The vulnerability of industrial symbiosis: a case study of Qijiang Industrial Park, China

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Abstract: China is promoting the National Demonstration Eco-Industrial Park Program through the establishment of national eco-industrial parks (EIPs) founded on the concept of industrial symbiosis (IS). However, IS networks can be vulnerable to unanticipated perturbations such as sudden collapse/drop-out of an enterprise or the variations in waste quality, which constrain the sustainable development of EIPs. In such cases, we used Qijiang Industrial Park in Chongqing, China, as the case to construct a material and energy exchange network, and the evaluation indicator of vulnerability is put forward based on traditional topological metrics such as node/edge betweenness and global efficiency. We then conducted simulation experiments including single node failure and edge failure considering cascading failure to measure each enterprise's and energy/material flow's destructive effect on the entire network. The result imply that the statuses of enterprise and energy/material vary considerably. Enterprises located in further upstream have relatively large influence in general, and the upstream exchange of energy/material influence the IS system to a large extent. Additionally, synergetic exchanges with larger amount have larger influence on the IS system. Based on our

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findings, we recommended design and management strategies, such as enterprises adopting a more flexible sourcing and production strategy for various wastes/by-products, increasing the connectivity of EIP, and promoting informationization, to lower the vulnerability of IS system.

Keywords: Industrial symbiosis; Vulnerability; Eco-industrial park; Complex network; Cascading failure; China

1. Introduction

Since Lowe, formerly the director of the Indigo Development Institute in the United States, first proposed the concept of Eco-Industrial Parks (EIPs) in 1995 (Lowe and Evans, 1995), many countries have subsequently actively explored and established various EIPs (Behera et al., 2012; Berkel et al., 2009; Gibbs and Deutz, 2005; Park et al., 2008; Sakr et al., 2011; Veiga and Magrini, 1996). EIPs entail both economic and environmental benefits that can be achieved through exchanges of wastes and by-products, step-by-step utilization of materials, energy and water, and infrastructure sharing among enterprises (Côté and Hall, 1995). Recently, Lombardi and Laybourn (2012) have proposed expanding the definition of EIPs to include "the exchange of knowledge, information, and expertise" which also "positively influences the physical flows of materials and energy" considered as sources of innovation.

When it comes to development of industrial symbiosis (IS) and EIPs, China should certainly be put at the center of the ongoing discussion and exploration (Shi et al., 2012). In 2001, to reconcile economic growth and environmental management, China launched its National Demonstration Eco-Industrial Park Program (Lombardi et al., 2012). Up to January 2016, 31 demonstration EIPs had passed the state examination, and there are altogether 77 national demonstration EIPs which have been authorized construction (MEPPRC, 2016). From Fig.1 we can see that the number of EIPs authorized construction per year is increasing, which is especially obvious since 2010.

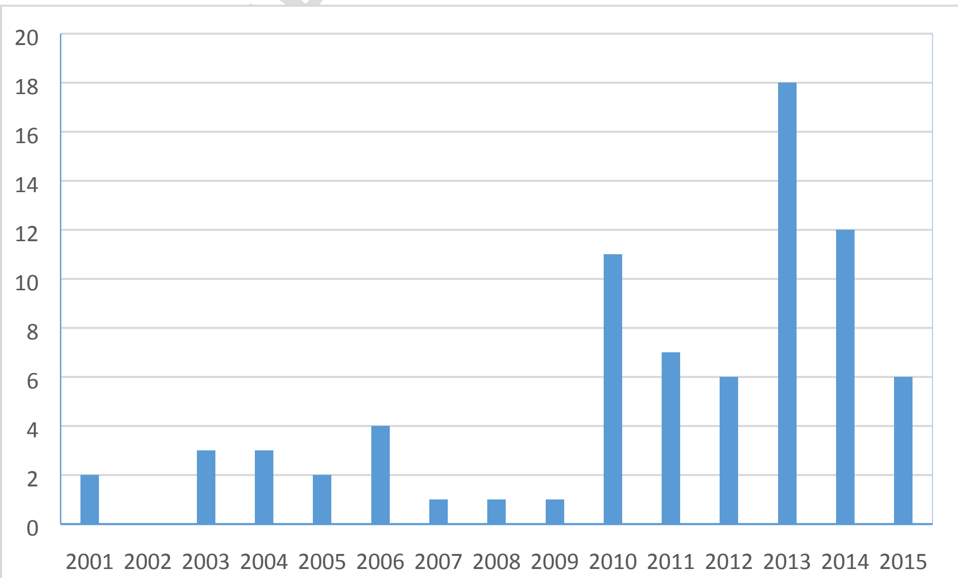

Fig.1. Numbers of the EIPs authorized construction per year.

While IS networks are highly complex and resource efficient with substantial economic and environmental benefits to the participating industries, they can also be vulnerable to unanticipated perturbations (Chopra and Khanna, 2014), because an EIP's establishment is influenced by numerous internal and external factors (Mannino et al., 2015; Veleva et al., 2015). A disturbance affecting even one industry (or node in the system) may lead to a domino effect, resulting in cascading impacts on the rest of the network (Allenby and Fink, 2005; Boons and Spekkink, 2012).

The instability of an IS system may emerge due to its special characteristics in ecological connections and developing environment (Wang et al., 2013). Additionally, Zhu et al. (2013) pointed out that a lack of prevention measures against the risk of an eco-industrial development is one of the major problems in China. Because of the fast pace of changes in markets and resources, and their complexity, production activities are difficult to coordinate, lacking effective integration of flows in materials, energy, and information between enterprises. As a result of fluctuations in material flows, downstream firms are unable to predict variations in the material components of upstream firms. Moreover, they cannot respond in a timely manner to ruptures in the industrial chain, changes in operation processes, or risks associated with product quality. This makes it difficult to achieve stable operation of the industrial chain and seriously impacts on the development of EIPs. Even the globally recognized Danish EIP, Kalundborg Industrial Park, has demonstrated a certain degree of vulnerability. For instance, in 1995, during a routine analysis of product components, it was discovered that gypsum at the Gyproc gypsum factory within the park contained a large amount of vanadium. Vanadium is a metallic element that can have detrimental effects on people. After conducting a comprehensive survey, the researchers eventually discovered the reason for the contamination of the gypsum with vanadium. This was because the Asnaes power plant was using a new kind of cheap fuel containing vanadium sourced from Venezuela. Vanadium was conveyed through the flow of materials within the symbiosis network, passing from upstream enterprises all the way to downstream enterprises. Eventually, the Asnaes power plant was compelled to improve its equipment to prevent the accumulation of vanadium in the gypsum and products of the flue gas desulfurization (FGD) device that led to the contamination of other products. This was not only costly in terms of time and money, but it also lowered the credibility of the gypsum factory. As Baldwin et al. (2004) have noted, technological changes and innovations, new external pressures, mergers and takeovers of enterprises, and other changes at Kalundborg Industrial Park will significantly influence the IS system, perhaps even resulting in its collapse. Cases of failing EIPs in China are not new. An example is the failure of an EIP, in Inner Mongolia that exploited the local coal, which was rich in aluminum and gallium, forming an industrial chain. The production process was as follows: coal mining→ coal→ electricity→ chemical coal industry→ extraction of alumina/gallium oxide from coal ash→ production of environmental protection materials from silicate-calcium slag. However, because of the fast-changing market, some key enterprises were unable to sustain production and dropped out, eventually leading to the collapse of the entire IS network.

The above examples are indicative of the widespread occurrence of instability in relation to EIPs, significantly impeding their development. Since most synergies in an IS network may be a result of social interactions between managers and owners of industries, the resulting network may not be strategically planned and be coincidental in nature, which makes it vulnerable to unforeseen and catastrophic events (Bain et al., 2010; Chertow, 2000, 2007; Ehrenfeld and Gertler, 1997). In real industrial systems, the production flow sometimes stops as a result of disruptions. Generally, disruptions could be categorized as (1) random changes, such as equipment faults/seasonal variations/operation errors, and (2) deliberate changes, such as process upgrading/shutting down of high-polluting companies (Li and Shi, 2015). The sudden collapse/drop-out of an enterprise or the variations in waste quality can significantly affect the operation of an IS system.

More and more scholars have taken note of the instable phenomenon taken place in IS system and tried to solve the problem using various approaches. There are three similar terms to describe the property of IS networks under disturbance: resilience, stability and vulnerability. Resilience was introduced to the ecological literature by Holling (1973), defined as the ability of a system to absorb changes and still persist, and distinguished from stability- the ability of a system to return to an equilibrium state (Zhu and Ruth, 2013). While the central idea of the often-cited definition of vulnerability is that vulnerability is the degree to which a system is susceptible to and is unable to cope with adverse effects (McCarthy et al., 2001). Despite the difference between the three concepts, the aim of research in the three aspects is common - to develop robust and credible measures, to incorporate diverse methods that include perceptions of risk and vulnerability, and to incorporate governance research on the mechanisms that mediate vulnerability and promote adaptive action and resilience (Adger, 2006). Hardy and Graedel (2002) applied food-web theory to a set of 19 actual and hypothetical eco-industrial parks and integrated biosys-tems and found that increased connectance in industrial ecosystems did not necessarily imply increased stability or improved environmental performance. Chen et al. (2012) analyzed 88 sample recycling projects in 23 eco-towns in Japan, and concluded that lager eco-towns tend to have higher operation stability, which is concordant with Bain et al. (2010) who claimed that more diverse industrial bases were shown to produce a greater number of by-product exchanges and collaborations. Fleig (2000) found that the greater the dependence of the companies within the IS system on each other, the greater the risk to the stability of IS. However, Zhu and Ruth (2013) claimed that an industrial ecosystem was less resistant and less resilient with high inter-firm dependency.

In fact, IS systems are highly complex like natural ecosystems, to maintain their functionality to counter stresses and adapt to external or internal changes (Ashton, 2009; Chopra and Khanna, 2014), making it difficult to manage the EIPs. Managers require decision-making tools and processes that support the identification or selection of companies, as well as those agencies responsible for monitoring and improving the park's operations (Chiu and Geng, 2004; Felicio et al., 2016; Oh et al., 2005; Sopha et al., 2010). The most widely used of these methods are life cycle assessment (Sokka et al., 2011a; Sokka et al., 2011b), material flow analysis (Geng et al., 2012; Sendra et al., 2007; Yong et al., 2009) and environmental indicators (Kurup and Stehlik, 2009; Pakarinen et al., 2010; Zhu et al., 2010). The use of these methods enables managers to assess the flow of materials and the environmental impacts of companies. They can also be used to facilitate decision making about which companies should be allowed to participate in the park. However, there are very few methods for analyzing the vulnerability of IS and enabling managers to improve stability and develop effective risk management.

When dealing with complex interaction and interdependency problems, the network is a good model to simplify system structure and uncover system features (Newman 2003). In 1998, an article by Watts and Strogatz titled “Collective dynamics of 'small-world' networks” was published in *Nature*. This article introduced the concept of a “small world” and established the small world network model. The following year, an article by Barabasi and Albert (1999) titled “Emergence of scaling in random networks” was published in *Science*, establishing a scale-free network model. These two articles immediately prompted research focusing on the transformation of simple networks into complex networks, resulting in the widespread application of complex networks within various fields such as physical, biological, social, and supply systems (Allesina et al., 2010; Dobson et al., 2007; Jeong et al., 2000; Mehra, 2005; Song et al., 2005; Zheng et al., 2007; Nair and Vidal, 2011).

In the domain of IS, network theory has been used to study the structure of IS networks (Shi and Shi, 2014; Domenech and Davies, 2011) and the impact of short mental distance in IS (Ashton, 2008; Ashton and Bain, 2012). It has also been used to assess the resilience (Zhu and Ruth, 2013; Zeng et al., 2013a; Chopra and Khanna, 2012) and stability (Xiao et al., 2016; Wang et al., 2013) of IS networks. However, little research has been done to assess the vulnerability of IS networks. The only existing study (Zeng et al., 2013b) on vulnerability assessment provides some evaluation indicators to evaluate nodes’ power and status and analyzes the vulnerability against cascading failures in symbiosis networks. However, the vulnerability assessment is conducted by a purely topological approach, and quality and amount of the waste/by-product are not taken into consideration, which may make the result inaccurate.

The purpose of this paper is to advance the understanding of the vulnerability of IS network and promote the application of complex network theory and information and communication technologies into IS system. To investigate vulnerability, we employed an interdependent network model that presents both the enterprises and the material exchange and developed a method to assess the vulnerability of IS network under certain changes. Based on the case of Qijiang industrial park, our main findings may contribute to the vulnerability problem in several ways. First, the statuses of enterprises in IS network are quite different, and there are several core nodes that influence the IS network significantly. Second, the significance of components in IS network is also not uniform, and the components with more frequent exchange and larger amount show greater impact on the IS system. Third, the purely topological analysis may lead to inaccurate results, and it is necessary to consider the operation reality of EIP and regard the IS network as an open system. Understanding and controlling of vulnerability should be an indispensable part of IS network research and planning.

The remainder of this paper is organized as follows. Section 2 present the research methodology applied in our research. In section 3, rules to establish an IS network and indicators of vulnerability are introduced. In section 4, a case from the Qijiang Industrial Park is introduced to construct a network topological structure. Both single node failure and edge failure simulation are done on the network cascading failure transmission, and the result is presented. Managerial insights are revealed in section 5. Finally, Section 6 concludes with a summary.

2. Research methodology

For this study, we applied qualitative and quantitative research methods. Qualitative methods entailed participant observation and interviews. Quantitative methods entailed a questionnaire-based survey and simulation analysis.

2.1. Participant observation

We were appointed as technical advisors by the administrative committee of the Qijiang Industrial Park to guide the process of designing the Smart Industrial Park program for circular economy development planning during the period from November 2015 to April 2016. As members of the program's internal team, we gained in-depth insights into related government processes and documents, as well as significant exposure to companies' waste treatment practices. To better understand actual operational conditions within the park, we conducted a series of observations. These observations usually focused on waste handling facilities, or factories visited during quick tours that were conducted whenever possible. They proved especially helpful in ascertaining concrete waste management practices and revealed contrasts between what respondents stated during interviews and what they actually did in practice.

2.2. In-person and telephone interviews

In-person semi-structured interviews were the primary means of collecting detailed quantitative information about operational practices at the plant level in Qijiang Industrial Park . Based on participant observation conducted at an early stage, a provisional interviewee list was produced comprising 16 companies located in the park that generated significant quantities of waste or by-products. The administrative committee of Qijiang Industrial Park played an important role in inviting the participation of firms included in the interviewee list. Representatives of all but two companies on the list agreed to be interviewed. Detailed notes were made during the interviews, and shortly after their completion, interviewees were requested to provide contact information for downstream firms. With the assistance of the firms and, in some cases, with that of the administrative committee of Qijiang Industrial Park, further interviews were conducted with the downstream enterprises. Altogether, 14 in-person interviews were conducted for the empirical research component. In several cases, there were follow-up telephone and email communications to verify information obtained during face-to-face meetings. These interviews helped us to better understand the operational conditions of the companies and the awareness and attitudes of the manager toward potential risks. The main interview questions are listed in Appendix A.

2.3. Questionnaire survey

With the assistance of the administrative committee of Qijiang Industrial Park, a questionnaire-based survey of 16 enterprises located in Qijiang Industrial Park was conducted to investigate the specific operational conditions and existing risk management awareness and measures taken within the enterprises. The survey provided us with input-output data for every enterprise that could be used to weight the enterprises' mutual influence. The administrative committee played a critical role in distributing questionnaires to the 16 companies and collecting completed ones from them. The distributed questionnaire is included in Appendix B.

2.4. Simulation analysis

To analyze the survey data, we charted the network topological structure and conducted a simulation experiment on the cascading failure mode of a single node and egde. Based on our proposed definition of vulnerability, we calculated the value of vulnerability and node/edge betweenness after randomly removing a node/edge within the diagram of the network topological structure. Consequently, we were able to estimate the vulnerability of each nodal enterprise and material/energy and to identify vulnerable ones as the key monitoring targets for reducing the network's vulnerability.

3. The eco-industrial network and its vulnerability

3.1. Establishment of an IS network

The principles for establishing IS networks, according to complex network theory, are the same as those described by Xiao et al. (2016) and Li and Shi (2015). We constructed the eco-industrial network, considering enterprises within the EIP to be the nodes. The edge of the network topological structure denoted the exchange behavior between enterprises, and its direction denoted the direction of exchanges of materials or energy. It should be noted that actual exchanges of materials or energy had to have occurred between enterprises within the EIP for their inclusion in the network topology map. Moreover, the edges were assigned weights using actual data on material or energy exchanges, thus enabling the network topological structure to better reflect the reality. Once the network is constructed, it is possible to understand the structural property of a system by calculating network metrics and observing the dynamic processes of the network.

3.2. Indicators of vulnerability

Albert et al. (2000) found that there was a high price to be paid for error tolerance, as extreme vulnerability to attacks (the selection and removal of a few nodes that play a vital role in maintaining the network's connectivity) is a generic property of communication networks. Traditional network measurement indexes, including connectedness and the degrees of cohesion and toughness, cannot comprehensively measure the functions of a network. Therefore, in this study, network efficiency was selected as a measure of the function of a symbiosis network. Latora and Marchiori (2001) have defined network efficiency between two nodes as the reciprocal of the distance between them. Therefore, global efficiency can be expressed as follows:

$$E_{glob} = \frac{1}{N(N-1)}\sum_{i \neq j} e_{ij} = \frac{1}{N(N-1)}\sum_{i \neq j}\frac{1}{d_{ij}} \tag{1}$$

This definition overcomes the defects of connectedness and the degrees of cohesion and toughness when calculating the network's function. However, formula (1) is only applicable to an undirected network or to networks that are dissimilarly weighted. Therefore, based on formula (1), Liu et al. (2011) proposed the following definition of the global efficiency of a similarly weighted network.

$$E_{glob} = \frac{1}{N(N-1)}\sum_{i \neq j} e_{ij} = \frac{1}{N(N-1)}\sum_{i \neq j} d_{ij}^{s} \tag{2}$$

In formulae (1) and (2), e_{ij} denotes partial network efficiency, d_{ij} is the distance between two nodes in a dissimilarly weighted network, and d_{ij}^{s} is the distance between two nodes in a similarly weighted network.

According to the general definition of system vulnerability and its characteristics, we can define the vulnerability of an IS network as the declined proportion of the system's function under external influences.

$$V(S, T) = \frac{f(S) - f[S(t)]}{f(S)} \tag{3}$$

In formula (3), S denotes the system comprising enterprises within the industrial park; T is the set of possible threats to the system; f is the measure function of the system function; f(S) is the system function, measured by E_{glob}; and f[S(t)] is the system function after the threat T attacks. $\Delta f = f(S) - f[S(t)] \geq 0$, $V(S, T) \in [0, 1]$.

To verify the validity of V(S, T), we introduced node betweenness, which is a traditional topological parameter denoting the proportion of the shortest paths passing node v_i in relation to the total number of shortest paths. Assuming that node m was linked to node n through node k, in a dissimilarly weighted network in which the weight would be proportional to distance. We denoted b_{mn}, which is the distance between m and n, as follows:

$$b_{mn} = w_{mk} + w_{kn} \tag{4}$$

However, in similarly weighted networks, higher weights are associated with greater proximity of the nodes and easier transmission of vulnerability. In other words, weight is inversely proportional to distance.

$$b_{mn}^{s} = {}^{1}\!/_{w_{mk}} + {}^{1}\!/_{w_{kn}} = \frac{w_{mk} * w_{kn}}{w_{mk} + w_{kn}} \tag{5}$$

In this study, node betweenness $b_v(i)$ indicates the influence of one enterprise over the others in relation to that of the others.

$$b_v(i) = \frac{1}{(n-1)(n-2)}\sum_{s \neq i \neq t} \frac{g_{s,t}(i)}{g_{s,t}} \tag{6}$$

In formula (6), $g_{s,t}$ denotes the total number of all of the shortest paths connecting node v_s to node v_t and $g_{s,t}(i)$ denotes the number of the shortest paths connecting node v_s to node v_t and passing node v_i. The shortest paths were calculated using the Dijkstra algorithm (Dijkstra, 1959).

The "edge betweenness" metric is defined as the number of shortest paths between pairs of vertices that run along an edge. In this paper, edge betweenness indicates the influence of a material/energy or waste/by-product.

$$b_e(i,j) = \frac{1}{2(n-1)}\sum_{a_{s,t} \neq a_{i,j}} \frac{\delta_{s,t}(i,j)}{\delta_{s,t}} \tag{7}$$

In formula (7), $\delta_{s,t}$ denotes the total number of all of the shortest paths connecting node v_s

to node v_t and $\delta_{s,t}(i,j)$ denotes the number of the shortest paths connecting node v_s to node v_t and passing edge $a_{i,j}$.

4. Simulation

4.1. A brief introduction to Qijiang Industrial Park

Qijiang Industrial Park is located in Chongqing, China (Fig. 2), which has been rapidly expanding, relying on its advantage in terms of coal production, amounting to an annual output of 10 million tons. The park's main products are various aluminous products intended for different uses, including cars, railways, and building materials. At the same time, several by-products are produced and utilized in the park, generating the following circulatory economy industrial chains: (1) FGD gypsum→ building gypsum products; (2) Gypsum flue-gas→ ammonium sulfate→ fertilizer; (3) Coal ash→ concrete blocks; and (4) Aluminum scrap→ secondary aluminum→ aluminum products.

Fig.2. Schematic map of Qijiang Industrial Park.

The park is a complex network given frequent intersections of material, energy, and information flows within these chains and the presence of transverse coupling. Fig. 3 presents the brief system network of the Qijiang Industrial Park, in which the sewage treatment plant is linked to every node within the network.

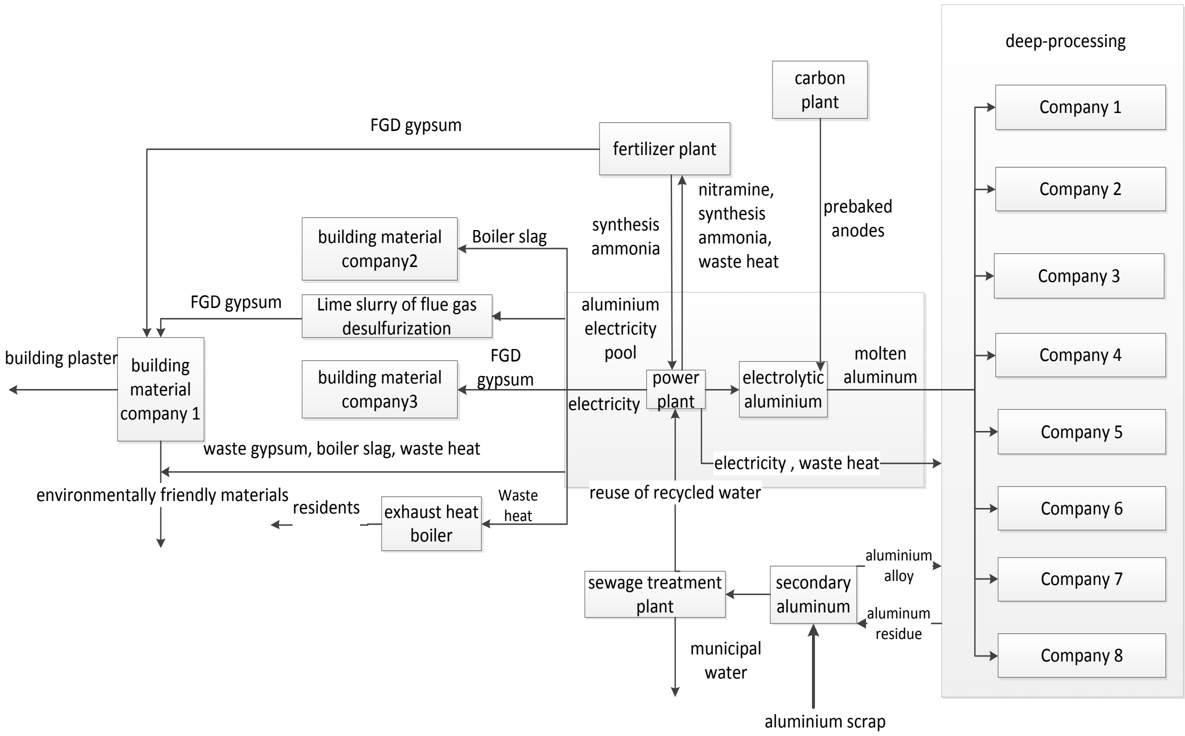

Fig. 3. Brief system network of Qijiang Industrial Park.

4.2. Weighting the mutual influence of enterprises and building a real network

To analyze the correlation between enterprises, we collected data on material exchanges and electricity consumption in 2015 (Table 1). The materials provided by an upstream firm A to a downstream firm B were calculated as P% of A's total output. The weight of the mutual influence between enterprises was calculated as a_{ij}= 5*P%. An adjacency matrix A was developed based on the P% result (Table 2). It was found that when i = j, a_{ij} = 5.

Table 1 Material exchanges and electricity consumption of the enterprises in Qijiang Industrial Park.

	input (10,000 tons)	electricity consumption (10,000 kWh)	output ($\cdot 10^4$)
f1	FGD gypsum:65	400	building plaster:60 m^3
f2	boiler slag:50.2	190	building plaster:50 m^3
f3	FGD gypsum :30	200	building plaster:50 m^3
f4	nitramine:21	3500	FGD gypsum:35 t
f5	coal:154 synthesis ammonia	4200	electricity:512949 kWh FGD gypsum:60 t

f6	waste water	2594	recycled water
f7	carbon	803	prebaked anodes:16 piece
f8	alumina:46	485077	liquid al:38 t
f9	waste aluminum:11	6000	aluminum alloy:10 t
f10	aluminum:15	3116	product 1
f11	aluminum:11	2890	product 2
f12	aluminum:1	500	product 3
f13	aluminum:1	570	product 4
f14	aluminum:7.5	1700	product 5
f15	aluminum:3	900	product 6
f16	aluminum:4	1050	product 7
f17	aluminum:4	980	product 8

Table 2 Adjacency matrix A of Qijiang Industrial Park.

	f1	f2	f3	f4	f5	f6	f7	f8	f9	f10	f11	f12	f13	f14	f15	f16	f17
f1	5	0	0	1.5	0.0191	0.0098	0	0	0	0	0	0	0	0	0	0	0
f2	0	5	0	0	0.0019	0.0005	0	0	0	0	0	0	0	0	0	0	0
f3	0	0	5	0	0.0019	0.002	0	0	0	0	0	0	0	0	0	0	0
f4	4	0	0	5	0.0341	0.0074	0	0	0	0	0	0	0	0	0	0	0
f5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
f6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
f7	0	0	0	0	0	0.0021	5	5	0	0	0	0	0	0	0	0	0
f8	0	0	0	0	4.7283	4.7804	5	5	0	5	5	5	5	5	5	5	5
f9	0	0	0	0	0.0585	0.0585	0	0	5	1.7	1.3	1.3	0	1.5	1.4	1.5	1.5
f10	0	0	0	0	0.0424	0.227	0	1.2727	1.8	5	0	0	0	0	0	0	0
f11	0	0	0	0	0.0145	0.0039	0	1.0606	1.5	0	5	0	0	0	0	0	0
f12	0	0	0	0	0.0195	0.0195	0	0.1515	0	0	0	5	0	0	0	0	0
f13	0	0	0	0	0.0056	0.0015	0	0.1564	0	0	0	0	5	0	0	0	0
f14	0	0	0	0	0.0306	0.0098	0	0.7955	0.4156	0	0	0	0	5	0	0	0
f15	0	0	0	0	0.0097	0.0098	0	0.4242	0.4214	0	0	0	0	0	5	0	0
f16	0	0	0	0	0.0095	0.0098	0	0.4356	0.4258	0	0	0	0	0	0	5	0
f17	0	0	0	0	0.0098	0.0098	0	0.4163	0.4071	0	0	0	0	0	0	0	5

The values in Table 2 show the conditions of material or electricity exchanges between the enterprises. Based on these values, we established a network topology (Fig. 4) using the UCINET software (a social network analysis program). In this study, enterprise interactions were similarly weighted. In other words, a higher weight was associated with greater proximity of the enterprises and easier transmission of vulnerability.

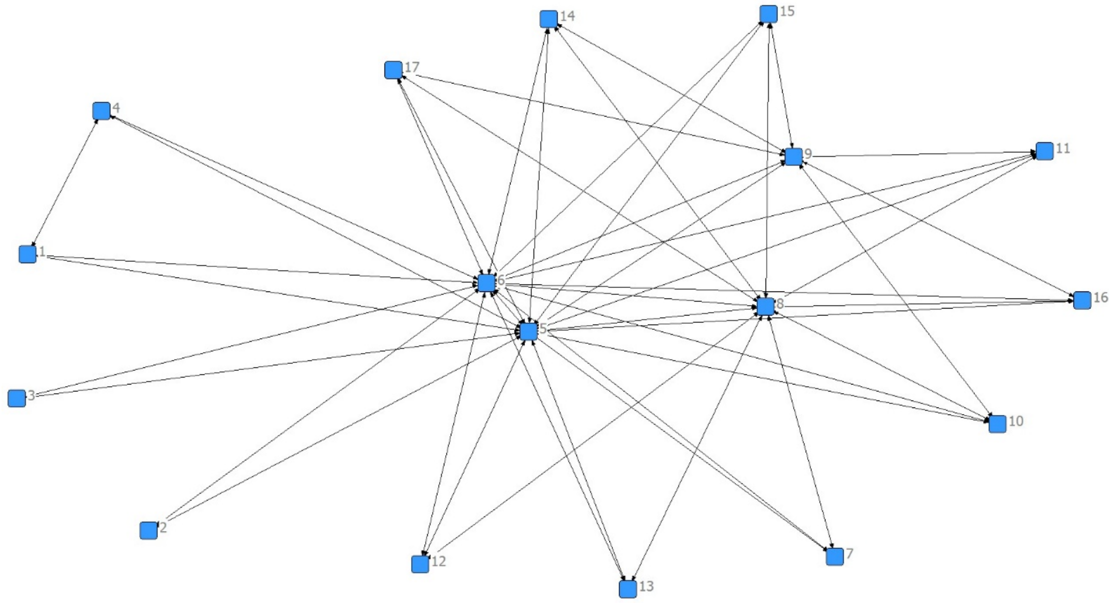

Fig. 4. Diagram of the network topological structure of Qijiang Industrial Park.

Once the network is built, some statistically characteristic parameters such as clustering coefficient, average degree and average path length can be calculated. Table 3 shows the representative statistically characteristic parameters of Qijiang industrial symbiosis network.

Table 3 Statistically characteristic parameters of Qijiang industrial symbiosis network

number of nodes	number of edges	clustering coefficient	average degree	average path length
17	84	0.0649	5.7647	1.6397

4.3. Simulation experiment and data analysis

In a real network, because of existing coupling relationships between nodes, a malfunction occurring in one or edge would induce the collapse of others as an immediate linkage effect that would ultimately lead to the collapse of a large number of nodes or possibly to the collapse of the entire system. This phenomenon is known as a cascading failure (Xiao et al., 2016). Cascading failures are common in large complex networks such as internet networks, transportation networks, power grids and supply systems (Motter and Lai, 2002; Motter, 2004; Moreno et al., 2002; Caldarelli and Vespignani, 2007; Sachtjen et al., 2000; Church and Scaparra, 2007). In the IS network, if a company node lost its essential incoming edge, the company would stop functioning and be marked as “failure.” Here, “essential” is an attribute of the edge, which means that the input material is necessary for the normal production of the company. In consideration of cascading failure effect, We assume that the failure of one company node would eliminate all its outgoing edges, which might cause the failure of other elements in the network. There are three modes of failure within a symbiosis network. Single node failure occurs when one enterprise breaks down or drops out, multi-node failure entails the simultaneous break down of two or more enterprises, and edge failure occurs when the correlativity between two enterprises cracks. However, in reality, the probability of several enterprises breaking down simultaneously is small. Therefore, we only analyzed the single node failure mode and edge failure mode.

4.3.1. Single node failure mode

We successively removed network nodes (Fig. 5a) and calculated the value of V(S, T) and node betweenness $b_v(i)$. The results are shown in Table 4, which indicates that in terms of vulnerability, the effects of each node varied considerably. For example, while global efficiency fell by 46.48% when f6 broke down, it only fell by 0.09% when f12 broke down. Some nodes within the network were found to have considerable influence in relation to node betweenness such as f6, f5, and f8, while some nodes such as f2, f12, and f13 had little influence. This indicates that the power plant (f5), sewage treatment plant (f6), and electrolytic aluminum plant (f8) exerted significant influence over the entire system, while the downstream firms had a relatively small impact on the system. This is because the power plant supplies electricity for all of the nodes within the industrial park, the sewage treatment plant disposes of industrial effluents for all of the nodes, and the electrolytic aluminum plant provides downstream firms with raw materials. If these three nodes break down, the entire system will be unable to function. However, some downstream enterprises such as f2, f12 and f13 have little influence to the IS system, which indicates that the counterforce of downstream enterprises is puny compared with the huge influence of some core upstream enterprises. Therefore, it can be concluded that enterprises located in further upstream have relatively large influence in general, complimenting the findings by Zhu and Ruth (2013) and Chopra and Khanna (2014).

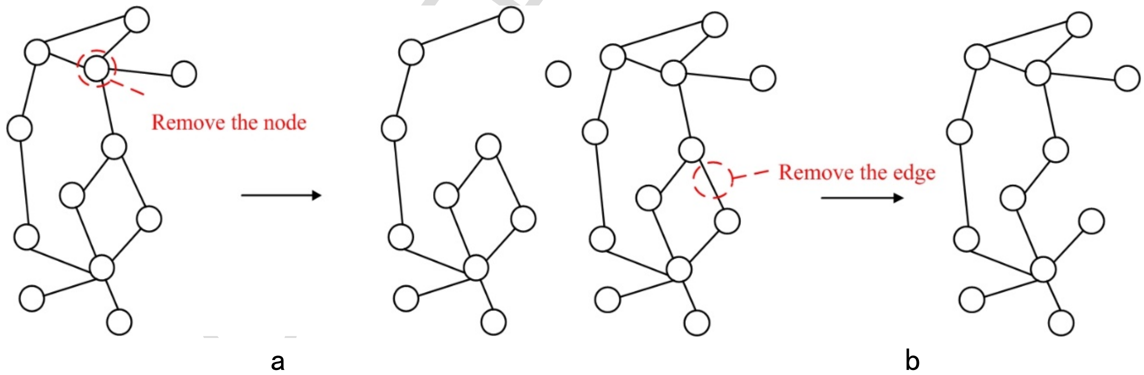

Fig. 5. A schematic illustration of the simulation experiment: (a) single node failure mode; and (b) edge failure mode.

Table 4 Vulnerability and node betweenness when nodes are removed.

serial number	Vulnerability in descending order			Node betweenness in descending order		
	f(i)	V(S,T)%	bv(i)	f(i)	V(S,T)%	bv(i)
1	f6	46.48	0.4771	f6	46.48	0.4771
2	f5	42.57	0.4190	f5	42.57	0.4190
3	f8	21.10	0.2426	f8	21.10	0.2426

4	f9	16.56	0.1458	f9	16.56	0.1458
5	f4	14.31	0.1277	f4	14.31	0.1277
6	f7	7.17	0.0868	f7	7.17	0.0868
7	f10	6.63	0.0633	f10	6.63	0.0633
8	f11	6.08	0.0617	f11	6.08	0.0617
9	f1	1.45	0.0002	f3	0.75	0.0015
10	f14	1.13	0.0000	f2	0.66	0.0015
11	f16	0.85	0.0000	f1	1.45	0.0002
12	f15	0.77	0.0000	f12	0.09	0.0000
13	f17	0.77	0.0000	f13	0.09	0.0000
14	f3	0.75	0.0015	f14	1.13	0.0000
15	f2	0.66	0.0015	f15	0.77	0.0000
16	f13	0.09	0.0000	f16	0.09	0.0000
17	f12	0.09	0.0000	f17	0.77	0.0000

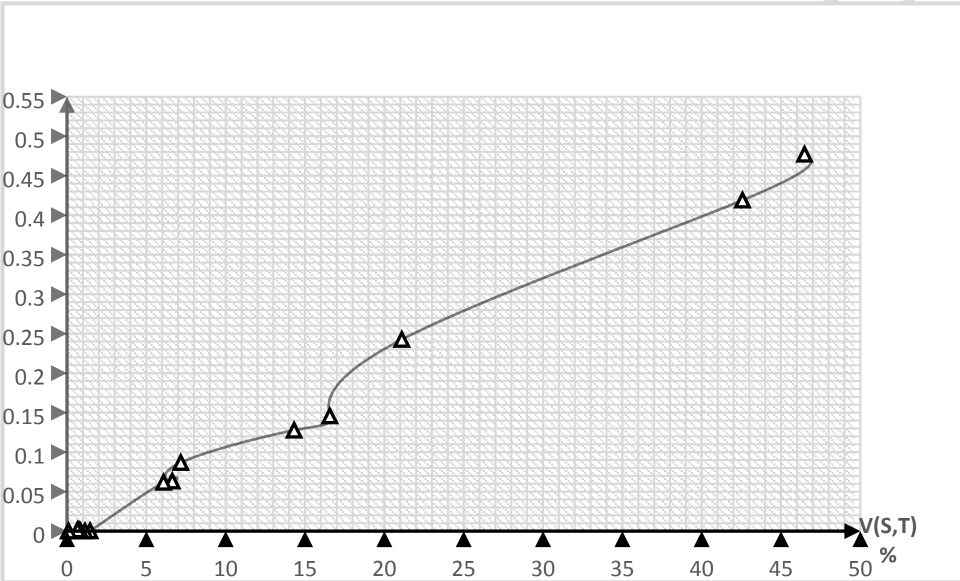

Fig. 6. A scatter diagram of vulnerability and node betweenness.

Fig. 6 indicates obviously an overall positive correlation between vulnerability and node betweenness that was tenable for relatively high values of vulnerability and node betweenness. However, when these values were low, this phenomenon was not clearly apparent, and there were also some exceptions such as f2, and f3. There are three underlying reasons for this. First, the vulnerability and node betweenness values were affected by the comprehensive influence of the number of nodes and the weight, and could only be high if both the number and weight were relatively high. Additionally, there are 17 nodes in Qijiang Industrial Park, which is an insufficient number, leading to uneven results.

4.3.2. Edge failure mode

Similar to single node failure mode, we removed the edge in sequence (Fig. 5b) and calculated the value of V(S, T) and edge betweenness $b_e(i,j)$. Because there are 84 edges altogether in the IS network, we selected some representative ones. The results are shown in Table 5 and Fig. 7, from which we found that the effects of removing each edge also varied considerably. We can see that edges such as $e_{5,8}$, $e_{5,9}$, $e_{6,5}$ have significant influence on the IS system while the influence of removing $e_{5,2}$, $e_{8,12}$ is negligible, which indicates that the upstream exchange of energy/material influence the IS system to a large extent. This can be explained by cascading failure existing in IS networks - once the variations in waste quality and/or waste composition associated with process changes take place in the upstream of material exchange, it may lead to a domino effect, resulting in the substandard products produced by the downstream enterprises.

In addition, as we further analyze the result data, it is found that there is a positive correlation between the vulnerability and the amount of energy/material exchange (Fig. 8), which indicates that the synergetic exchanges with larger amount have larger influence on the IS system.

Table 5 Vulnerability and edge betweenness when edges are removed.

ranking	e(i,j)	V(S,T)%	bv(i)
1	$e_{5,8}$	32.61	0.5388
2	$e_{5,9}$	14.31	0.3596
3	$e_{6,5}$	12.17	0.3325
4	$e_{5,7}$	7.62	0.1728
5	$e_{9,10}$	6.39	0.1542
6	$e_{5,10}$	5.68	0.1433
7	$e_{8,10}$	5.33	0.1424
8	$e_{8,11}$	5.24	0.1412
9	$e_{4,1}$	1.26	0.0947
10	$e_{5,14}$	1.08	0.0843
11	$e_{8,14}$	1.07	0.0843
12	$e_{8,16}$	0.83	0.0584
13	$e_{8,15}$	0.67	0.0511
14	$e_{5,2}$	0.58	0.0487
15	$e_{8,12}$	0.08	0.0087

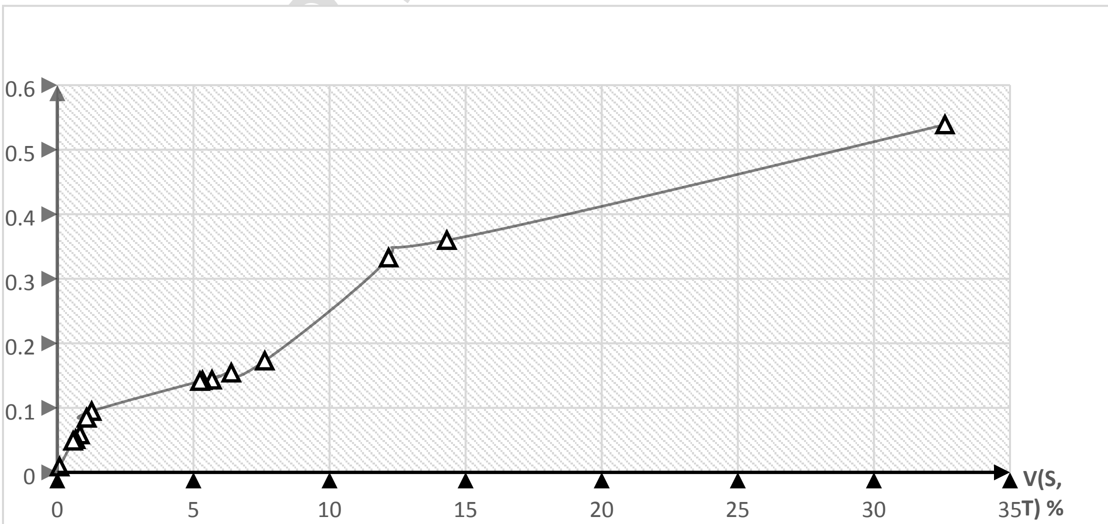

Fig. 7. A scatter diagram of vulnerability and edge betweenness.

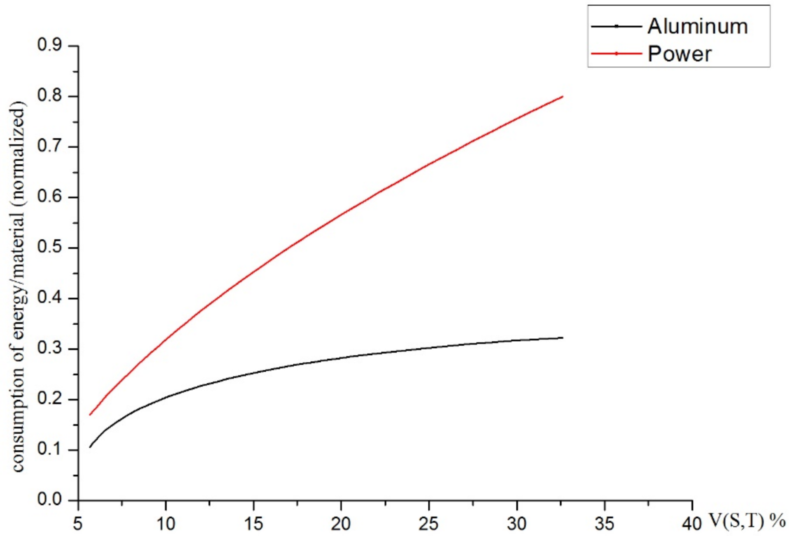

Fig. 8. The correlation between the amount of energy/material and vulnerability.

5. Discussion and recommendations

This work focused on studying the network properties of IS network with a case of China. We proposed an evaluation method by conducting single node failure and edge failure simulation considering cascading failure. This evaluation method can help us to identify the critical nodes and edges effectively. The results of the simulation revealed that the statuses of nodes and edges in IS network vary considerably. Enterprises and energy/material located in further upstream have relatively large influence in general, and the synergetic exchanges with larger amount have larger influence on the IS system. In Qijiang Industrial Park, the power plant emerges as the highest vulnerable node and the power it transmit to electrolytic aluminum plant emerges as the most vulnerable edge from a network topology perspective, calling for greater efforts to secure them as they may have the largest cascading impact on the IS system, thus threatening its functionality. Theoretically, the vulnerability of IS system will be decreased by (1) ensuring the smooth operation of core enterprises in the IS network, and (2) guaranteeing the transmission of critical energy/material, anmatd (3) preventing the volatility of the waste and by-product and guaranteeing the quality of them. In practice, we propose following recommendations.

First, to ensure the smooth operation of core enterprises, we suggest the power plant and electrolytic aluminum plant adopt a more flexible sourcing and production strategy for various wastes/by-products in case of the fluctuation from the carbon plant. More adaptive strategies should be adopted by the enterprises, such as increasing the stocks of essential materials and using a more flexible production procedure (Pettit et al., 2010). This advice has been adopted by the park's management committee, and they have signed an agreement with an enterprise outside the park as a standby carbon supplier. In addition, we suggest the core enterprises expand the industrial chains by using other wastes or by-products such as CO_2 to produce polymeric materials. Redundancy in an IS context is maximized by encouraging multiple connections in the network, which means more distinct industries with similar commodity synergies may aid in absorbing the impact of degradation of an industry in the network (Ahern, 2011). An increase in redundancy of synergies and industries in an IS may axiomatically lower the vulnerability by favoring flexibility or plasticity of the network that provides alternative opportunities for synergies if a node or edge is removed, thus ensuring the adaptive capability of the IS (Chopra and Khanna, 2014). It is also recommended that the manufacturing equipment in enterprises should be inspected periodically, considering the poor condition of it.

Second, to guarantee the smooth transmission of energy/materials, we suggest increase the connectivity of EIP by improving the construction of infrastructure. When an EIP is understood as a system that performs functions, connectivity is often the critical parameter –and the lack of connectivity is often a prime cause of malfunction or failure of particular functions (Ahern, 2011). Therefore, more backup electric lines, pipes that bridge districts across the river and form pipe cycles should be built to secure the supply, especially in the water and power network (Li and Shi, 2015). The transportation network should also be improved, making it convenient and efficient for material transmission.

Third, we suggest monitor the key components of wastes/by-products in real time, focusing on the problem of inconsistent quality caused by the volatility of the key components and the transfer of harmful elements. Cascading failure can arise from any link or kink in a convoluted IS network, possibly leading to an irreparable amount of damage to the IS system. With too much data to deal with, traditional management methods are no longer adequate. In consequence, we suggest promote informationization of EIPs. The new type of industrialization in China has a strong element of information technology in its design and is promoted by means of a new approach to information which is described as ''informationization'' (Ren, 2003). The strategy for informationization focuses on encouraging Information and Communication Technology (ICT) and Internet of Things (IoF) in enterprises. In order to keep track of the operation of production process in a realtime way, it is imperative that environmental information systems be established within industrial parks and zones to provide integrated and reliable data (Fang et al., 2007). The data would include surveys of the members, detailed information about inputs and outputs of materials, environmental monitoring, and other data. The data would be collected and evaluated locally, transforming into a more visualized form by the information system, which can be simply used by the managers of the park.

Response to accelerating market change forces firms to reform their ways of management (Cottrill, 2000). ICTs allow firms to try new management practices through enabling them to handle increasingly complicated information flows, to coordinate more efficiently different internal functions, to form new supply linkages, and to develop new customer linkages (Liu et al., 2004). In fact, managers of Qijiang Industrial Park have fully recognized the importance of establishing an information system. In 2015, the management committee invest 120 million CNY to build an information platform for conducting information analysis and evaluating the potential value of the collected information. As a reward, the electrolytic aluminum plant reduced the number of hired inspectors by 20, thereby saving labor costs of 2.6 million CNY in one year. Moreover, real time monitoring is more accurate than human monitoring, enabling problems to be discovered in a timely way and helping to identify and effectively avoid risks for managers. Perhaps in the near future, EIPs may evolve into a more advanced form combining many functions such as intelligence monitoring, information processing and risk prevention, which we tentatively call Smart Industrial Parks (SIP).

6. Conclusions

Vulnerability as an emergent feature of a system's ability to defend against external or internal threats is a meaningful issue that deserve to be studied. Researchers have argued that an increase in vulnerability of nodes may correlate with a decrease in resilience or adaptive capability of the network (Folke, 2006; Miller et al., 2010). By applying complex network theory, we measured the mutual influence of enterprises within an adjacent matrix constructed for Qijiang Industrial Park and established a symbiosis network topology. We subsequently designed and conducted simulation experiments including single node failure mode and edge failure mode, evaluating each enterprise's and energy/material flow's destructive effect on the entire network. The results indicate that the statuses of enterprise and energy/material vary considerably. Enterprises located in further upstream have relatively large influence in general, and the upstream exchange of energy/material influence the IS system to a large extent. Additionally, synergetic exchanges with larger amount have larger influence on the IS system. Consequently, we identified the most critical nodal enterprises and most vulnerable energy/material exchanges in the industrial park. Based on our analysis, we have made recommendations aimed at reducing the vulnerability of the symbiosis network. The necessity and benefit of establishing information system and applying ICTs is particularly emphasized, and we predict the prospect of EIPs audaciously.

The evaluation method proposed in this study fully considers the complexity of IS network and correlations of the enterprises, enabling us to identify the vulnerable nodes and edges in the IS networks in an efficient manner. This study facilitates the application of complex network theory into IS networks and provide insights for designers and managers of EIPs. However, the number of enterprises in this case was insufficient so that the results of the simulation were to some extent uneven. Future uncovering studies can focus on promoting ICTs and IoT application to EIPs, and the acceleration regime for informationization of enterprises.

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Appendix A. Primary interview questions

Interview questions	Where are your raw materials from? How do you deal with your by-products or wastes? Where do they

	flow to? What do you think is the potential risk of your company? What would happen if your upstream/downstream companies broke down and is there a risk emergency plan? What do you think is the position of your company in the EIP and how does your company contribute to the industrial symbiosis? Have you applied any ICT in your company? What are the main reasons you do or do not apply this technology?

Appendix B. The questionnaire distributed to companies

Company name		
Data source		
Main product	Product name	Quantity
Raw material	Name	Quantity
By-product or waste	Name	Quantity
Energy consumption	Type Electricity Coal Natural gas	Quantity
Use of waste heat and energy	Output Utilized quantity	

References

Adger, W.N., 2006. Vulnerability. Glob. Environ. Change. 16(3), 268-281.

Ahern, J., 2011. From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. Landsc. Urban Plan. 100, 341-343.

Albert, R., Jeong, H., Barabási, A.L., 2000. Error and attack tolerance of complex networks. Nature. 406, 378–382.

Allenby, B., Fink, J., 2005. Toward inherently secure and resilient societies. Science 309(5737), 1034-1036.

Allesina, S., Azzi, A., Battini, D., Regattieri, A., 2010. Performance measurement in supply chains: new network analysis and entropic indexes. Int. J. Prod. Res. 48, 2297–2321.

Ashton, W., 2008. Understanding the organization of industrial ecosystems. 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.

Bain, A., Shenoy, M., Ashton, W., Chertow, M., 2010. Industrial symbiosis and waste recovery in an Indian industrial area. Resour. Conserv. Recycl. 54, 1278–1287.

Baldwin, J.S., Ridgway, K., Winder, B., Murray, R., 2004. Modelling industrial ecosystems and the problem of evolution. Prog. Ind. Ecol. 1(1-3), 39-60.

Barabasi, A.L., Albert, R., 1999. Albert, R.: Emergence of Scaling in Random Networks. Science 286(5439), 509–512.

Behera, S.K., Kim, J.H., Lee, S.Y., Suh, S., Park, H.S., 2012. Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework. J. Clean. Prod. 29, 103–112.

Berkel, R.V., Fujita, T., Hashimoto, S., Geng, Y., 2009. Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006. J. Environ. Manag. 90(3), 1544–1556.

Boons, F., Spekkink, W., 2012. Levels of Institutional Capacity and Actor Expectations about Industrial Symbiosis. J. Ind. Ecol. 16(1), 61–69.

Côté, R., Hall, J., 1995. Industrial parks as ecosystems. J. Clean. Prod. 3(1-2), 41–46.

Caldarelli, G., Vespignani, A., 2007. Large scale structure and dynamics of complex networks. World Scientific.

Catherine, H., Graedel, T.E., 2002. Industrial Ecosystems as Food Webs. J. Ind. Ecol. 6(6), 29–38.

Chertow, M.R., 2000. Industrial symbiosis: literature and taxonomy. Annu. Rev. Energy. 25, 313-337.

Chertow, M.R., 2007. "Uncovering" industrial symbiosis. J. Ind. Ecol. 11, 11-30.

Chiu, A.S.F., Geng, Y., 2004. On the industrial ecology potential in Asian Developing Countries. J. Clean. Prod. 12(8–10), 1037–1045.

Chopra, S.S., Khanna, V., 2014. Understanding resilience in industrial symbiosis networks: Insights from network analysis. J. Environ. Manag. 141(141C), 86-94.

Church, R.L., Scaparra, M.P., 2007. Protecting Critical Assets: The r -Interdiction Median Problem with Fortification. Geogr. Anal. 39(2), 129–146.

Cottrill, K., 2000. Speedier supply chains. Traffic World, Vol. 261, 16–17.

Dijkstra, E.W., 1959. A note on two problems in connexion with graphs. Numer. Math. 1, 269–271.

Dobson, I., Carreras, B.A., Lynch, V.E., Newman, D.E., 2007. Complex systems analysis of series of blackouts: cascading failure, critical points, and self-organization. Chaos 17(2), 026103.

Doménech, T., Davies, M., 2011. The role of embeddedness in industrial symbiosis networks: Phases in the evolution of industrial symbiosis networks. Bus. Strategy. Environ. 20(5), 281-296.

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

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

Felicio, M., Amaral, D., Esposto, K., Durany, X.G., 2016. Industrial symbiosis indicators to manage eco-industrial parks as dynamic systems. J. Clean. Prod.118, 54–64.

Fleig, A.K., 2000. Eco-industrial parks, a strategy towards industrial ecology in developing and newly industrialized countries, Deutsche Gesellscchaft für Technische Zusammenardbeilt. Working Paper 1-48

Folke, C., 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. Glob. Environ. Change. 16, 253-267.

Geng, Y., Fu, J., Sarkis, J., Xue, B., 2012. Towards a national circular economy indicator system in China: an evaluation and critical analysis. J. Clean. Prod. 23(1), 216–224.

Gibbs, D., Deutz, P., 2005. Implementing industrial ecology? Planning for eco-industrial parks in the USA. Geoforum 36(4), 452–464.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. 4, 1-23.

Jeong, H., Tombor, B., Albert, R., Oltvai, Z.N., Barabási, A.L., 2000. The Large-Scale Organization of Metabolic Networks. Nature 407(6804), 651–654.

Kurup, B., Stehlik, D., 2009. Towards a model to assess the sustainability implications of industrial symbiosis in eco-industrial parks. Prog. Ind. Ecol. 6(2), 103–119.

Latora, V., Marchiori, M., 2001. Efficient behavior of small-world networks. Phys. Rev. Lett. 87(19), 198701.

Li, Y., Shi, L., 2015. The Resilience of Interdependent Industrial Symbiosis Networks: A Case of Yixing Economic and Technological Development Zone. J. Ind. Ecol. 19, 264–273.

Liu, T., Zeng, D., Hong, R.Y., 2011. Effect of distribution of weight on the efficiency of weighted networks. Acta Phys. Sin-CH Ed. 60(2), 307–351.

Lombardi, D.R., Lyons, D., Shi, H., Agarwal, A., 2012. Industrial Symbiosis. J. Ind. Ecol. 16(1), 2–7.

Lombardi, D.R., Laybourn, P., 2012. Redefining Industrial Symbiosis. J. Ind. Ecol. 16(1), 28–37.

Lowe, E.A., Evans, L.K., 1995. Industrial ecology and industrial ecosystems. J. Clean. Prod.3(1–2), 47–53.

Mannino, I., Ninka, E., Turvani, M., Chertow, M., 2015. The decline of eco-industrial development in Porto Marghera, Italy. J. Clean. Prod. 100, 286–296.

McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.), 2001. Climate Change 2001: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge.

Mehra, A., 2005. The Development of Social Network Analysis: A Study in the Sociology of Science by Linton C. Freeman. Admin. Sci. Quart. 50, 148–151.

MEPPRC (Ministry of Environmental Protection of the People's Republic of China), 2016. National environmental protection plan. http://www.zhb.gov.cn/

Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharawani, S., Ziervogel, G., Walker, B., Birkmann, J., Van der Leeuw, S., Rockström, J., 2010. Resilience and vulnerability: complementary or conflicting concepts? Ecol. Soc. 15, 1-25.

Moreno, Y., Gómez, J., Pacheco, A., 2002. Instability of scale-free networks under node-breaking avalanches. Europhys. Lette. 58(4), 630.

Motter, A.E., 2004. Cascade control and defense in complex networks. Phys. Rev. Lett. 93(9), 098701.

Motter, A.E., Lai, Y.-C., 2002. Cascade-based attacks on complex networks. Phys. Rev. E 66(6), 065102.

Nair, A., Vidal, J.M., 2011. Supply network topology and robustness against disruptions – an investigation using multi-agent model. Int. J. Prod. Res. 49(5), 1391–1404.

Newman, M.E., 2003. The structure and function of complex networks. Siam. Rev. 45(2), 167-256.

Oh, D.S., Kim, K.B., Jeong, S.Y., 2005. Eco-Industrial Park Design: a Daedeok Technovalley case study. Habitat Int. 29(2), 269–284.

Pakarinen, S., Mattila, T., Melanen, M., Nissinen, A., Sokka, L., 2010. Sustainability and industrial symbiosis—The evolution of a Finnish forest industry complex. Resour. Conserv. Recycl. 54(12), 1393–1404.

Park, H.S., Rene, E.R., Choi, S.M., Chiu, A.S., 2008. Strategies for sustainable development of industrial park in Ulsan, South Korea - From spontaneous evolution to systematic expansion of industrial symbiosis. J. Environ. Manag. 87(1), 1–13.

Pettit, T.J., Fiksel, J., Croxton, K.L., 2010. Ensuring supply chain resilience: development of a conceptual framework. J. Bus. Logist. 31, 1-21.

Ren, B., 2003. Neo-type industrialization: the innovation on China's economic strategy. Economist 3, 4-11.(in Chinese)

Sachtjen, M., Carreras, B., Lynch, V., 2000. Disturbances in a power transmission system. Phys. Rev. E 61(5), 4877.

Sakr, D., Baas, L., El-Haggar, S., Huisingh, D., 2011. Critical success and limiting factors for eco-industrial parks: global trends and Egyptian context. J. Clean. Prod. 19(11), 1158–1169.

Sendra, C., Gabarrell, X., Vicent, T., 2007. Material flow analysis adapted to an industrial area. J. Clean. Prod. 15(17), 1706–1715.

Shi, H., Shi, L., 2014. Identifying emerging motif in growing networks. Plos One 9(6), e99634.

Shi, H., Tian, J., Chen, L., 2012. China's Quest for Eco - industrial Parks, Part I. J. Ind. Ecol. 16(1), 8.

Sokka, L., Lehtoranta, S., Nissinen, A., Melanen, M., 2011a. Analyzing the Environmental Benefits of Industrial Symbiosis: Life Cycle Assessment Applied to a Finnish Forest Industry Complex. J. Ind. Ecol. 15(1), 137–155.

Sokka, L., Pakarinen, S., Melanen, M., 2011b. Industrial symbiosis contributing to more sustainable energy use – an example from the forest industry in Kymenlaakso, Finland. J. Clean. Prod. 19(4), 285–293.

Song, C., Havlin, S., Makse, H.A., 2005. Self-similarity of complex networks. Nature 433(7024), 392–395.

Sopha, B.M., Fet, A.M., Keitsch, M.M., Haskins, C., 2010. Using systems engineering to create a framework for evaluating industrial symbiosis options. Syst. Eng. 13(2), 149–160.

Veiga, L.B.E., Magrini, A., 1996. Eco-industrial park development in Rio de Janeiro, Brazil: a tool for sustainable development. Pediatrics 98(1), 311–313.

Veleva, V., Todorova, S., Lowitt, P., Angus, N., Neely, D., 2015. Understanding and addressing business needs and sustainability challenges: lessons from Devens eco-industrial park. J. Clean. Prod. 87(1), 375–384.

Wang, G., Feng, X., Chu, K.H., 2013. A novel approach for stability analysis of industrial symbiosis systems. J. Clean. Prod. 39, 9-16.

Watts, D.J., Strogatz, S.H., 1998. Collective dynamics of 'small-world' networks. Nature 393(6684), 440–442.

Xiao, Y.Z., Renbin, 2014. Modelling of cluster supply network with cascading failure spread and its vulnerability analysis. Int. J. Prod. Res. 52(23), 6938–6953(6916).

Xiao, Z., Cao, B., Sun, J., Zhou, G., 2016. Culture of the stability in an eco-industrial system centered on complex network theory. J. Clean. Prod. 113, 730–742.

Yong, G., Pan, Z., Côté, R.P., Tsuyoshi, F., 2009. Assessment of the National Eco-Industrial Park Standard for Promoting Industrial Symbiosis in China. J. Ind. Ecol. 13(1), 15–26.

Zeng, Y., Xiao, R., Li, X., 2013a. A resilience approach to symbiosis networks of ecoindustrial parks based on cascading failure model. Math. Probl. Eng. 2013: 1-11.

Zeng, Y., Xiao, R., Li, X., 2013b. Vulnerability analysis of symbiosis networks of industrial ecology parks. Procedia Computer Science 17, 965-972.

Zheng, J.F., Gao, Z.Y., Zhao, X.M., 2007. Modeling cascading failures in congested complex networks. Phys. A 385(2), 700–706.

Zhu, J., Ruth, M., 2013. Exploring the resilience of industrial ecosystems. J. Environ. Manag. 122(10), 65-75.

Zhu, L., Zhou, J., Cui, Z., Liu, L., 2010. A method for controlling enterprises access to an eco-industrial park. Sci. Total Environ. 408(20), 4817–4825.