Elasticity analysis in chemical industry parks

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ABSTRACT
Based on the social network analysis (SNA) and the cascading failure model, this paper develops a model of elasticity analysis of the Industrial Symbiosis (IS) network and evaluates the Nanjing Chemical Industry Parks (NCIP) by the metrics of network efficiency and survival rate of the nodes. This paper finds that the NCIP is mainly composed of three major industrial chains, involving the circulation flow of the material, by-products, and energy, and show heterogeneous. Under an intentional attack on the consumer nodes, most of the node’s failure cause a chain reaction and bring about changes in network efficiency, and the resilience is not identical accordingly. The network efficiency increases with the augment of the elasticity level, it will not change when reached a certain peak, and the survival rate of the node also increases with the increase of the elasticity level. Therefore, the choice of the optimal elasticity level is helpful to the construction and normal operation of the symbiosis network. At the same time, in order to improve the resilience of the symbiotic network, enterprises should communicate periodically. Because of the ability to find and eliminate the adverse factors, periodic checks are critical for symbiosis between nodes. In order to prevent a network collapse, the NCIP management committee should evaluate the resilience of the IS network regularly, and the government should support the construction of the IS network and give tax subsidies or deductions.

I. Introduction
With the rapid development of the economy and society in China, the problem of air pollution is becoming more serious. The establishment of an industrial symbiosis network is a proven approach to prevent further deterioration of the ecological environment (Fraccascia, Albino, & Garavelli, 2017; Holling, 2003; Joao, Lovisa, Simon, & Leonardo, 2018; Walker, Holling, Carpenter, & Kinzig, 2004). This can help imitate the natural ecological system. Industrial symbiosis is a sustainable model of modern industrial development and engages traditionally separate industries in a collective approach, involving an exchange of materials, energy and by-products for the sake of realizing the combination of economic and ecological benefits. Eco-Industrial Park (EIP) is one of the organizational forms of industrial symbiosis. EIP has become popular all over the world because it can reduce environmental pollution and improve the economic benefits. Many industrial parks have been established around the world including Denmark, the United States, Japan, South Korea, Holland, Australia, China, India, etc. (Ferrer, Cortezia, & Neumann, 2012; Shi, Tian, & Chen, 2012; Song, Geng, & Dong, 2018; Stert & Ott, 2004). However, the construction of such parks is easier than their management.

The productive capacity of the enterprises may erode or fail for a variety of reasons. These results will inevitably affect the other enterprises and even cause an irreversible collapse of the EIP. For example, the Cape Charles ecological park in the USA has now stopped cycling of wastewater and materials (Deutz, Gibbs, & Proctor, 2003). Let us consider another example, because of a change in top management, a production process that lasted a long time was restructured and improved. However, instead of making things better, the circular flow path of raw materials was cut off and some of the original ecoindustrial chains was changed or even ruptured (Wu, Deng, & Duag, 2005). Therefore, when the productive capacity of an enterprise may erode or fail for a variety of reasons, it is necessary to study the influence of the result on other enterprises. It is also helpful to understand the level of the park’s economic benefit and ecological benefit so that executives can respond more quickly to changes in the motion of EIP.

In recent years, more and more IS systems have been studied. Especially, most of the research on IS has focused primarily on production mechanisms and evolution of IS networks (Chertow, 2000; Ehrenfeld & Gertler, 2010; Shi, Chertow, & Song, 2010), and the effects of IS.
networks on the environment (Fei, Feng, & Zhao, 2014; Hu, Wen, & Jason, 2017; Kasai, 1999; Li & Li, 2014; Liu et al., 2011; Mattila, Lehtoranta, Sokka, Melanen, & Nissinen, 2012; Sokka, Lehtoranta, Nissinen, & Melanen, 2011; Yong, Zhang, Ulgiati, & Sarkis, 2010; Zhang, Zheng, & Fath, 2015). Research methods include social network analysis (SNA), life cycle assessment (LCA), emergency analysis, complex networks theory, system dynamics and multi-objective planning (Zhao, Zeng, Ma, & Chen, 2012; Zheng, Zhang, & Yang, 2015). Researchers have discussed industrial systems from different aspects such as park planning, environmental benefits, resource utilization and so on. However, few people pay attention to the effect that the enterprises have on each other in the IS network. One consequence for economic agents is that the symbiosis between economic agents is breaking down. Therefore, when the symbiosis system’s habitual patterns of action are disturbed by uncertainty, it is important to study the influence between enterprises and identify the network elasticity.

By borrowing lessons from ecosystem and supply chain research (Christopher & Peck, 2004; Holcomb & Ponomarov, 1990; Zhu & Ruth, 2013), this paper can apply elastic concept to industrial symbiosis network, defining resilience as the capability of a system to maintain eco-efficient material and energy flows under disruptions, even if the level of production and technology of the firm are changed or resources are redistributed due to the collapse of the enterprise. Similarly, when subjected to external attack, the network can absorb losses and restore to its previous structure and function if the network has remarkably resilient (Zeng, Xiao, & Li, 2013). Based on this understanding of resilience, this paper define resilience of the IS network as a capability with the following three general features: (a) the ability of an IS network to soak up disruptions come from external attack; (b) the capacity of an IS network is to self-organize which stems from endogenous rather than exogenous drivers; (c) the ability of an IS network to adapt is the existence of mechanisms for the evolution of learning or innovation (Carpenter, Walker, Anderies, & Abel, 2001; Chopra & Khanna, 2014; Korhonen & Seager, 2008). As for measuring the resilience of the IS network, Zeng et al. (2013) investigate the resilience of the Jinjie eco-industrial system in Shansi province of China through the cascading model and derive the critical threshold. Zhu and Ruth (2013) explore the resilience with high inter-firm dependency, preferentially organized physical exchanges and under disruptions targeted at highly connected firms through network simulation. Chopra and Khanna (2014) understand resilience via a network-based approach with application to the Kalundborg Industrial Symbiosis (KIS). However, the combination SNA and cascading model has not been applied extensively to enhance understanding of resilience, and this paper attempt to bridge this gap by analysing the IS network.

IS systems demonstrate a complexity similar to that of the electric and transport networks (Paolo, Vito, Massimo, & Andrea, 2004; Zheng, Gao, & Zhao, 2007), that is, the network's composition of the cooperative and competitive relationships among the enterprises profoundly influence their conduct and performance. Each enterprise is in a different position and plays a different role in the IS network. For some reason, the damage stemming from a node's failures spread in the network like a virus. If managers fail to take timely and effective measures to strengthen coordination and administration, severe disruption in IS network can occur and might even lead to the union disbanding. In particular, our contributions made in this paper are as follows:

- The structure diagram of the ecological and economic circular flow between enterprises is constructed.
- The SNA and cascading model are proposed to measure the structure and resilience of the IS network.
- An optimal metric is proposed to calculate the efficiency of the Nanjing Chemical Industry Parks (NCIP).

The rest of the paper is organized as follows: Section A presents the formation of the industrial symbiosis network; Section B measures the structure parameters of the NCIP; Section C gives elastic analysis of the NCIP; and finally, Section II draws the conclusion.

A. The formation of IS network

This paper take the NCIP as an example to analyse the formation of IS networks in ecological and economic circles. The NCIP, which was founded in 2001, is a national petrochemical base ratified by the National Development and Reform Commission. The park occupies excellent natural geographical conditions. It is located in the Yangtze River Delta region, it has a planned area of 45 km² and is 30 km from Nanjing, and the location maps of the NCIP are as shown in Figure 1.

Many chemical enterprises are located in the park and their production focuses on natural gas, chemicals, petroleum, organic chemicals, fine chemicals, etc. This paper discusses, from the angle of three major industrial chains, the complex symbiotic relations among the enterprises. The three major industrial chains are Chlor-alkali industrial chain (CAIC), ethylene oxide industrial chain (EOIC) and C1 chemical industrial chain (CCIC), respectively. The Chlor-alkali industrial chain mainly produces chlorine containing fine chemicals and PVC with chloric alkaline in the leading role. The ethylene industrial
Figure 1. The location maps of the NCIP.

Figure 2. The simple structure of the NCIP.

chain consists mainly of crude oil deep processing (three benzene, triene), the production of PTA, styrene, caprolactam, synthetic rubber, synthetic fibre, synthetic resin, three drug intermediates and so on – tyre, coating, engineering plastics, textile fabrics and other fine chemical products. The C1 chemical industrial chain mainly consists of natural gas, coal, synthetic gas, acetate, acetic anhydride, acetic acid, vinyl acetate, paint, wood glue, adhesive and other fine chemicals. The material cycle relationship is formed through the production, consumption and decomposition in the industrial chains. The producer of the resource is defined as the upstream enterprise using coal, oil, natural gas and Chlor-alkali as material in this paper. The consumer is defined as the middle enterprise which takes products of the producers as the raw material. A decomposer is defined as the downstream enterprise which produces the end product, such as plastic, resin and so on, including three wastes treatment enterprises. In order to minimize the input and maximize the output, each enterprise in the eco-industrial park has to make a constant exchange in matters, energy and by-products to form a symbiotic network. The network structure can be seen in Figure 2. After visiting the investigation sites and collecting related internet survey data, we give the ecological and economic circular flow between enterprises in the NCIP as shown in Figure 3. Because each enterprise’s name is longer, this paper has to use the enterprise’s abbreviation, and the enterprise is represented by a number from 1 to 43. As you can see from Figure 3, the enterprises in EIP is combined by matter, energy and by-products. For example, as a leading enterprise in CCIC, Nanjing Wison (NJWISON) is energetically developing the recycling economy and utilizing the clean coal technology to realize the clean use of coal and ensure non-pollution emission. Oxygen as its material mainly comes from Nanjing Air Products and Chemicals Co. Ltd. (NJAPC) at the park. Carbon monoxide and methanol produced by NJWISON are raw materials for the downstream enterprise Nanjing Celanese Chemical Co., Ltd. (NJCC). The raw material intercourse between upstream and downstream enterprises is connected by a pipe gallery. Besides, some 100,000 tons of waste residues are produced each year which is used as an additive in a cement factory (CF). Part of the coarse slag can also be used for paving. 15,000 tons of sulphur recycled is sent to the Nanjing Chemical Company Attached Sulfuric Acid Factory (NCCASAF) in liquid form as the raw material. The layout of the infrastructure is scientific and rational and the infrastructure can reduce energy consumption and corresponding emissions. Hence, the recycling economy
Figure 3. The ecological and economic circular flow between enterprises.

at the park can reduce pollution and improve the utilization of regional resources indeed. In order to understand the implications for the resilience of the network metrics, we have a detailed analysis of the topological structure.

B. The structure parameters analysis of the NCIP

Based on Figure 3, each enterprise in the eco-industrial park has to make a constant exchange in matters, energy and by-products to form a symbiotic network. Considering the difficulty of obtaining data, we will extract the NCIP as an undirected and unweighted symbiosis network and derive the adjacency matrix from collecting data. Then we could obtain the symbiosis network, as is shown in Figure 4. The network nodes represent the enterprise, and the network edges represent exchange in matters, energy and by-products between enterprises in the NCIP. As can be seen from Figure 4, there are 43 nodes and 68 edges in the network. According to the property of an ecological network, we divide
the nodes into three groups $V = V_1 \cup V_2 \cup V_3$ and $V_1 \cap V_2 \cap V_3 = \phi$, where the set $V_1$, $V_2$ and $V_3$ denote the set of producers, consumer and decomposers, respectively. The set $V_3$ includes eight nodes which are all called ecological nodes, and the ecological nodes mainly treat waste water, exhaust gas, waste residues and all kinds of wastes.

In order to further understand the structural features of the network, this paper measures the basic properties of the network by the degree of the node. The degree of node $i$ represents the number of edges connected to it. The greater the degree of a node, the more important it is in the network. The degree of node $i$ is defined as $k(i) = \sum_{j \in \tau(i)} e_{ij}$, where $\tau(i)$ is a set of nodes that are connected to node $i$, and $E = \{e_{ij}\}$ is a set of corresponding edges. Analysing the degree of each node in the symbiosis network, the result is shown that the number of nodes with 1 degree is 62.79% of the total node, the degree of the rest of the node is more than one; thereby such attachment causes matters, energy and by-products flow between enterprises. There are not a lot of nodes whose degrees are high. The highest degree is 19, and the average degree is 3.163. That is, large flows to and from a node in the IS network are rare because of the constraint on cleaner production and emissions mitigation technology. We first introduce the so-called power-law degree distribution function (Shi, 2011), which can be expressed as $P(k) = k^{-\gamma}$, and $k$ denotes the number of links of a randomly chosen node in the IS network and $\gamma$ are scaling exponent. This function follows a straight line with a slope $-\gamma$ on the $\ln P(k) - \ln k$ plane. Figure 5 illustrates the log–log degree distributions of the IS network. Then, we obtain power-law degree distribution,

$$P(k) = 1.117 \times k^{-1.182},$$

where the scaling exponent in the network is 1.182, and its coefficient of correlation $R$ is 0.968, the fitting results are very good. Note that, as shown in the insets of Figure 5, most of the nodes have a few edges while a few nodes have many edges. That is to say, the networks are found to be having heterogeneous.

### C. Elastic analysis of the network

From what has been discussed above, the network is found to be having heterogeneous with power-law
degree distribution. Hence, the network is fragile against intentional attacks, and cascading failure can occur. In fact, industrial enterprises had ordered to move out of the NCIP. So, it is reasonable to analyse the resilience of the IS network on the intentional attacks. Then the IS network efficiency and survival rate of the nodes are calculated on intentional attacks to measure the resilience of the network.

C.1 Measurement of the NCIP’s efficiency based on cascading model

In order to strike a balance between economic growth and environmental protection, the state of the producers and decomposers do not generally change at the two extremes of chains, and changing the state of the consumer to extend the industrial chain for reducing its pollution (Xiao, Zhou, & Wang, 2012). According to statistics, the NCIP’s profit rose 30% due to extending the industrial chain and service chains in 10 months ahead in 2009. Hence, this paper mainly analyse that the consumer in the network is chosen as an object of intentional attacks and measure network efficiency after cascade failure. In order to fully reflect the length of the industrial chain, we define the network efficiency by the shortest distance from the producer to the decomposer. The metric is given as follows:

\[
E_0 = \frac{1}{|V_1||V_3|} \sum_{j \in V_1} \sum_{i \in V_3} \frac{1}{d_{ij}},
\]

where \(E_0\) denotes network efficiency after cascade failure; \(|V_1|\) and \(|V_3|\) represent the number of elements contained in the set \(V_1\) and \(V_3\) after cascade failure, respectively. We define \(d_{ij}\) as the shortest distance from the decomposer to the producer. From the perspective of the connotation, the smaller \(E_0\) of a note is, the more important the node will be. Then, we define \(L_k\) as betweenness centrality of a node and it is

\[
L_k = \frac{1}{n(n-1)} \sum_{i \neq j \in V} \frac{\sigma_{ij}(k)}{\sigma_{ij}},
\]

where \(\sigma_{ij}\) is the number of geodesics linking from node \(i\) to \(j\), and \(\sigma_{ij}(k)\) is the number of geodesics linking that contain sector \(k\), the number of nodes are \(n\) and \(V\) is a set of nodes in the network. After node \(k\) is deleted from the network on intentional attacks, its neighbour node will receive from its load. We adopt the following iterative rule at each time \(t\),

\[
L_i'(t+1) = \begin{cases} 
L_i(t+1) + \frac{L_i'(t)}{\sum_{j \in \Gamma_i} L_j'(t)} L_k'(t) & i \in \Gamma_k, \\
L_i(t+1) & i \notin \Gamma_k,
\end{cases}
\]

where \(\Gamma_k\) denotes a set which includes neighbour node of node \(k\); \(L_i'(t)\) represents the load of node \(i\) at time \(t\).

Due to the constraint by cost in symbiosis network, the load of a node is finite. We define the maximum load as the capacity of the node. Therefore, it is reasonable that the capacity \(C_k\) of node \(k\) is proportional to its initial load \(L_k(0)\), that is

\[
C_k = (1 + \lambda)L_k(0),
\]

where \(\lambda \geq 0\) is an elasticity level parameter. The betweenness centrality of a node represents its initial load in the IS network. When a load of a node exceeds its capacity, the node will fail, then be removed from the IS network. Its load is redistributed to its neighbour node. This step-by-step process is called cascading failure. Figure 6 describes the process clearly.

By calculating betweenness centrality (initial load), Table 1 delivers the top six consumer node suppose the

**Figure 6.** The flow chart of the cascading failure.
NCIP is a closed IS network, we analyse the process of cascade failure after choosing $\lambda = 0.3$. For example, node 10 fails on deliberate attacks, and part of its load will be passed to the node 14. The result of the calculation shows that a load of node 14 exceeds its capacity, and therefore ceases production. In this way, we analyse the consumer nodes in the top 6 betweenness centrality, then give their cascading failure processes and weight ranking, as shown in Table 2. As we can see from Table 2, the failure of a node can generally trigger a chain reaction, but node 22 is a rare exception and its failure does not trigger other node failures.

Additionally, the significance of each node will change dramatically after cascade failure. Based on betweenness centrality perspective, the first six consumer nodes are node 10(0.152), node 14(0.055), node 24(0.030), node 22(0.027), node 16(0.016) and node 41(0.007), respectively. However, from the perspective of the cascade failure, node 24 comes first because its failure trigger cascading failure of other node and network efficiency hit zero. The result shows that the failure of node 24 can lead to network collapse. In that case, the resilience of the network is weakest and the system’s vulnerability is strongest. Consequently, node 24 is a potential key node and should be specially protected. By comparison, we calculate network efficiency defined by Paolo et al. (2004), the result is shown in Table 2. Their order of weight does not change, but the value of $E_0$ is higher than $E$. Hence, based on the connotation of network efficiency, the average length of the industrial chain impressed by $E_0$ is shorter than $E$, and it can discriminate minute variations in the resilience of the network. The reason is that index $E$ measures mainly network efficiency such as electric network and transport network, etc. But if you measure the efficiency of the symbiotic network using the index $E$, then it does not reflect its characters. Further studies reveal that network efficiency varies with elasticity level. We analyse the consumer node in the top 6 betweenness centrality, Figure 7 delivers the variation tendency for network efficiency with elasticity level. From Figure 7, one can see that the network efficiency rises with the elasticity level. After reaching a certain peak, network efficiency will not change. In other words, the phenomenon of cascade failure won’t happen again. For example, through theoretical analysis for node 14, the result shows that the phenomenon of cascade failure does not happen again when $\lambda > 0.582$. Due to the constraint by cost in symbiosis network, the load of a node is finite. Therefore, the elasticity level cannot be indefinitely large, we should find a suitable elasticity level to make a loss of enterprise to a minimum on intentional attacks.

### II. Conclusion

By analysing NCIP, we find that it is composed of three major industrial chains. The symbiotic relations between firms are formed in the chain. In the meantime, there are

| Table 2. The cascading failure process and the sequencing result of network efficiency. |
| --- |
| Node number | Cascading failure process | $E_0$ | $E$ | Sequence |
| 24 | {13,22,31}→{34,37}→{28,30,41}→{9,10,16,27}→{4,8,14} | 0.00 | 0.379 | 1 |
| 16 | {19,30}→{4,13,28,31}→{34,37,41}→{8,9,10,14,24,27}→{22} | 0.00 | 0.418 | 2 |
| 10 | {14,19,24}→{9,13,22,28,31}→{34,37,41}→{4,30} | 0.160 | 0.484 | 3 |
| 14 | {9}→{4,13,30,34,37}→{10,16,19,41}→{22} | 0.160 | 0.484 | 4 |
| 41 | {13,31}→{34,37}→{16,19,24,28,30} | 0.336 | 0.484 | 5 |
| 22 | no | 0.484 | 0.418 | 6 |

We analyse the consumer node in the top 6 betweenness centrality, Figure 7 delivers the variation tendency for network efficiency with elasticity level. From Figure 7, one can see that the network efficiency rises with the elasticity level. After reaching a certain peak, network efficiency will not change. In other words, the phenomenon of cascade failure won’t happen again. For example, through theoretical analysis for node 14, the result shows that the phenomenon of cascade failure does not happen again when $\lambda > 0.582$. Due to the constraint by cost in symbiosis network, the load of a node is finite. Therefore, the elasticity level cannot be indefinitely large, we should find a suitable elasticity level to make a loss of enterprise to a minimum on intentional attacks.

#### C.2. The survival rate of the node

In order to further understand the resilience of the IS network, in this section, we are going to give a metric that reflects the performance of the IS network. If the phenomenon of cascade failure won’t happen again on intentional attacks, the ratio of the number of normal production of enterprises to the number of entire enterprises is defined as follows:

$$F = \frac{k}{n},$$

where $F$ denotes the survival rate of a node. We take node 10 and node 14 as an example to analyse $F$. Through the software of Matlab, when $\lambda = 0.2$, it offers the process of cascade failure of node 14: $\{9\}→\{4,13,30,34,37\}→\{10,16,19,24,41\}→\{22\}$, there are eighteen failure node, and the survival rate of node 14 is 0.581. By the same way, we can analyse the survival rate of node 10 under different elasticity level, the result is shown as follows (Figure 8). It shows that the survival rate of the nodes increases with the increase of the elasticity level for node 10 and node 14, and the other node is no exception. Hence, the higher survival rate of the nodes can be obtained in higher elasticity level.

![Table 1. The sequencing result of betweenness centrality.](attachment:image.png)

| Serial number | Betweenness centrality | Serial number | Betweenness centrality |
| --- | --- | --- | --- |
| 10 | 0.152 | 22 | 0.027 |
| 14 | 0.055 | 16 | 0.016 |
| 24 | 0.030 | 41 | 0.007 |

![Table 2. The cascading failure process and the sequencing result of network efficiency.](attachment:image.png)
coupling relations between chains. Finally, each enterprise in the eco-industrial park has to make the constant exchange in materials, energy, and by-products to form a symbiotic network. To understand the implications for the resilience of the network metrics, we analysed the topological structure in detail. The analysis of our results is that the network density has a value of 0.075 and it is a low-density network. The result shows that direct contact among sectors is very low from the aspect of material energy flow exchanges. The average degree is only 3.163, and there are four nodes whose degree surpasses 10, about 9% the total number of the node. Further analysis of the network shows that it is heterogeneous with power-law degree distribution, and the scaling exponent is 1.182. Hence, we identify that the IS is a scale-free network and is robust against random failures of nodes but fragile to intentional attacks. This paper studies the resilience resulting from deliberate attacks on the IS network.

To strike a balance between economic growth and environmental protection, we generally change the state of the consumer to extend product lines for reducing its pollution instead of the state of the producers and decomposers at the two extremes of chains. Hence, the consumer in the network is chosen as an object of intentional attacks. We find that a node with high betweenness centrality is important concerning the influence it has over the material energy flow between other nodes. By calculating betweenness centrality of consumer node, the first six consumer nodes are node 10(0.152), node 14(0.055), node 24(0.030), node 22(0.027), node 16(0.016) and 41(0.007), respectively. Then the IS network efficiency
and survival rate of the nodes are calculated on intentional attacks. The results show that the failure of most of the nodes can lead to a chain reaction. The IS network efficiencies have also changed to varying degrees. Their order from the largest to the smallest is node 24, 16, 10, 14, 41, 22. Compared with the betweenness centrality, the sorting of the network efficiency is different. For example, now node 24 comes first. The result shows that the failure of node 24 can lead to network collapse. In that case, the resilience of the network is weakest and the system’s vulnerability is strongest. Consequently, node 24 is a potential key node and should be specially protected. At the same time, from the result of the calculation, it is understood that network efficiency increases with the elasticity level. After reaching a certain peak, the efficiency of the network will not change. The elastic level can reflect the network construction cost, and the efficiency increase with the increase of the elasticity level but construction cost is limited. Therefore, the choice of an optimal elasticity level is helpful for the construction and normal operation of the symbiosis network. This action not only can reduce construction cost but also improve the resilience of the network. Further, the study concludes that the survival rate of the nodes increases with an increase in the elasticity level too. Taken together, it is necessary to improve the elasticity level.

Based on the analysis, we realize that a highly coupled component is formed through an exchange of materials, energy and by-products. Failure of each enterprise can trigger cascading impacts or even result in network collapse. Hence, resilience as a property to absorb stress is vital for IS networks attempting to be sustainable. At present, the assessment method of resilience and theoretical analysis for the IS networks are still far from reaching a desirable state. We ought to further explore the definition and the connotation of resilience for the IS networks, and develop a uniform model or indicator system to evaluate resilience. At the same time, to improve the elasticity of the symbiotic network, enterprises should communicate periodically. Because of the ability to find and eliminate the adverse factors, periodic checks are critical for symbiosis between nodes. To prevent a network collapse, the NCIP management committee should evaluate the resilience of the IS network regularly, and the government should support the construction of the IS network and give tax subsidies or deductions.

The weighted directed network system should be explored if one wants a deeper understanding of the coupling relations between firms. Besides, it is worth studying how to measure the resilience of the weighted directed network system. In future studies, we will explore further the weighted directed network system to provide some references for EIP’s construction and management.

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