http://www.analytictech.com/ucinet/), we created graphical representations of each of the eight industrial symbioses (Fig. 2). Nodes in the network represent members of the system, and directional line segments between the nodes (i.e., arrows) represent the transfer directions.

2.3 Network analysis

Network density and network degree centralization refer to different aspects of the overall "compactness" of a network. The network's density describes the general level of cohesion within a network, and can be used to analyze the number of ecological paths within the network and the frequency of the interactions resulting from symbiotic exchanges. In contrast, the network degree centralization describes the extent to which this cohesion is organized around particular focal nodes, and can indicate whether one or more "focal" members are linked to all or most of the other members in the network (Scott, 2000). Therefore, they are important but complementary measures that provide different insights into the overall characteristics of the network (Scott, 2000).

2.3.1 Degree of network completeness

In our study, one of our goals was to analyze the completeness of the network. The most common parameter used in this analysis has been given two names in the literature. First, it has been referred to as density (Ashton and Bain, 2012), which is the name that is widely used in the social sciences. Density (D) directly describes the ratio of the actual number of paths (L) to the maximum number of paths that could theoretically exist and thus represents the degree of completeness of a network (Scott, 2000; Ashton and Bain, 2012). To account for the direction of the paths, the theoretical maximum is denoted $n(n-1)$, where n represents the number of nodes in the network and is also referred to as the "network scale". The second name is the connectance metric described by van Berkel et al. (2009). The connectance in a food web equals the number of observed trophic links divided by the total number of possible links, which is given by the square of the number of species in the web (n) if we include cannibalism; excluding cannibalism, it is $n(n-1)$. The level of connectance is related to the statistical distribution of the links per species. As the level of connectance increases, the distribution of the links changes from following a (partial) power-law to following exponential and then uniform distributions (Dunne et al., 2002). Because our analysis includes some social systems, we chose the density metric. The calculation formula is:

$$D = \frac{L}{n(n-1)}. \tag{1}$$

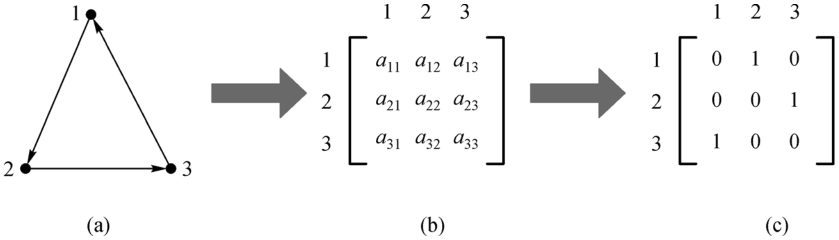
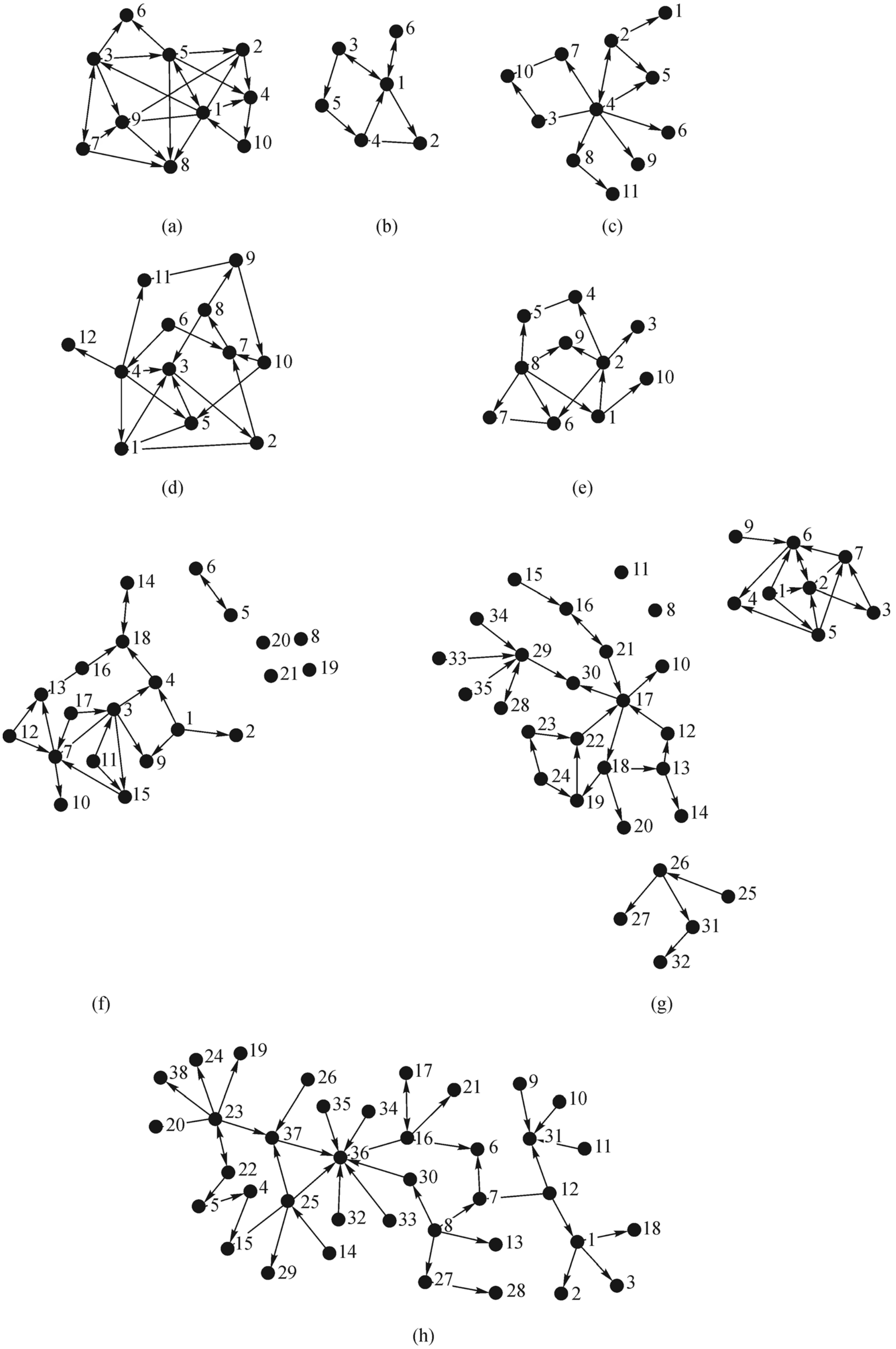


Fig. 1 Connections between nodes and the resulting adjacency matrix: (a) the exchanges within an industrial network, including the flow directions; (b) the corresponding elements in the adjacency matrix; and (c) the adjacency matrix for the industrial network shown in (a). Notes: 1, 2, and 3 represent members of the industrial network (nodes); a_{ij} represents the resource exchanges from Member i to Member j. In the simplified network shown in (a), we have assumed that there are no exchanges internal to each member of the network, thus the adjacency value is 0.


1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6
1 2 3 4 5 6 7 8 9 10 11
1 2 3 4 5 6 7 8 9 10 11 12
1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38

(a) (b) (c)

(d) (e)

(f) (g)

(h)

If each node is directly connected to all other nodes within the network graph, the density of the graph reaches its maximum (i.e., 1.0). Thus, density is a basic metric that reflects how complete a network is, and what proportion of the theoretical maximum symbiosis has been achieved. Density values range between 0 and 1, and the closer the density is to 1, the more paths exist among members of the network.

2.3.2 Network degree centralization (dependence)

There are various measures of centralization, including network degree centralization, which is based on the number of paths that connect to a node; betweenness degree centralization, which is defined as the number of times a node lies on the shortest path between two other nodes; and closeness degree centralization, which is the sum of the graph-theoretical distances from all other nodes, with the "distance" referring to the length of the shortest path from one node to the other. Each type of centralization can be divided into a nodal degree to characterize each node and a network degree centralization to describe the group of nodes (i.e., the network). Borgatti (2005) proposed measures for "transfers" that are referred to as the Freeman closeness centralization and the betweenness centralization. In our study, one of our goals was to

Fig. 2 Industrial symbiosis networks for the eight eco-industrial parks. Details of each park are shown in Online Supplemental Figures S1 to S8.

(a) The Guangxi Guigang eco-industrial park.

Notes: 1, sugar refinery; 2, alcohol plant; 3, pulp and paper mill; 4, compound fertilizer plant; 5, power plant; 6, wastewater treatment plant; 7, alkali recovery plant; 8, cement mill; 9, light calcium plant; 10, sugarcane planting system.

(b) The Xinjiang Shihezi eco-industrial park.

Notes: 1, *Achnatherum* cultivation system; 2, paper-making system; 3, animal husbandry system; 4, wastewater treatment system; 5, animal-products processing system; 6, eco-tourism industry.

(c) The Kalundborg eco-industrial park.

Notes: 1, liquid fertilizer; 2, Statoil refinery; 3, Asnaes fish farm; 4, Asnaes power plant; 5, Gyproc gypsum board plant; 6, Alborg cement plant; 7, Novo Nordisk biopharmaceutical plant; 8, Kalundborg city; 9, recovered nickel and vanadium; 10, farm; 11, A-S Bioteknisk Jordens.

(d) The Shandong Lubei eco-industrial park.

Notes: 1, ammonium phosphate plant; 2, sulfuric acid plant; 3, cement plant; 4, thermal power plant; 5, chlorine plant; 6, aquaculture plant; 7, bromine plant; 8, salty gypsum production plant; 9, raw salt production; 10, chlor-alkali plant; 11, potassium and magnesium salt production; 12, living area.

(e) The Choctaw eco-industrial park.

Notes: 1, tire crushing plant; 2, tire pyrolysis plant; 3, hard rubber tire manufacturers; 4, carbon black processing plant; 5, ink cartridge production and recovery plant; 6, plastics plant; 7, plastic products plant; 8, wastewater treatment plant; 9, greenhouse; 10, crushed steel recovery plant.

(f) The Kitakyushu eco-industrial park.

Notes: 1, plastic bottle recycling plant; 2, car disassembly factory; 3, office equipment wastes plant; 4, home appliance recycling factory; 5, PCB treatment facilities; 6, composite core facility; 7, construction waste treatment plant; 8, medical equipment plant; 9, fluorescent lamps plant; 10, empty cans plant; 11, computer recycling plant; 12, recreational machine plant; 13, waste wood and plastics plant; 14, cooking oil plant; 15, styrofoam plant; 16, ink cartridges plant; 17, scrap car plant; 18, organic solvent and waste plastics plant; 19, waste paper plant; 20, kitchen waste treatment plant; 21, food wastes treatment plant.

(g) The Tianjin TEDA eco-industrial park.

Notes: 1, TEDA water treatment plant; 2, industrial, commercial, and residential users; 3, TEDA wastewater treatment plant; 4, construction companies; 5, Guahua cogeneration plant; 6, Binhai energy cogeneration plant; 7, TEDA new water source company; 8, TEDA eco-landscaping company; 9, desalination plant; 10, FAW resource recovery company; 11, other Toyota-family firms; 12, Toyota FAW dies company; 13, Tianjin Rainbow Hills cast iron company; 14, other automobile die makers; 15, Tianjin AW automatic transmission company; 16, Tianjin Toyotsu aluminum smelting; 17, Tianjin Toho FAW Toyota motor company; 18, Tianjin Toyotsu resource management company; 19, Takaoka Lioho industries; 20, Tianjin pipe corporation; 21, Tianjin FAW Toyota engine company; 22, Toyota-family automobile part manufacturers; 23, CMW industrial company; 24, steel scrap contractors; 25, refineries; 26, Cabot chemical company; 27, TEDA chemical park corporation; 28, Tianjin Tong Tee industrial company; 29, Tianjin Toho lead recycling company; 30, Tianjin cement mill; 31, Kumho tire company; 32, Tianjin Aoxing rubber company; 33, Tianjin Motorola China; 34, Tianjin Yuasa batteries company; 35, various users of lead-acid batteries.

(h) The Styria eco-industrial park.

Notes: 1, paper-producing industry 3; 2, pressboard plant; 3, paper-producing industry 4; 4, scrap material dealer; 5, wastewater treatment plant; 6, mining company; 7, paper-producing industry 1; 8, wastepaper dealer; 9, textile plant 1; 10, textile plant 2; 11, chemical plant; 12, sawmill; 13, paper-producing industry 6; 14, iron scrap dealer; 15, construction materials plant 1; 16, power plant 1; 17, region of Voitsberg; 18, stone and ceramic industry 2; 19, cement plant 6; 20, construction materials plant 2; 21, cement plant 3; 22, region of Graz; 23, power plant 2; 24, cement plant 4; 25, iron manufacturing industry; 26, used tire dealers; 27, paper-producing industry 5; 28, plastics plant; 29, color industry; 30, paper-producing industry 2; 31, stone and ceramic plant 1; 32, used oil dealer 3; 33, used oil dealer 2; 34, used oil dealer 1; 35, fuel producer; 36, cement plant 2; 37, cement plant 1; 38, cement plant 5.

determine whether one or more “core nodes” existed in the networks, so we chose to analyze the network degree centralization.

Network degree centralization characterizes the network’s overall degree of dependence on individual nodes (i.e., the number of nodes connected to a given node) by measuring the network’s degree of dependence on certain “central” nodes (Scott, 2000). It therefore indicates the degree of asymmetry in the distribution of connections within the network and in the roles of the nodes. A high degree centralization score indicates that some members have more connections (i.e., function as “central” nodes) than others (Scott et al., 2005). Determining the degree centralization first requires calculation of the sum of the differences between the maximum nodal degree in the network and the nodal degree of each node; this sum is then divided by the sum of the maximum possible difference between the maximum nodal degree in the network and the nodal degrees of each node. Network degree centralization can be categorized into absolute degree centralization and relative degree centralization, which is calculated from the absolute degree. In this analysis, we chose to use the relative degree centralization because the industrial symbioses differed sufficiently in scale that an absolute comparison would be misleading. The calculation formula for the absolute degree centralization is as follows:

$$C_{\mathrm{AD}} = \frac{\sum_{i=1}^{n}(C_{\mathrm{ADmax}} - C_{\mathrm{AD}i})}{(n-1)(n-2)}, \tag{2}$$

where C_{AD} is the absolute degree centralization of the network, n is the network scale (number of nodes), C_{ADmax} is the maximum absolute nodal degree of all nodes in the network, and $C_{\mathrm{AD}i}$ is the absolute nodal degree of node i, which represents the number of nondirectional relationships that interact with node i.

We can then calculate relative degrees. If $C_{\mathrm{RD}i}$ reflects the relative nodal degree of node i, and C_{RDmax} reflects the maximum relative nodal degree of all nodes in the network, then C_{RD} reflects the relative degree centralization calculated from these two values. As the relative nodal degree ($C_{\mathrm{RD}i}$) equals the absolute nodal degree ($C_{\mathrm{AD}i}$) divided by the number of nodes that can potentially interact with node i (i.e., n–1), the left side of Eq. (2) should be divided by n–1. The resulting calculation for relative degree centralization is:

$$C_{\mathrm{RD}} = \frac{\sum_{i=1}^{n}(C_{\mathrm{RDmax}} - C_{\mathrm{RD}i})}{(n-2)}. \tag{3}$$

The relative degree centralization ranges from 0 to 100%.

3 Results and analysis

3.1 Using ecological theory to categorize industrial symbiosis systems

In the industrial symbioses in this study, we have defined all exchanges related to by-products, wastes, or other “useless” (unused or underutilized) resources. Therefore, all of the relationships that link to each node represent a mutual benefit between two enterprises, because they make use of these resources, and the industrial networks therefore become mutualistic. This is the most beneficial characteristic of industrial symbiosis systems. The methods for reusing and recycling resources in industrial symbiotic networks are similar to the resource utilization that occurs in natural systems. The “interspecies relationships” that result from the interactions among organisms in a natural system resemble the relationships among the enterprises in an industrial symbiosis, so we can use easily understood analogies with a natural ecological system to help understand the industrial system. In the present study, we mainly focus on the completeness and concentration trends in the overall network, which are similar in meaning to the “connectance” (Graedel and Allenby, 1995) and “key species” (Paine, 1969) theories for natural systems. Thus, these theories can be treated as the theoretical grounding for dividing the mutualistic industrial symbioses into different types.

First, according to “connectance” theory for natural systems, we can divide these industrial symbioses into two types. In food webs, the connectance is the number of observed trophic links divided by the total number of possible links, and the level of connectance is therefore related to the statistical distribution of the links for each species. In this study, we used the density (D) to represent connectance. Second, we based our analysis on the “key species” theory in natural systems to further divide these systems. In this theory, some key species may play particularly important roles in the biodiversity and stability of the system; as a result, their disappearance or a weakening of their role (e.g., a decrease in numbers) would cause the overall community or the ecosystem to change significantly. In this study, we used C_{RD} to represent the key species. Applying these two theories to industrial symbiosis systems can help to classify each type in a way that improves our understanding of their nature.

As is the case for natural systems with high or low connectance, some networks have a low degree of completeness, and we proposed “weak degree of completeness” as the description of this type. In contrast, where the level of interaction among the members of the network is strong, we proposed “strong degree of completeness” as the description of this type. However, systems with a strong degree of completeness can be further assessed in terms of whether key species exist. On this basis, we defined two types of strong degree of completeness: "anchor tenant" mutualism and "equality-oriented" mutualism. The "anchor tenant" mutualism means that one or more core nodes exist in the network; however, note that "anchor" is descriptive, not prescriptive (i.e., creating anchor nodes may or may not improve the flows in the network). The "equality-oriented" mutualism means that the members of the network have relatively equal roles and the network does not rely excessively on a single node.

However, it would be problematic to directly compare the eight systems because of the large differences in their sizes, complexity, industrial characteristics, history, and national contexts. Instead, we have chosen these examples to illustrate how our approach can be used to identify and describe a range of different network types and reveal similarities and differences in their characteristics using a flexible method based on only two structural attribute metrics (i.e., network density and network degree centralization). Table 2 presents the results of these calculations.

Table 2 The density (D) and relative degree of centralization (C_{RD}) of the eight systems

Name of system	D	C_{RD}/%
Guangxi	0.26	24
Xinjiang	0.20	55
Lubei	0.15	15
Choctaw	0.14	17
Kalundborg	0.12	34
Kitakyushu	0.06	11
Tianjin	0.04	7
Styria	0.03	8

Based on the results of the density and network degree centralization, and the two above-mentioned theoretical groundings, we determined the boundaries for categorizing the eight industrial symbioses into three different types. First, by arranging the densities of these eight systems in descending order (Table 2), we can calculate their median density and round the values to two decimal places of precision, which was the minimum required to distinguish among the values for the eight cases. On this basis, we chose a median density of 0.10 as the dividing line between the types with strong and weak degrees of completeness (Table 3). Next, we calculated the median of the network degree centralization for the systems belonging to the types with a strong degree of completeness, and after rounding the percentage to the nearest integer value, we found that a centralization of 20% represented the dividing line between the "anchor tenant" type and the "equality-oriented" type (Table 3). Note that our choices of median values (0.10 and 20%) are arbitrary, and it may be possible to choose different thresholds (e.g., means, modes, quartiles) to support different management priorities, and this alternative division would lead to different conclusions. By combining these two metrics, we divided the eight industrial symbioses among the three distinct network types (Table 3).

3.2 Structural characteristics of the strong degree of completeness types

The industrial symbioses with a strong degree of completeness differed based on their network degree centralization.

3.2.1 "Anchor tenant" mutualism

For the "anchor tenant" type of mutualism, the densities of Guangxi (0.26), Xinjiang (0.20), and Kalundborg (0.12) were all greater than 0.10, which means that their degrees of completeness were relatively high. The density of the Guangxi eco-industrial park was the highest among the eight parks. This indicates that its network is highly complete and that the interactions among its members are frequent. The corresponding degrees of centralization were 24%, 55%, and 34%, respectively, which means that their degrees of centralization are also relatively high. The high degree of centralization means that these three parks all have core nodes (the sugar refinery, the *Achnatherum* cultivation system, and the Asnaes Power Plant and Statoil Refinery, respectively) and that the network depends strongly on these nodes. Furthermore, the centralization of the Xinjiang eco-industrial park is roughly twice the centralization of the Guangxi and Kalundborg parks. This means that the affiliated members depend strongly on the *Achnatherum* cultivation system.

The high degree of centralization of these three parks results partially from their formation and development

Table 3 Criteria for the three types

Type ("Connectance" theory)	Density (D)	Centralization degree (C_{RD})/%	Mutualism sub-type ("Key species theory" in a natural system)	Industrial symbioses
Weak degree of completeness	$0 \leqslant D < 0.10$	—	—	Kitakyushu, Tianjin TEDA, Styria
Strong degree of completeness	$0.10 \leqslant D < 1.0$	$20 \leqslant C_{\mathrm{RD}} < 100$	"Anchor tenant"	Guangxi Guigang, Xinjiang Shihezi, Kalundborg
		$0 < C_{\mathrm{RD}} < 20$	"Equality-oriented"	Shandong Lubei, Choctaw

history. The Guangxi and Xinjiang parks formed and expanded around the sugar refinery and the *Achnatherum* cultivation system, respectively. The Guangxi park was established by the state and has gradually evolved from a stand-alone refinery to an industrial symbiosis, and symbiotic exchanges were established between the sugar refinery and other enterprises to improve the park's environmental benefits. The high degree of centralization of the park (24%) means that the sugar refinery still plays a somewhat core role in the park. For the Kalundborg park, a web of symbiotic interactions evolved among the power plant, the oil refinery, the biopharmaceutical plant, the gypsum board plant, the soil remediation plant, and the local municipality. The other enterprises developed with a reliance on these core nodes, and the degree of centralization is therefore relatively high.

3.2.2 "Equality-oriented" mutualism

For the "equality-oriented" mutualism type of symbiosis, the densities of the Lubei (0.15) and Choctaw (0.14) parks were greater than 0.10, which means that their degrees of completeness were relatively high. The degrees of centralization of these parks were 15% and 17%, respectively. These low degrees of centralization mean that members in these parks are relatively independent, with no obvious centralizing tendency and few or no core nodes.

In the Shandong Lubei park, there are three coupled industrial chains: poly-generation of ammonium phosphate, sulfuric acid, and cement; ocean chemical engineering that fully utilizes the seawater resource; and co-generation of salt, alkali, and electricity. Because the enterprises exchange and interact with each other within the context of a mixed eco-industrial park, the members have gradually become somewhat independent of each other. The Choctaw park is based on a master plan that proposed the development of an eco-industrial park, with the goal of eliminating the significant current problem of storing and utilizing shredded tires, and the internal enterprises equally cooperate with each other to reuse or recycle these formerly "useless" resources.

3.3 Structural characteristics of the weak degree of completeness symbiosis

Among the eight industrial symbioses, the densities of Kitakyushu (0.06), Tianjin (0.04), and Styria (0.03) were all less than the median value of 0.10. There are few industrial symbiotic paths among the members of these parks. Thus, there are fewer exchanges of by-products and wastes, and relatively sparse networks form. In addition, the degree of network centralization of the three parks was relatively low ($<12\%$). However, the centralization of Kitakyushu (11%) was higher than those of Tianjin (7%) and Styria (8%). These values of network degree centralization indicate that there is no trend towards concentration of resource flows in these networks, and the members are equally distributed, but there may still be concentration of flows in small areas. For example, the members of the Kitakyushu park rely somewhat on core nodes such as the office equipment wastes plant and the construction wastes treatment plant.

4 Discussion

The different structural attributes of the eight parks influenced their exchanges of resources and their network activities. This influence may be positive or negative and may create threats to future development of the network. Based on the structural attributes of each system, we discuss how these different attributes influence the exchanges of resources in sections 4.1 and 4.2. We will first describe the dominant characteristics of the industrial symbioses in a given category, and then choose a single network per category to provide an example of specific suggestions or directions for future development. These insights can provide references for other networks of the same type, but with whatever modifications are necessary to account for differences in the system's ecological and socioeconomic context. We have proposed these suggestions based on the availability of wasted or underutilized resources and the production processes of a system's enterprises. Our goal is to inspire local engineers to confirm whether our suggestions make sense rather than to encourage managers to implement our suggestions uncritically. This caution is required because many economic, social, and environmental factors must be accounted for when considering these suggestions, and only the engineers and managers of these networks have access to enough information to make the necessary judgments. In section 4.3, we have focused on the Lubei eco-industrial park in China's Shandong Province because it has implemented many new symbiotic exchanges in recent years to improve its internal structure and its resource utilization efficiency. By examining the effect of these added paths on a network's structural attributes, it is possible to evaluate whether the network is developing towards more completeness or stability as a result of these innovations. The characteristics of all three types of industrial symbiosis are summarized in Table 4.

4.1 Network performance of the strong degree of completeness types

Online Supplemental Text S9 provides some details for each of the eight symbioses. Here, we will summarize the characteristics of each symbiosis category and provide one example of general improvements that can be made.

4.1.1 “Anchor tenant” mutualism

The common characteristic of the three networks with an “anchor tenant” type of mutualism is that the core enterprises delivered by-products and wastes to downstream enterprises, thereby promoting the development of the downstream members, while also improving their own development environment by receiving resources from other nodes. Core and affiliated enterprises have combined into an organic symbiotic association: the affiliated enterprises gain materials and energy from the core enterprises by disposing of their by-products and wastes, and the affiliated members mostly exchange resources with the core members (i.e., they rarely or never exchange resources with each other), so the flexibility of the system is relatively low (Fig. 3(a)). However, if the core enterprises change their production processes, they may no longer provide enough by-products or wastes to downstream enterprises, making the network unstable because some of the former paths would disappear.

As a result, symbiotic connections between affiliated enterprises should be promoted to decrease their dependence on the core enterprises. Establishing symbiotic connections among the affiliated members can mitigate the dependence on the core members, thereby lowering the threat that would result from adverse changes in the core members, and can bring unexpected information or opportunities to the affiliated members by encouraging an exchange of innovative techniques. Therefore, the affiliated members would play an essential role in the “disposal” of currently unused or underutilized resources and should be the subject of careful analysis in future planning for the system’s development (Granovetter, 1973).

Table 4 Characteristics of the three types

Type	Structural characteristics	Network activities
Weak degree of completeness	The network is relatively sparse, with few connections and paths among the members	The degree of completeness is low
“Anchor tenant” mutualism	The members can be divided into important and less-important ones; affiliated enterprises depend on core (anchor) enterprises	The degree of completeness is relatively high, but the dependence on core nodes is too high
“Equality-oriented” mutualism	The members have relatively equal roles; there are few or no core and affiliated enterprises	The degree of completeness is relatively high; the symbiosis paths are diverse and the system is flexible; the network is relatively stable

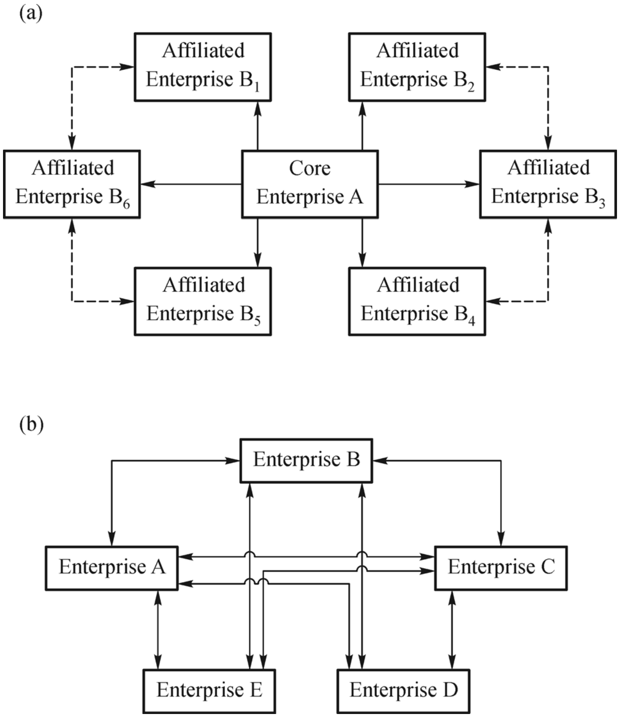


Fig. 3 Networks with (a) “anchor tenant” mutualism and (b) “equality-oriented” mutualism. Dashed lines in (a) indicate potential new paths.

Using the Xinjiang Shihezi park as an example (Online Supplemental Fig. S2), we can propose some future programs to improve the park's efficiency. It would be reasonable to establish symbiotic paths among the surrounding enterprises other than the *Achnatherum* cultivation system; for example, the ecological industry of the paper-making system could enrich the eco-tourism industry by providing visits to observe the advanced technology, and treated water from the wastewater treatment system could be delivered to the animal husbandry system to wash the barns, to the animal-products processing system for landscaping (e.g., irrigation of gardens), and to the paper-making system to serve as low-quality industrial water. These connections can increase the utilization efficiency of water. After establishing these paths (dashed lines in Online Supplemental Fig. S2), the degree of centralization would decrease from 55% to 25% (i.e., a decrease of 55%), and the density would increase from 0.20 to 0.33 (i.e., an increase of 65%). These measures would reduce the dependence on the *Achnatherum* cultivation system and increase the symbiotic connections between affiliated enterprises. As Xinjiang is a water-poor region, water cascading is crucial to improving the park's degree of completeness.

4.1.2 "Equality-oriented" mutualism

Although parks with an "equality-oriented" type of mutualism combine many enterprises that develop independently, these enterprises can gain ecological and economic benefits through the development of multiple paths for the exchanges of by-products and wastes (Fig. 3(b)). Members can benefit from their advantages in processing certain by-products or wastes by receiving these resources from multiple members of the network. Symbiotic paths have developed between members, and these paths increase the efficiency of recycling and the cascading utilization of energy and materials. The main characteristic of these systems is that if one or more members change their production processes, and stop producing resources that other nodes use as inputs, those nodes can still obtain the necessary inputs from other nodes.

Using the Choctaw park as an example (Online Supplemental Fig. S5), it is clear that the completeness of the network (network density) can be improved. The wastewater treatment plant could also collect the wastewater from other members of the park (e.g., the tire crushing plant) in addition to urban sewage, which would increase the scale of water recycling and reuse. If the tire pyrolysis plant can produce surplus waste heat after supplying the greenhouses, that heat could be delivered to the tire crushing plant, hard rubber tire manufacturers, and the carbon black processing plant as industrial energy. Two additional paths could then be established (dashed lines in Online Supplemental Fig. S5): the tire crushing plant can deliver wastewater to the wastewater treatment plant, and the tire pyrolysis plant can deliver waste heat to the tire crushing plant. These changes would increase the park's degree of completeness from 0.14 to 0.18 (i.e., an increase of 29%), and increase the degree of centralization from 17% to 21% (i.e., an increase of 25%). As the network's scale is small, establishing only two new paths greatly would increase the park's degree of completeness, while improving the dependence of other nodes on the wastewater treatment plant, indicating a high efficiency of water reuse and recycling.

4.2 Network performance of the weak degree of completeness symbiosis

For the weak degree of completeness symbiosis, the three systems are all located in relatively large regions, and the average distances between any two enterprises that exchange materials and energy are higher than they would be in systems located in smaller regions. This will increase transportation costs and decrease the frequency of exchanges between members. For example, in the TEDA and Styria systems, the resources are mostly exchanged on a small scale, and the enterprises nearest to each other tend to form symbiotic relationships. These complicated small-scale relationships are important because they can increase the completeness of the overall system.

Furthermore, there are more members in these parks than in the other ones, so adding a few linkages can only bring about small changes in their structural attributes, but these changes can nonetheless reflect a tendency towards a more complete and independent network. To improve the overall degree of completeness in these parks, it is necessary to increase the exchanges of resources among members throughout the network. To improve the completeness of a network, it is easy to add relationships between the recycling and reuse plants and other members of the network such as the wastewater treatment plant that can supply them with materials. However, this will increase the dependence on the source plants to some degree. This represents a tradeoff: on the one hand, the new links increase the network completeness, but on the other, they significantly increase the importance of some nodes, which may not promote the long-term stable development of the park. The latter problem should be avoided in long-term planning.

Consider the Styria park as an example (Online Supplemental Fig. S8). On the basis of the existing paths between cement plants and power plants, we can establish new paths: Power Plant 2 can deliver gypsum to Cement Plant 3, and Power Plant 1 can deliver flue ash to Cement Plant 1, Cement Plant 4, and Cement Plant 5. In the future, the park can establish multilateral cooperation among all the power and cement plants to enhance the network's stability. After establishing the potential paths (dashed lines in Online Supplemental Fig. S8), the park’s degree of completeness would increase from 0.031 to 0.033 (i.e., an increase of 6%), and the degree of centralization would decrease by 2% if we calculated centralization to one decimal place of precision, indicating that establishing exchanges among the enterprises that engage in the same industry could not only make the network more mutualistic, but also increase redundancy and improve the network’s stability against changes in the scale of the exchanges of by-products and wastes.

4.3 Effectiveness of planned projects

To build on the analysis in section 4.2, we chose the Shandong Lubei eco-industrial park as an example of how analyzing the network’s structure revealed ways to increase the effectiveness of the park. Some of these ways have been implemented. This is important because it transforms our previously theoretical discussion into a more concrete discussion of the meaning of our results.

First, let us consider the waste heat produced by the cement plants. The previous approach to reduce pressures and temperatures in the steam lines of these plants involved the release of energy and steam. To capture some of this energy, managers of the plants introduced a turbine to drive an 1800-kW fan, and the work performed by this fan will lower the electricity consumption by these plants. The turbine therefore replaced the previous method and also produces low-temperature and low-pressure steam. Accepting this steam has allowed the sulfuric acid plant to produce more sulfur, reduce its emission of carbon dioxide, and decrease its energy use. The low-temperature and low-pressure steam can also be delivered to other enterprises, such as the phosphogypsum production plant, and to the residential living area. It is also more economical than it used to be to deliver the more than 100 t of sulfur that is produced to the ammonium phosphate plant or to export this material.

Second, the managers of the ammonium phosphate plant chose to improve the utilization of their phosphoric acid production equipment. To do so, they improved the utilization of different grades of phosphoric acid, in which purification of phosphoric acid by means of a wet process based on defluorination, desulfuration, and deferrization allowed the production of compound fertilizer, sodium tripolyphosphate, and monopotassium phosphate. This project thus improved the socioeconomic benefits from the ammonium phosphate plant (i.e., produced better fertilizer that will improve the quality of agriculture) and improved utilization of the phosphoric acid resources, without imposing additional environmental effects.

Third, producing more sulfur produced more waste heat, so managers of the sulfur plant attempted to reutilize the heat. If the high-level energy produced by burning of liquid sulfur and the intermediate-level heat transferred from the resulting sulfur dioxide could be more fully utilized, then the steam that is produced could be delivered to the ammonium phosphate plant or the aquaculture plant. These three projects illustrate how developing paths between nodes can improve the reuse and recycling of resources, such as steam and phosphoric acid, thereby providing more social, economic, and environmental benefits.

Based on this analysis, we can propose that managers add linkages between the cement plants and the phosphogypsum production plant or to create more residences, and between the sulfuric acid plant and the ammonium phosphate plant or aquaculture plant. After establishing these paths (dashed lines in Online Supplemental Fig. S4), the park’s degree of completeness would increase from 0.15 to 0.17 (i.e., an increase of 13%), and the degree of centralization would increase from 15% to 17% (i.e., an increase of 13%), indicating that these paths are effective for adding more exchanges and improving network completeness. In addition, increasing the roles of several members of the park in this way does not change the equality-oriented relationships among the members. Therefore, after calculating the density and network degree centralization, these paths appear to be effective and useful for the park’s future development.

5 Conclusions

In this paper, we demonstrated how network analysis provided insights into the key structural attributes of eight diverse industrial symbioses. By analyzing the degree of network density and network degree centralization, we were able to define and compare the degrees of completeness and dependence of a diverse range of industrial symbiotic networks.

Combining the two metrics let us divide the eight systems into three distinct types: one with a weak degree of completeness (Kitakyushu, Tianjin, and Styria), one with a strong degree of completeness in the form of “anchor tenant” mutualism (Guangxi, Xinjiang, and Kalundborg), and one with a strong degree of completeness in the form of “equality-oriented” mutualism (Choctaw and Shandong Lubei). We then analyzed the structural attributes of each type and their influence on the exchanges of resources, and identified the threats that could destabilize each park. The results showed that the networks with a weak degree of completeness were sparse and there were few connections among nodes; for the “anchor tenant” mutualism, the degree of completeness was relatively high, but the affiliated members were too dependent on core members; and the members in the “equality-oriented” mutualism had equal roles and their symbiotic paths were diverse and flexible. Finally, we chose a typical eco-industrial park in China to illustrate how its managers have analyzed their network to improve the effectiveness of its use of previously underutilized resources.

Our results show how an analytical method based on only two metrics can provide insights into differences among the structures of different networks without requiring large quantities of complex data. Moreover, this approach successfully applied network analysis to evaluate a group of diverse industrial symbioses from China and around the world. However, it's important to note that network analysis is a large and complex field of research, and that we use only two of a large number of metrics to analyze some structural attributes of the symbiotic networks. There are many other perspectives that could be considered, such as using the flows among the network's members to identify the relationships between pairs of members, determining the hierarchical structure (i.e., where the members fit within the system), or comparing the functional and structural attributes of a system to summarize their similarities and differences. Future research should also investigate the potential insights provided by different combinations of metrics, which would reveal more or different internal characteristics of the system, or even the attributes of each member.

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References

Ashton W S (2008). Understanding the organization of industrial ecosystems: a social network approach. J Ind Ecol, 12(1): 34–51

Ashton W S (2009). The structure, function, and evolution of a regional industrial ecosystem. J Ind Ecol, 13(2): 228–246

Ashton W S, Bain A C (2012). Assessing the "short mental distance in eco-industrial networks". J Ind Ecol, 16(1): 70–82

Borgatti S P (2005). Centrality and network flow. Soc Networks, 27(1): 55–71

Chen D J (2003). Analysis, integration and complexity study of industrial ecosystems. Dissertation for PhD Degree. Beijing: Tsinghua University (in Chinese)

Chertow M R (2000). Industrial symbiosis: literature and taxonomy. Annu Rev Energy Environ, 25(1): 313–337

Chertow M R (2007). "Uncovering" industrial symbiosis. J Ind Ecol, 11 (1): 11–30

Chertow M R, Lombardi D R (2005). Quantifying economic and environmental benefits of co-located firms. Environ Sci Technol, 39 (17): 6535–6541

Côté R P, Cohen-Rosenthal E (1998). Designing eco-industrial parks: a synthesis of some experiences. J Clean Prod, 6(3–4): 181–188

Dai T J (2010). Two quantitative indices for the planning and evaluation of eco-industrial parks. Resour Conserv Recycling, 54(7): 442–448

Doménech T, Davies M (2009). The social aspects of industrial symbiosis: the application of social network analysis to industrial symbiosis networks. Prog Ind Ecol Internat J, 6(1): 68–99

Doménech T, Davies M (2011). Structure and morphology of industrial symbiosis networks: the case of Kalundborg. Procedia Soc Behav Sci, 10: 79–89

Dunne J A, Williams R J, Martinez N D (2002). Food-web structure and network theory: the role of connectance and size. Proc Natl Acad Sci USA, 99(20): 12917–12922

Ehrenfeld J, Chertow M (2002). Industrial symbiosis: the legacy of Kalundborg. In: Ayres R, Ayres L, eds. Handbook of Industrial Ecology. Cheltenham: Edward Elgar Publishing Ltd, 334–350

Ehrenfeld J, Gertler N (1997). Industrial ecology in practice: the evolution of interdependence at Kalundborg. J Ind Ecol, 1(1): 67–79

Engberg H (1992). Industrial Symbiosis in Denmark. New York: Leonard N. Stern School of Business

Fang Y P, Côté R P, Qin R (2007). Industrial sustainability in China: practice and prospects for eco-industrial development. J Environ Manage, 83(3): 315–328

Fath B D, Patten B C (1999). Review of the foundations of network environ analysis. Ecosystems (N Y), 2(2): 167–179

Feng J T (2003). Development and practice of eco-industrial linkages in Lubei Group. China Population Resource and Environment, 1: 110–112 (in Chinese)

Fichtner W, Tietze-Stöckinger I, Rentz O (2004). On industrial symbiosis networks and their classification. Prog Ind Ecol Internat J, 1(1/2/3): 130–142

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

Graedel T, Allenby B R (1995). Industrial Ecology. New Jersey: Prentice-Hall

Granovetter M S (1973). The strength of weak ties. Am J Sociol, 78(6): 1360–1380

Hardy C, Graedel T E (2002). Industrial ecosystems as food webs. J Ind Ecol, 6(1): 29–38

Harper E, Graedel T (2004). Industrial ecology: a teenager's progress. Technol Soc, 26(2–3): 433–445

Heeres R R, Vermeulen W J V, de Walle F B D (2004). Eco-industrial park initiatives in the USA and the Netherlands: first lessons. J Clean Prod, 12(8–10): 985–995

Jacobsen N B (2006). Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects. J Ind Ecol, 10(1/2): 239–255

Kitakyushu Eco-Town Plan by the City of Kitakyushu (2012). http://www.hkip.org.hk/plcc/download/Japan.pdf

Kitakyushu Eco-Town Project (2005). http://pub.iges.or.jp/contents/APEIS/RISPO/inventory/db/pdf/0147.pdf

Lambert A J D, Boons F A (2002). Eco-industrial parks: stimulating sustainable development in mixed industrial parks. Technovation, 22 (8): 471–484

Lowe E A (1997). Creating by-product resource exchanges: strategies for eco-industrial parks. J Clean Prod, 5(1–2): 57–65

Lowe E A (2001). Eco-Industrial Park Handbook for Asian Developing Countries. http://teclim.ufba.br/jsf/producaol/indigo%20ecopk%

2001_18.PDF

Martin S A, Weitz A, Cushman R, Sharma A, Lindrooth R C, Moran S R (1996). Eco-Industrial Parks: A Case Study and Analysis of Economic, Environmental, Technical, and Regulatory Issues. Research Triangle Park, NC: Research Triangle Institute. Project Number 6050 FR

Mihelcic J R, Zimmerman J B (2010). Environmental Engineering: Fundamentals, Sustainability, Design. New York: John Wiley & Sons

Mirata M, Emtairah T (2005). Industrial symbiosis networks and the contribution to environmental innovation: the case of the Landskrona industrial symbiosis programme. J Clean Prod, 13(10–11): 993–1002

Muto Y (2004). Sustainable Management Activities in Kitakyushu Eco-Town. Office for International Environmental Cooperation, Environmental Bureau, City of Kitakyushu http://www.env.go.jp/earth/coop/neac/neac13/session3/295-303.pdf

Paine R T (1969). A note on trophic complexity and community stability. Am Nat, 103(929): 91–93

Potts Carr A J (1998). Choctaw eco-industrial park: an ecological approach to industrial land-use planning and design. Landsc Urban Plan, 42(2–4): 239–257

Schwarz E J, Steininger K W (1997). Implementing nature's lesson: the industrial recycling network enhancing regional development. J Clean Prod, 5(1–2): 47–56

Scott J (2000). Social Network Analysis: A Handbook. London: Sage Publications

Scott J, Tallia A, Crosson J C, Urzano A J, Stroebel C, DiCicco-Bloom B, O'Malley D, Shaw E, Crabtree B (2005). Social network analysis as an analytic tool for interaction patterns in primary care practices. Ann Fam Med, 3(5): 443–448

Shi H, Chertow M, Song Y Y (2010). Developing country experience with eco-industrial parks: a case study of the Tianjin Economic-Technological Development Area in China. J Clean Prod, 18(3): 191–199

TEDA Trade Promotion Centre (2012). http://www.tradeteda.org/en/.

van Beers D, Bossilkov A, Corder G, van Berkel R (2007). Industrial symbiosis in the Australian minerals industries: the cases of Kwinana and Gladstone. J Ind Ecol, 11(1): 55–72

van Berkel R V, Fujita T, Hashimoto S, Fujii M (2009). Quantitative assessment of urban and industrial symbiosis in Kawasaki, Japan. Environ Sci Technol, 43(5): 1271–1281

Wells P E, Darby L (2006). Rewriting the ecological metaphor, Part 2: the example of diversity. Prog Ind Ecol Internat J, 3(1/2): 129–147

Wright R A, Côté R P, Duffy J, Brazner J (2009). Diversity and connectance in an industrial context: the case of Burnside Industrial Park. J Ind Ecol, 13(4): 551–564

Wu Y P, Duan N, Qiao Q, Liu J Y (2004). Study on industrial symbiosis chain and net structure of the all new type ecosystem industrial parks. China Population. Resources and Environment, 14: 125–130 (in Chinese)

Yang L, Hu S Y, Liang R Z, Chen D J, Fang X, Li Y R, Shen J Z, Feng J T, Kong L Q (2004). The Lubei eco-industrial model of China. Chinese Journal of Process Engineering, 4: 467–474 (in Chinese)

Zhang Y, Yang Z F, Fath B D, Li S S (2010). Ecological network analysis of an urban energy metabolic system: model development, and a case study of four Chinese cities. Ecol Modell, 221(16): 1865–1879

Zhang Y, Zheng H M, Chen B, Yang N J (2013). Social network analysis and network connectedness analysis for industrial symbiotic systems: model development and case study. Front Earth Sci, 7(2): 169–181

Zhong G, Cao J, Cao L J, Wang S P (2010). Quantitative analysis of industrial symbiotic network's structure. In: Chinese Society for Environmental Sciences, ed. Proceedings 2010 China Environmental Science Society Annual Meeting, 5–7 May, Shanghai. Beijing: China Environmental Science Press, 1192–1200 (in Chinese)

Zhu Q E, Lowe E A, Wei Y, Barnes D (2007). Industrial symbiosis in China: a case study of the Guitang Group. J Ind Ecol, 11(1): 31–42