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Procedia Computer Science 17 (2013) 965 – 972

Procedia Computer Science

Information Technology and Quantitative Management (ITQM2013)

Vulnerability analysis of symbiosis networks of industrial ecology parks

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Abstract

The rapid development of industrial ecology parks is indicative of one practical pattern of theories and methods in industrial ecology. They severely affect the development of the modern society. In this paper, through adopting the social network analysis method, we could go into the interior of symbiosis networks and construct a cascading model on symbiosis networks of industrial ecology parks by using complex theory. Under the model, we then provide some evaluation indicators to evaluate nodes' power and status and analyze quantitatively the vulnerability against cascading failures in symbiosis networks according to a new framework. All these analyses and results could support the study of eco-industrial parks in methods and technology and help us to promote the construction of symbiosis networks of industrial ecology parks, especially improve the reliability and robustness.

Keywords: Industrial Ecology Park; Social Network Analysis; Node Importance; Vulnerability

1. Introduction

The ideas of industrial ecology have become a major part of industrial engineering. Industrial ecology parks are designed to create communities consisting of independent but interconnected manufacturers who voluntarily form links under a kind of industrial symbiosis, matching inputs and outputs to the environment load capacity. The development of industrial ecology has significant impact on the society and economy. On the other hand, network analysis is a methodology to study some larger systems. By using this method, a system can be abstracted as a network of nodes and the connections between them. In one system, if there is a flow of matter or energy between any two objects, we think that there is a direct transaction between them. In the modern society, we know that symbiosis networks of eco-industrial parks seriously affect the economic development. It is known that if one enterprise malfunctions, we could not imagine the results of this event. For instances, if there is insufficiency of goods supply, the enterprise will be closed. This will induce that other

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doi:10.1016/j.procs.2013.05.123

enterprises have no materials and even lose their functions. Furthermore, the same failures will occur in others of this region. Therefore, huge economic losses of the society will happen. So the safety of industrial ecology parks is the most important issue and we must pay more attention to it.

With the development of industrial ecology parks, much research has been devoted to the complexity of eco-industrial systems. In order to understand and transform the principles of the natural ecosystems into the industrial ecosystems well, many studies of industrial ecology have been performed [1-5]. Cote et al. introduced many ecological terms to describe industrial ecology park, and they focused mainly on the different types of symbiosis relationships [1, 2]. Chertow adopted the material exchange types as the criteria to distinguish the taxonomy of eco-industrial parks between their various models [3]. Different from this method, Korhonen [4] proposed that the activity of eco-industrial parks should be based on four principles, that is, roundput, diversity, locality and gradual change. In addition, the typology of natural and industrial ecosystems was presented by Ayres [5]. Thomas et al. introduced the flow path of material or energy in the industrial region network of Rhine-Neckar and made clear the relationship between the enterprise inside the network and that outside the network [6]. The importance of the diversity was confirmed in several contemporarily functioning industrial ecosystems and was described in the related literature [7, 8]. In order to measure the relations among enterprises in industrial ecology parks, the concept of eco-connectness for quantitative assessment of eco-industrial parks was put forward Dai et al. [9].

Although the research on the complexity of industrial ecology systems has made a great breakthrough, these studies on industrial ecology parks focus on the exchange analysis of material or energy. Only a little research has been published on the topology structure of symbiosis networks and gone into the interior of symbiosis networks of industrial ecology parks. Facing the upsurge of industrial ecology park construction, a set of scientific evaluation index system needs to be established. A challenging problem in industrial ecology is whether industrial symbiosis systems can bear complexity features if the systems are described only from their mass or energy interlinkages. Additionally, similar with other networks [10,11], various nodes have various impacts on the operation and management of the industrial ecology system in the symbiosis network of an industrial ecology park, especially for the ecological degree which is employed to measure the relation of exchanging by-products and wastes. In this paper, we use complex network theory to go into the interior of symbiosis networks and analyze the vulnerability in symbiosis networks of industrial ecology parks. We extract an industrial ecology park as the symbiosis network and build a model for the symbiosis network according to the industrial ecology park's characteristics. Under the proposed model, we furthermore raise a measure to quantitatively evaluate the power and status of the nodes. As a result, some potential critical nodes are found. Moreover, we investigate the relationship between the vulnerability of the symbiosis networks and the two parameters in our symbiosis network model. Our results could be beneficial to protect the critical nodes effectively and also enhance the reliability and robustness in symbiosis networks of industrial ecology parks. The study will promote the construction of symbiosis networks of industrial ecology parks.

2. Symbiosis network of industrial ecology park

An industrial ecology park is a public or private partnership where this industrial ecology approach to industry is contained in one development. The aim of this development is that the waste material or product of one company can be recycled into the manufacturing process of one or more companies. Industrial ecology parks are developed to produce mini-mal emissions, minimal noise and ground pollution, and minimal waste. In an industrial ecology park, enterprises are designed to fit the environment instead of adjusting the environment to fit the enterprise. Thus, we can attain minimal transportation and production costs. Most systems can be viewed as networks, that is, elements that interact with each other. A network can be thought of as a set of nodes connected through edges. In this section, in order to analyze the structural characteristics of industrial ecology parks by using complex network theory, we will extract the industrial ecology park as an undirected and unweighted symbiosis network first.

Following we assume that the symbiosis network G of an industrial ecology park is defined as a non-empty set of nodes $V = \{v_1, v_2, ..., v_N\}$ and a non-empty set of edges $V = \{(u_1, v_1), (u_2, v_2), ..., (u_N, v_N)\}$. In an industrial ecology park, we regard products, by-products, wastes and energy as the foundation nodes. Besides, we also add some nodes outside the parks who exchange energy with nodes within the parks as the supplement nodes. Realistic systems have many such interacting components. When there is a flow of matter or energy between any two nodes in that industrial ecology system, we say that there is a direct connection between them, which is called an edge in the symbiosis network. After the nodes and edges are confirmed, we write a matrix, which is used to define a network and also called adjacency matrix. The adjacency matrix is used to describe the direct paths by 0 and 1. Matrix column position is on behalf of relationship senders, the row position is on behalf of relationship recipients. If there is at least one relation between longitudinal and transverse members, the crossover box is filled with 1, that is $a_{ij}=1$; otherwise 0, that is $a_{ij}=0$.

Because that if one node malfunctions, the downstream enterprises could not get sufficient supply of resources. In addition, the matter or energy outflow of the upstream enterprises could also decrease at the inverse direction. We regard symbiosis networks of industrial ecology parks as undirected networks. Considering that the exchange data of matter or energy between nodes is difficult to obtain and the measurement standard can not be unified in an industrial ecology park, we furthermore extract industrial ecology parks as undirected and unweighted symbiosis networks.

In this paper, we take the Gongyi system in Henan Province of China as a case to build a symbiosis network model. This industrial ecology system is designed to transform resources in situ, develop comprehensive utilization of materials and produce minimal emissions. The industrial economy is a very important branch in the economy of Gongyi City. By investigating the eco-industrial park and collecting data, we choose products, by-products, wastes and energy from a certain scale of enterprises as 92 nodes in the symbiosis network. This industrial ecology system is made up of refractory material, coal, electricity, aluminium, iron, steel, cement, machinery equipment, chemical fibre, wire and cable, and so on. There are a lot of exchanges of matter or energy existing in the industrial ecology system. It is a relatively complex industrial symbiosis network. We investigate the interrelations about the members of the industrial ecology system and then obtain the adjacency matrix. By using Ucinet 6.0, we get the symbiosis network of Gongyi industrial ecology park, as is shown in Fig. 1.

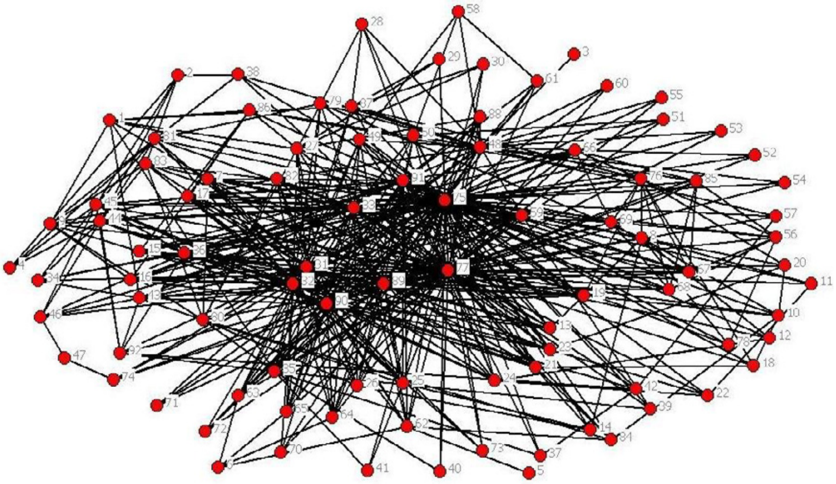

Fig. 1 Symbiosis network of Gongyi industrial ecology park

3. The model

3.1. Node importance evaluation method for symbiosis networks of industrial ecology parks

For the symbiosis networks of industrial ecology parks, various nodes have various power and status on the operation and management of the industrial ecology system. The failures of those critical nodes are more likely to cause the collapse of the whole industrial ecology system because of cascading failures. So evaluating the nodes and identifying the critical nodes in the industrial ecology networks are needed greatly. Considering that the development goal of industrial symbiosis system is designed to achieve the maximum utilization of material and energy, in order to reflect the features of symbiosis networks different from other networks, we propose a new measurement to characterize the nodes' status and power in symbiosis networks of industrial ecology parks. In the following, the set V of all nodes in the symbiosis network is divided into two categories $V=V_1 \cup V_2$. The set V_1 represents the set of ecological nodes and consists of waster nodes and by-product nodes which are all called ecological nodes. The set V_2 consists of all other nodes which are called product nodes. We consider the cascading failures triggered by removing a single node of network. We assume

$$I_i = 1 - \frac{\sum_{v_j \in V_1 \cap V_i'} k_{ij}'}{\sum_{v_m \in V_1} k_m} \tag{1}$$

where V_i' is the set of the nodes which can maintain the normal operations after cascading breakdowns, and k_{ij}' is the degree of residual node j after cascading breakdowns induced by removing node i. Obviously, the value of I_i reflects the damage degree of node i to the ecological connectance of symbiosis networks.

3.2. Cascading phenomenon for symbiosis networks of industrial ecology parks

Cascading failure phenomenon is common in most of networks which are the basic components of our lives and industry, including symbiosis networks of industrial ecology parks [12-15]. When an upstream enterprise or link failure emerges, the insufficiency of goods supply to the downstream enterprises will happen. Even though the failure emerges very locally in an industrial ecology system, it will also quickly spread like a plague to large areas, eventually result in the entire network collapsing. In this way, the entire symbiosis networks can be largely affected due to cascading failures. If the node has a small initial load, the removal cannot trigger the disastrous results, so the networks can recover from the load redistribution. However, if the deleted node has a large load, the local redistribution will trigger cascading breakdowns over the networked systems and lead to serious consequences.

The load of a node is associated with its degree and the degrees of its neighbor nodes in some actual networks, so we assume that the initial load of node i is as follows

$$L_i = [k_i(\sum_{m \in \Gamma_i} k_m)]^{\beta} \tag{2}$$

where β is a tunable parameter, k_i and Γ_i are the degree of node i and the set of its neighbour nodes.

Because each node of symbiosis networks of industrial ecology parks represents a member and has a capacity threshold which is the largest load that the node can tolerate. Furthermore, the load capacity of the node in actual network is limited by the cost of the node, so we assume that the load capacity of node i is proportional to its initial load, i.e.,

$$C_i = \alpha L_i(0), \qquad i = 1, 2, ..., N \tag{3}$$

where $\alpha>1$ is the tolerance parameter which can characterize the resistance to the intentional attacks and natural disasters. In symbiosis networks of industrial ecology parks, the tolerance parameter α reflects the construction cost of the enterprises. Since the capacity is limited, if node i malfunctions, its load will be redistributed to its neighbor nodes, so the load of neighbor node j of node i becomes $L_j + \Delta L_{ij}$. If $L_j + \Delta L_{ij} > C_j$, then node j will failure, which will lead to further redistributing the load of node j, this may lead to other failures, therefore the cascading failures occur. If $L_j + \Delta L_{ij} \leqslant C_j$, then the whole network can maintain the normal operations.

3.3. The critical threshold

The safety of industrial ecology networks severely affects the economic development and social stability. We must pay more attention to it. In order to reflect the features of industrial ecology parks and improve the reliability and robustness based on considering the ecological degree of industrial ecology parks, we propose a new method to measure the vulnerability of symbiosis networks of industrial ecology parks.

The number of failure nodes is investigated after the cascading process is over. We use TN_i to denote the avalanche size i.e., the number of broken nodes induced by removing node i. The damage caused by removing node i is quantified in terms of the avalanche size. It is evident that $0 \leqslant TN_i \leqslant N_1 - 1$. We adopt the normalized avalanche size to quantify the vulnerability of the whole network, which is defined as follows.

$$TN = \frac{\sum_{i \in V_1} TN_i}{N_1(N-1)} \tag{4}$$

where the summation is obtained by removing each node in V_1 initially at each time, and N_1 represents the number of wastes and by-product nodes.

When the value of the tunable parameter β is given, if the value of the tolerance parameter α is sufficiently small, it is easy for the whole network to fully collapse in the case of an arbitrary node failure. It is because that the capacity of each node is too limited. The system maintains its normal and efficient functioning for sufficiently large α, which is because that all nodes have the larger extra capacities to handle the load, but at same time that needs greater construction cost. In other words, when the value of α increases, the symbiosis networks have some crossover behaviour that they change from large scale breakdown to no breakdown, going through small scale ones. Therefore, we use the crossover behaviour, i.e., the critical threshold α_c, to quantify the vulnerability of symbiosis networks. If $\alpha>\alpha_c$, the symbiosis system maintains its normal and efficient functioning; while if $\alpha<\alpha_c$, TN suddenly increases from 0 and cascading failure emerges. The critical threshold α_c is the least value of protection strength to avoid cascading failure. So this indicator is reasonable to measure the vulnerability of symbiosis networks.

The critical threshold controls all the properties of the network. If we are able to select the value of the tolerance parameter and construct industrial ecology parts designedly, the construction cost of the industrial ecology park will be saved on the basis of the improvement of the vulnerability of symbiosis networks. In this way, many existing problems in the current planning and construction of the industrial ecology park are solved.

4. Simulation results

In this section, we will take the symbiosis network of Gongyi industrial ecology park in China as a case to discuss the nodes' power and the vulnerability in the symbiosis network by using our proposed model. This symbiosis network has 92 nodes. We divide the 92 nodes into two categories $V=V_1 \cup V_2$. The set V_2 of the ecological nodes include 13 nodes, such as waste water, waste residue, waste gas, and so on. Other 79 nodes belong to the set V_1.

Under our proposed model, we start from removing every node of the symbiosis network one by one in the set V. After the cascading process is over, we investigate the number of the nodes which can maintain the normal operations induced by removing node i in the whole network and then calculate I_i according to Eq. (1) for each node. Table 1 reports the node number and the ranking of the top 5 critical nodes in the industrial ecology park. The simulation result shows that the low degree node may also occupy an important status. For instance, the degree of node 33 is not high. However, the removal of node 33 leads to neighbour nodes malfunction firstly because the capacity of the nodes is insufficient to handle the extra load. As a result, this triggers a cascade of overload failures and eventually results in the whole network almost collapsing. After the cascading process is over, there is a large drop in the ecological degree of the whole network. These results imply that node 33 is actually a potential critical node. Therefore, the node importance does not absolutely depend on the node degree, especially for symbiosis networks of industrial ecology parks. According to the simulation results, we also see that the proposed measurement on node importance can help us to identify critical nodes in symbiosis networks of industrial ecology parks well. If we can protect these critical nodes in the operation and management in advance and make an effort to strengthen their construction, then security and robustness of symbiosis networks of industrial ecology parks can be improved. At the same time the development of this industrial ecology park will be promoted systematically with the step-by-step breakthrough method.

Table 1. Node importance ranking of the top 5 places

Node number	Node importance I	Ranking
77	1	1
75	0.9962	2
89	0.9367	3
91	0.8731	4
33	0.6527	5

Next, we start from removing every node one by one in the set V_1 and calculate the corresponding results, e.g., removing node i and calculating TN_i after the cascading process is over. We then calculate the value of TN according to Eq. (4). We investigate the effect of the tolerance parameter α for the normalized avalanche size TN first. As show in Fig. 2, we see that the value of TN increases rapidly as the decrease of the tolerance parameter a, which indicates that the removal of nodes can lead to serious results to the ecological degree in the symbiosis network due to cascading failures. We also find an interesting phenomenon in our cascading model. From Fig. 2, it is shown that when $\beta=0.5$, in the case of the same a, all TN are minimums. In order to verify this problem, we give further numerical simulation, which is shown in Fig. 3. According to Fig. 3, all values on the curve $\beta=0.5$ are smaller than the ones on other curves in the case of the same a. This result agrees well with the finding of Fig. 2. Fig. 4 reports the relation between the tunable parameter β and the critical threshold α_c. From Fig. 4, we see that α_c also attains the minimal value when $\beta=0.5$. Therefore, we can draw a conclusion that the symbiosis network reaches the strongest robustness level against cascading failure at $\beta=0.5$.

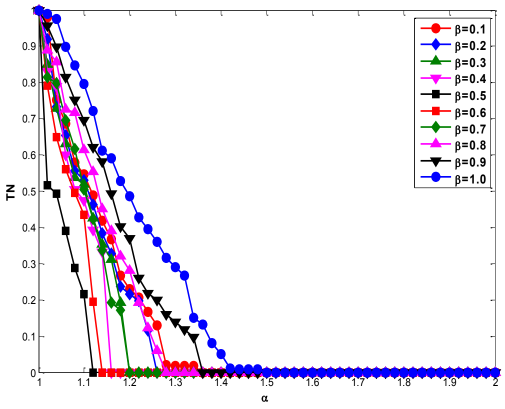

Fig. 2. Normalized avalanche size *TN* as a function of the tolerate parameter α

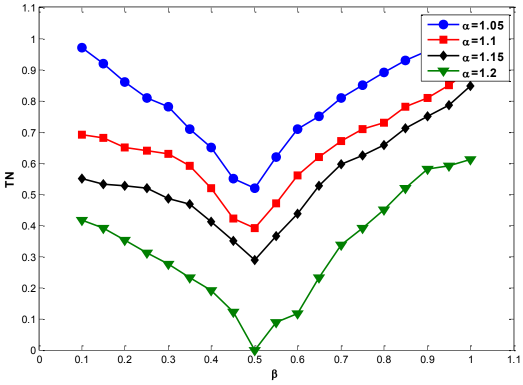

Fig. 3. Normalized avalanche size *TN* as a function of the tunable parameter β

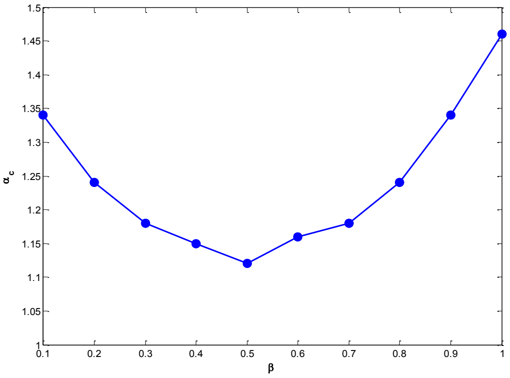

Fig. 4. Relation between the tunable parameter β and the critical threshold α_c

5. Conclusions

In this paper, we explore the power and status of nodes and the vulnerability against cascading failures in symbiosis networks of industrial ecology parks by using complex network theory. According to the features of industrial ecology parks, we build a cascading model with tunable parameter of symbiosis network and propose a new evaluation method of node importance considering cascading failure. This evaluation method can help us to find some critical nodes effectively. Based on the proposed cascading model, we propose a new measure i.e., the critical threshold to quantify the vulnerability of symbiosis networks of industrial ecology parks. To illustrate the effectiveness and feasibility of the proposed model, we furthermore extract Gongyi industrial ecology system in Henan Province of China as an undirected and unweighted symbiosis network. We investigate the cascading failure behaviours on the symbiosis network of the industrial ecology park with respect to the initial removal of each node. We find out the potential critical nodes in the symbiosis network. The simulation results also show that symbiosis network display the strongest robustness level against cascading failure at the tunable parameter β=0.5. The result could help me to select the optimal value of the parameters to attain the optimal robustness. In summary, our work may have practical implications for protecting the key nodes selected effectively and avoid cascading-failure-induced disasters in symbiosis networks. It is very useful for the construction of symbiosis networks of industrial ecology parks. Moreover, our cascading model has great generality for characterizing cascading-failure-induced failures in nature, as well as providing valuable reference to many real-life networks, such as transportation networks, supply chain networks, and so on. It is expected that the presented model may help us to promote the construction of symbiosis networks of industrial ecology parks and better understand cascading phenomena in the real world.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (No. 60974076).

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