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Complex Network Method Towards Evaluating Industrial Symbiosis

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The construction of industrial park has become one of the main ways of cleaner production, energy saving and emission reduction in industrial development. Most industrial symbiosis (IS) networks are very complex. A method of evaluating IS networks is proposed based on complex network theory. Firstly, according to TOPSIS (technique for order preference by similarity to an ideal solution), taking the multi-attribute decision-making method to identify key enterprises in IS networks. Secondly, it realizes quantitative detection by the community partition of complex network. Finally, we evaluate the results of detection based on Girvan-Newman modularity and the cohesion of communities. The case analysis shows that the multi-attribute decision-making method can identify core enterprises effectively. The quantitative detection for community structure of IS networks is feasible with the method of complex network community detection. The integration degree of IS networks can be evaluated from the aspects of nodes and community structures.

1. Introduction

Symbiosis is material contact between two or more different members. With further research, the ideas of symbiosis have been developed more extensive research and applied in many fields. IS networks are the production organization pattern of symbiotic relationship. It is the major form of cooperation among enterprises, and has the dual nature of industrial ecological system and network organization. It mainly emphasizes chain distribution of resources and energy among enterprises (Porkka et al., 2013). Not only does it improve energy and resource efficiency, but it reduces the destruction of ecological environment. Making full use of resource and energy can realize clean production of IS system and minimize the waste of resource and energy, such as wastewater treatment (Ochoa, 2016) and waste heat utilization (Yong et al., 2016). IS system has become the effective environmental management way of industrial parks. The win-win pattern of industrial production and environmental protection has been achieved (Raafat et al., 2013).

Aimed at the evaluation of symbiotic system, many scholars put forward evaluation methods. The asymmetric distribution coefficient is proposed to analysize the stability of symbiotic bioenergy park (Ng et al., 2014). Jung et al. (2013) use discounted cash flow and multi-attribute global inference of quality methods to evaluate the performance of eco-industrial park pilot projects. Emergy analysis is proposed to conduct an assessment on Hefei economic and technological development area to quantify the performance of industrial symbiosis (Fan et al., 2016). In recent years, the method of evaluating IS networks based on complex network theory has been developed gradually. Meanwhile, the theory system of symbiosis networks structural analysis could be constructed. It achieved characteristic analysis of IS networks. The structure and characteristic of IS networks are studied. A comprehensive methodological and analytical framework is provided to understand the structural elements of IS networks (Domenech et al., 2011). For key enterprises of IS networks, key nodes are identified by analysing internal structure of IS networks and enterprises relationship, on the basis of combined social network analysis and complex network theory (Zhong et al., 2010). The network connectedness and related attributes of these hybrid ecological and IS systems are studied (Zhang et al., 2013). According to calculation of network topology parameters, the vulnerability of ecological symbiosis networks is analysed quantitatively, such as node betweenness and network efficiency. Then important enterprises are identified by

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simulation analysis of node failure (Xiang et al., 2016). Taking Kalundborg IS water network as an example, important nodes are found based on network metrics and complete disruption. Chopra et al.(2014) design strategies to develop resilient and sustainable of IS networks. Aimed at detection problem of IS networks, Huang et al. (2014) propose a structure detection method based on the algorithm of community detection.
Considering the importance of core enterprises in IS networks, an identification method by evaluating node importance based on TOPSIS is proposed in this work. In addition, through adopting the community structure theory, we could achieve the community structure detection of complex IS networks and realize the quantitative description of IS networks. It’s effective to analyse the structure characteristic quantitively and the connection degree of each community structure of IS networks.

2. Core enterprises identification of complex IS networks

2.1 Selection of node importance index

Four quantitative indices are selected to describe the node importance.

Table 1: The formula and definition of index

Node importance indices	Formula	Definition
DC(degree centrality)	$DC_i=k_i$	*DC* is equal to the node degree.
FBC(flow betweenness centrality)	$FBC(i)=\sum_{s<t}^{i}\frac{g_{st}}{g_{st}}$	It’s the proportion of paths passed node *i*, among all nonredundant paths.
CC(closeness centrality)	$CC_i=n/\sum_{j=1}^{n}d_{ij}$	It’s the reciprocal of average the shortest distance between node *i* and others.
EC(eigenvector centrality)	$EC_i=\lambda^{-1}\sum_{j=1}^{n}a_{ij}x_j$	Its value is eigenvector of the greatest eigenvalue of adjacency matrix.

2.2 Determination of index weight

Utilizing the analytic hierarchy process (AHP) to calculate the weight of each index.
(1) Establish the comparison matrix
We take the three-demarcation method (0,1,2) to analyse the importance of four indexes. *DC* mainly reflects local information of network. Compared with others, its importance is the lowest. Due to the value of *DC* only relates to the number of adjacent nodes, and it ignores nodes which connected indirectly. *FBC* represents the ability of node to control the entire network. *CC* reflects the extent of the nodes in network center. They all consider from overall perspective of network. Therefore, we give them same evaluation. Not only does *EC* consider the node importance from overall perspective of network, but it reflects the combined influence of each node. So, *EC* is the most important index. The comparison matrix *E* is established and shown in Table 2.

$$E=e_{ij}=\begin{cases}2 & \text{index } i \text{ is more important than index } j\\ 1 & \text{index } i \text{ is same important with index } j,\\ 0 & \text{index } j \text{ is more important than index } i\end{cases}\quad b_i=\sum_{j=1}^{4}e_{ij}. \tag{1}$$

Table 2: Comparison matrix

E	*DC*	*FBC*	*CC*	*EC*	b_i
DC	1	0	0	0	1
FBC	2	1	1	0	4
CC	2	1	1	0	4
EC	2	2	2	1	7

(2) Construct the judge matrix by range method

$$C=(c_{ij})=\begin{bmatrix} c & DC & CC & FBC & EC & M_i & W_i & \overline{W_i}\\ DC & 1 & 1/3 & 1/3 & 1/9 & 1/81 & 1/3 & 0.0625\\ FBC & 3 & 1 & 1 & 1/3 & 1 & 1 & 0.1875\\ CC & 3 & 1 & 1 & 1/3 & 1 & 1 & 0.1875\\ EC & 9 & 3 & 3 & 1 & 81 & 3 & 0.5625\end{bmatrix} \tag{2}$$

Where *B*=max(b_1,…,b_4)-min(b_1,…,b_4), $c_{ij}=c_b^{(b_i-b_j)/B}$, c_b=9, $M_i=\prod_{j=1}^{4}c_{ij}$, $W_i=\sqrt[4]{M_i}$, $\bar{W_i}=W_i/(\sum_{i=1}^{4}W_i)$. Finally, the consistency is checked. The weighting of four indexes is $\overline{W}=[0.0625\quad 0.1875\quad 0.1875\quad 0.5625]$

2.3 Comprehensive evaluation of node importance based on multi-attribute decision method

The multi-attribute decision method based on TOPSIS can evaluate node importance in network. Node importance is evaluated by comparison of the distance between every choice and the positive or negative ideal solution (Yu et al., 2013).

(1) There are n nodes to be evaluated, $x=\{x_1,x_2,\ldots,x_n\}$. The number of evaluation indexes is m, $s=\{s_1,s_2,s_3,\ldots,s_m\}$. $x_i(s_j)$ represents the jth index of node i. $P=[x_i(s_j)]_{n\times m}$ is the decision matrix. The dimension of each index is unified in order to compare conveniently. By standardizing P, we get the matrix $R=(r_{ij})_{n\times m}$, where $r_{ij}= x_i(s_j)/x_i(s_j)_{max}$.

(2) The weight of the jth index is $w_j(j=1,2,\ldots,m)$, $\sum w_j=1$. Then caculate the weighted normalized decision matrix $Y=(y_{ij})_{n\times m}=(r_i w_j)_{n\times m}$. The positive ideal solution A^+ and the negative ideal solution A^- are determined as.

$$A^+=\{\max_{i\in L}(y_{i1},y_{i2},\cdots,y_{im})\}=\{y_1^{\max},y_2^{\max},\cdots,y_m^{\max}\},\quad A^-=\{\min_{i\in L}(y_{i1},y_{i2},\cdots,y_{im})\}=\{y_1^{\min},y_2^{\min},\cdots,y_m^{\min}\} \tag{3}$$

(3) Based on Euclidean distance, the distance from evaluation value of each node to the positive ideal solution A^+ and the negative ideal solution A^- are calculated. Eq(5) is the comprehensive evaluation index.

$$D_i^+=\sqrt{\sum_{j=1}^{m}(y_{ij}-y_j^{\max})^2},\quad D_i^-=\sqrt{\sum_{j=1}^{m}(y_{ij}-y_j^{\min})^2} \tag{4}$$

$$Z_i=\frac{D_i^-}{D_i^-+D_i^+} \tag{5}$$

3. Community structure detection of complex IS networks

3.1 Methods of the community detection

The research about community structure of complex network has a close relationship between graph partition in computer science and hierarchical clustering in sociology. The graph partition mainly includes Kernighan-Lin algorithm and spectral bisection method. Hierarchical clustering mainly includes GN (Girvan-Newman) algorithm. Combined with the method of complex network community detection, we choose spectral bisection method to achieve community structure detection of IS networks, which has obvious community structure.

3.2 Steps of the community detection

In view of general characteristics of IS networks structure, Capocci spectral bisection method based on the normal matrix is adopted to finish community structure detection (Capocci et al., 2005). Steps are as follows:

(1) Constructing normal matrix $N=K^{-1}A$, where A is adjacency matrix, whose element a_{ij} is equal to 1 if i points to j and 0 otherwise. K is the diagonal matrix with elements $k_{ii}=\sum a_{ij}$.

(2) Calculating the eigenvalue and eigenvector of the matrix N, there is always an eigenvalue equal to 1.

(3) The first non-trivial eigenvalues (closes to 1) to corresponding eigenvectors drawing is roughly ladder-like distribution. The number of ladder series matches with the number of community.

Considering structure characteristics of community in IS networks, we evaluate community detection method based on concepts of cohesion coefficient $Coh(C_i)$ and modularity Q. $Coh(C_i)$ and Q are linear fitted by the form of $y=a+bx$. According to the value of correlation coefficient r_i, the result of community detection can be evaluated. If $r_i\geq0.75$, there are better performance of independence among communities, closely connected interior nodes in community and clear community structure. On the contrary, the detection result is not good.

$$Q=\sum_{i=1}^{n}\left[\frac{l_c}{L}-\left(\frac{d_c}{2L}\right)^2\right] \tag{6}$$

$$Coh(Ci)=\frac{E(Ci)}{E(Ci)+\sum_{j\neq i}A(Ci,Cj)} \tag{7}$$

Where l_c is the number of links inside module C. L is the total number of links in network. d_c is the total degree of nodes in module C. Where $E(C_i)$ is the total number of links of community C_i. n_i is the number of nodes in community C_i, and $\sum_{j\neq i}A(C_i,C_j)$ is the total number of links between community C_i and C_j.

4. Case study

Austrian Styria eco-industry park is a typical IS network, which has 36 enterprises, such as cement mill, power plant and ceramics factory. There are frequent material exchange and energy flow among enterprises. Its material flow diagram is shown in Figure 1. Each enterprise is regarded as a node, then material and energy exchange among nodes as the edge of network. Styria IS network has characteristics of complex network based on measurement of complexity. Thus, we can use the node importance evaluation method to identify core enterprises. On the other hand, it can be detected community based on community partition algorithm of complex network. To improve accuracy of result and calculate conveniently, Styria IS network is regarded as an undirected and unweighted network. The network of Styria IS park is shown in Figure 2.

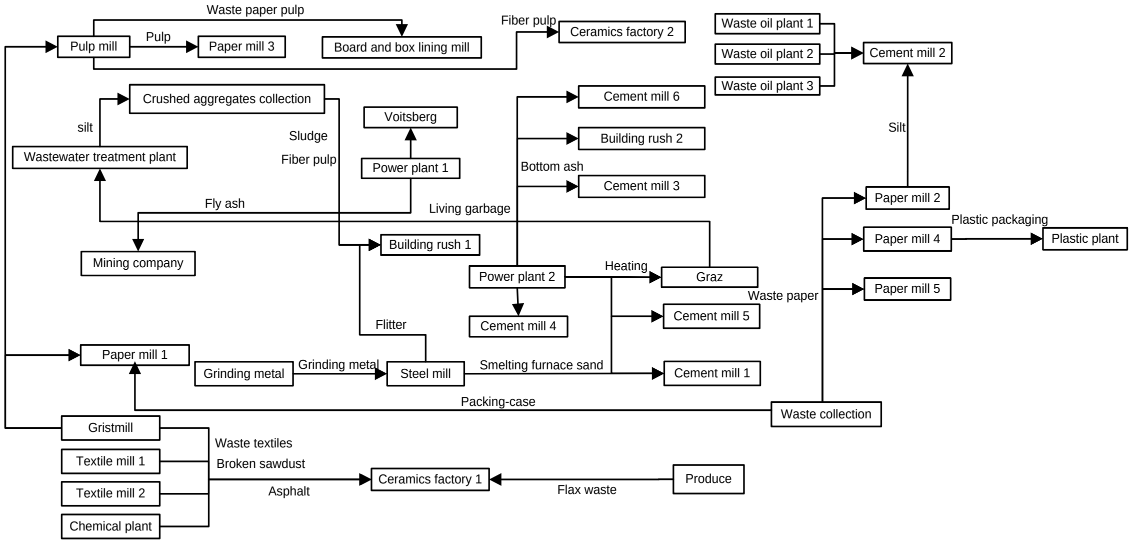


Figure 1: Material flow diagram of Austrian Styria eco-industry park

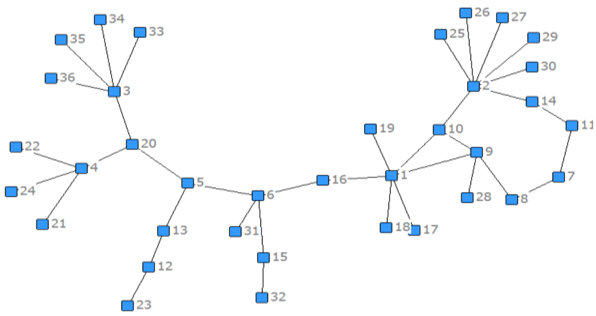


Figure 2: The network of Austrian Styria eco-industry park

4.1 Identification of core enterprises

DC, *FBC*, *CC*, *EC* and Z_i of each node of Styria IS network are shown in Table 3. According to the numerical magnitude of Z_i, node 1, node 2, node 10, node 9 and node 16 are key nodes. In other words, core enterprises contain cement mill 2, power plant 2, cement mill 1, steel mill and paper mill 2. So, we need to focus on the operation of these enterprises. Compared with the identification methods by Zhong et al. (2010), this method can reduce the complexity of computation and enhance the search efficiency. In addition, the result is more reliable due to using the comprehensive indicator.

4.2 Community detection

Through the analysis and empirical study of different community partition algorithm, the improved spectrum split method is more suitable for community detection of IS networks. At first, with the help of Matlab7.0, we get the first non-trivial eigenvalue (selecting the maximum) from normal matrix *N* and the first non-trivial eigenvectors corresponding with each node. They are shown in Table 4. Meanwhile, the first non-trivial eigenvectors are sorted by size and plotted by Origin 8.0. Thus, we see that the dots present six ladder-like distributions in Figure 3a. Styria IS network is divided into six communities, including C_A, C_B, C_C, C_D, C_E and C_F. The detection of nodes in each community is as follows. C_A:3,4,20,21,22,24,33,34,35,36; C_B:5,12,13,23; C_C:6,15,31,32; C_D:16; C_E:1,17,18,19; C_F:2,7,8,9,10,11,14,25; 26,27,28,29,30.

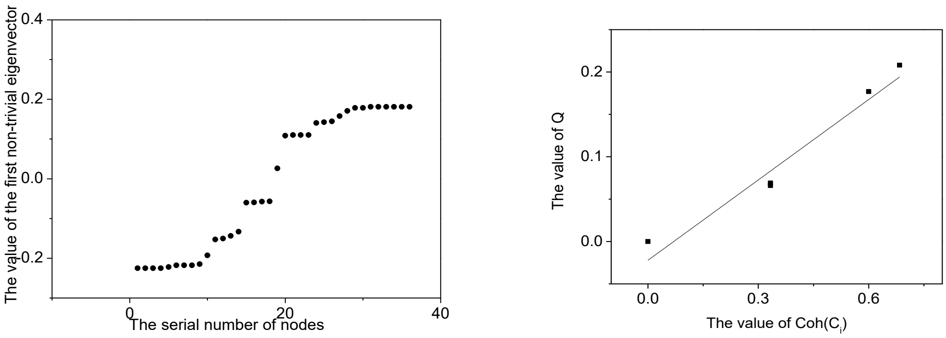
According to the identification of core enterprise as mentioned above, we find node 1 (cement mill 2) is located in C_E. It is the key node of C_E and link three communities including C_D, C_E and C_F. Node 2 (power plant 2), node 10 (cement mill 1) and node 9 (steel mill) are located in C_F. Among them, power plant 2 supplies some enterprises for power. C_D only contains node 16 (paper mill 2). Node 16 not only links C_C, C_D and C_E, but also plays an important role in keeping network connectivity.

Table 3: The value of centricity index and Z_i.

Node	*DC*	*FBC*	*CC*	*EC*	Z_i	Node	*DC*	*FBC*	*CC*	*EC*	Z_i
1	6	346.334	0.293	0.478	0.984	19	1	0	0.229	0.157	0.304
2	7	169.334	0.231	0.406	0.784	20	3	254	0.248	0.023	0.218
3	5	130	0.211	0.013	0.132	21	1	0	0.174	0.004	0.015
4	4	99	0.208	0.011	0.106	22	1	0	0.174	0.004	0.015
5	3	316	0.279	0.046	0.275	23	1	0	0.160	0.002	0.000
6	4	350	0.298	0.100	0.348	24	1	0	0.174	0.004	0.015
7	2	9.334	0.186	0.074	0.144	25	1	0	0.189	0.133	0.255
8	2	9.334	0.212	0.150	0.291	26	1	0	0.189	0.133	0.255
9	4	44.500	0.255	0.383	0.692	27	1	0	0.189	0.133	0.255
10	3	10.500	0.263	0.415	0.710	28	1	0	0.206	0.125	0.243
11	2	9.334	0.169	0.076	0.146	29	1	0	0.189	0.133	0.255
12	2	34	0.188	0.006	0.045	30	1	0	0.189	0.133	0.255
13	2	66	0.226	0.017	0.093	31	1	0	0.232	0.033	0.094
14	2	9.334	0.195	0.158	0.303	32	1	0	0.193	0.012	0.039
15	2	34	0.235	0.03	0.107	33	1	0	0.176	0.004	0.017
16	2	306	0.298	0.189	0.456	34	1	0	0.176	0.004	0.017
17	1	0	0.229	0.157	0.304	35	1	0	0.176	0.004	0.017
18	1	0	0.229	0.157	0.304	36	1	0	0.176	0.004	0.017

Table 4: The first non-trivial eigenvalue and eigenvector of the matrix N

Eigenvalue	Eigenvector
0.9855	-0.2252, -0.2252, -0.2252, -0.2252, -0.2219, -0.2178, -0.2178,-0.2178, -0.2147, -0.1927,-0.1526, -0.1504, -0.1438, -0.1330, -0.0602, -0.0593, -0.0576, -0.0567, -0.0263, 0.1085, 0.1101, 0.1101, 0.1101, 0.1404, 0.1425, 0.1446, 0.1578, 0.1706, 0.1785, 0.1786, 0.1812, 0.1812, 0.1812, 0.1812, 0.1812, 0.1812



(a) (b)

Figure 3: a) is the distribution of eigenvalues and b) is the fitting curve of Q and Coh(C_i)

4.3 Result evaluation of the community detection

The modularity Q and cohesion coefficient $Coh(C_i)$ of each community of Styria IS network are calculated. Table 5 lists the value of Q and $Coh(C_i)$. The fitting curve of Q and $Coh(C_i)$ is shown in Figure 3b by using Origin 8.0. As show in Table 5, the correlation coefficient r is equal to 0.940. It suggests that the evaluated method of community partition is feasible. The result of Q and $Coh(C_i)$ curve fitting reflects that the degree of independence among different communities. The correlation coefficient r=0.94>0.75, it indicates each community has a stronger independence in Styria IS network. Thus, Austrian Styria eco-industry park has a higher degree of enterprise cluster. The supply and demand can achieve a balance in this IS network. Additionally, all communities either connected each other or being independent. It can improve agglomeration effect between industrial clusters, achieve circular economy, and improve competitiveness of enterprises.

Table 5: The fitting result of Q and $Coh(C_i)$ of Austrian Styria eco-industry park

IS network	Methods of community detection	Result of partition	$Coh(C_i)$	Q	Fitted value r
Austrian Styria eco-industry park	Capocci spectral bisection method	C_A	0.600	0.177	0.940
		C_B	0.333	0.069	
		C_C	0.333	0.069	
		C_D	0	0	
		C_E	0.333	0.066	
		C_F	0.684	0.208	

5. Conclusion

Case analysis shows that we can find core enterprises based on the node importance evaluation method of complex network. Compared with other methods, we take into account multiple indices. Thus, this method is more comprehensive, and result of identification is more accurate. Core enterprises play an important role in the entire IS networks. In order to ensure the efficiency of system, we must pay more attention on core enterprises. Furthermore, IS networks can be divided into communities with the community structure theory of complex network, so as to realize quantitative detection of IS networks and quantitative analysis of its structure features. Then through linear fitting of community cohesion coefficient and modularity, we can evaluate quantitatively the partitioning result according to fitting coefficient. From the case of Austrian Styria eco-industry park, we can conclude that the evaluation method presented in this study can evaluate quantitatively the core enterprises identification and communities division in industrial symbiosis network.

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