Culture of the stability in an eco-industrial system centered on complex network theory

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ABSTRACT

Different types of technical barriers in the operation of an eco-industrial system have been identified theoretically as a result of the exploration and implementation of ecological industrial parks since the 1990s. However, the vulnerability of these systems is amplified by inadequate management. In this paper, we describe the indicators of stability in an eco-industrial system based on complex network theory to build a cascading failure model for the system. A case from the Qinghai Salt Lake Ecological Industrial Park is introduced to construct the network topological structure and simulate the network cascading failure transmission. We discuss how two types of node enterprises impact the stability of the eco-industrial system. The results show how various node enterprises with different mechanisms affect the systematic stability of the eco-industrial network and how the removal of core node enterprises can lead to greater damage to the network. Managers of eco-industrial systems should focus on structural core enterprises and core industrial chains. In this paper, the managerial implications can provide reliable guidance for stable operations in an eco-industrial system.

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1. Introduction

For many years, consumers and environmental groups have been concerned with sustainability and the environmental impact of the products they consume (Chin et al., 2013). Consumer preference is for products produced with environmentally friendly production and abatement technologies such as recycling and the use of less polluting inputs (Amacher et al., 2004). Some countries have therefore resorted to trade policies and consumer action to reduce the negative environmental impacts of the products they consume (Engel, 2004), such as the use of environmental sustainability labels (eco-labels) to shift patterns of household consumption (Hallstein and Villas-Boas, 2013). However, traditional green solutions suffer from many weaknesses. For example, an end-of-pipe approach cannot eliminate pollutants or wastes but merely transforms them from one form to another. One response to this has been the rise of eco-industrial production, which is a concept that has been a subject of study for almost 30 years as a strategy for improving the economics of production facilities while reducing waste (Kantor et al., 2015; Seok et al., 2013). Eco-industrial production is characterized as a more sustainable practice that minimizes pollutants or wastes dumped into the environment through an optimal usage of wastes, water cascades and energy and that reduces the use of raw materials and the resulting pollution. Recently, eco-industrial production has become an immeasurably pervasive modern industrial manufacturing method with the establishment of the Kalundborg Symbiosis in Denmark. Many countries, including the United States, Canada, Japan, Australia, and other European nations, have also made progress in building thousands of EIPs (ecological industrial parks). This method of manufacturing has brought significant economic benefits, while also generating a series of problems because the establishment of an eco-industrial park is influenced by numerous internal and external factors (Ilda et al., 2015; Veleva et al., 2015). Roberts (2004) noted the assortment of challenges/difficulties in EIPs development, both within China and abroad. Zhu et al. (2010) showed that the major challenges and problems in China were (1) the lack of preclusion processes to mitigate the risks of eco-industrial development; (2) the need to precisely measure the development and function of EIPs; (3) the uncertain roles of government and public bodies in the development and operation of EIPs; (4) scarce management systems and practices; and (5)
misapprehension of the nature of EIPs. These criticisms are similar to those exposed by Chiu and Yong (2004) in their study of EIPs in Asia. Fleig (2000) further found that the greater the dependence of the companies within the industry ecosystem on each other, the greater the risk.

It is indeed because of these problems that many studies on the stability of eco-industrial systems have been commissioned. Cohen-Rosenthal (2000) studied the internet's ability to defend against random attacks and proposed an analytical method of finding the core nodes of the internet based on the network connectivity rate after removing the nodes. Hardy and Graedel (2002) found that an increase in the connectedness of the industrial ecosystem cannot improve its stability or environmental performance. Liu and Chen (2007) discussed the stability and robustness of a supply chain network under different disturbances based on complex networks. Allesina et al. (2010) developed a new quantitative measurement of complexity for a supply network based on network analysis. Nair and Vidal (2011) examined the relationship between a supply network's topology and its robustness in the presence of targeted attacks and random failures. Xiao and Zhou (2011) analyzed the structural stability and performance drift by conducting experiments on systematic nodes under random disturbances and intentional disturbances. They concluded that intentional disturbances are much less influential to the stability of the network compared to random disturbances.

A cascading failure could cause huge damage, as measured in both life and industry development, which is a common phenomenon observed in reality systems and networks. Coh et al. (2002) found that the fluctuations occurring in the stochastic process of connecting and disconnecting edges are important features of the Internet dynamics. Albert et al. (2004) studied the power grid from a network perspective and found that although it is robust to most perturbations, a cascading power failure affecting key transmission substations greatly reduces its ability to function. Leonardo et al. (2007) concluded that network detrimental responses are observed to be larger when interdependencies are considered after internal or external disruptions, and effective mitigation actions could take advantage of the same network interconnectedness that facilitates cascading failures. Richard and Maria (2007) presented a new integer-linear programming model for identifying optimal fortification strategies of supply systems in the event of intentional attacks that result in cascading failure. There occurs a deficiency in the supply of goods to the downstream enterprises when a failure happens in the upstream enterprises in the symbiosis network of an EIP. Even though the failure emerges very locally in the eco-industrial system, it quickly spreads like a plague to larger areas and causes potentially serious damage to the whole system, sometimes even resulting in global collapse. According to the EIPs' characteristics, Zeng et al. (2013) put forward a critical threshold by developing a cascading model to quantitatively assess the resilience of symbiosis networks of EIPs. Zeng and Xiao (2014) built a new cascading model for a cluster supply chain network to explain the cascading phenomenon through complex network theory and social network analysis.

Many researchers have investigated the cascading phenomenon in power grid networks and traffic networks (Dobson et al., 2007; Zheng et al., 2007), but little research has been done on the cascading phenomenon in EIP symbiotic networks. The EIP symbiotic network is a typical complex network and includes the cascading phenomenon. The only existing study (Zeng et al., 2013) only emphasizes the reuse of increasing waste and by-products in the EIP development process and no attention is paid to the cascading phenomenon that occurs after randomly removing a node.

In this paper, based on the above understandings and by adopting the theory of complex network and the failure transmission mechanism for the operation of an eco-industrial system, we propose a cascading failure model for eco-industrial networks that can be utilized for the more stable operation of an eco-industrial system.

The remainder of this paper is organized as follows. The measurable indicators for stability in an eco-industrial network based on complex network theory are proposed in Section 2. Section 3 analyzes a cascading failure model for an eco-industrial network. In Section 4, a case from the Qinghai Salt Lake Ecological Industrial Park is introduced to construct a network topological structure, and simulation is done on the network cascading failure transmission. Managerial insights are revealed in Section 5. Finally, Section 6 concludes with a summary.

2. Measurable indicators of stability in an eco-industrial network based on complex network theory

The analysis of the dynamic stability for an eco-industrial network is based on the material flow of the real network, so the measurable indicators designed should be close to the conditions of the real eco-industrial network and accurately interpreting the relationship of node enterprises in the network.

2.1. Indicator for structural stability

The structural stability reflects network connectivity. Réka and Albert-László (2002) proposed that the scale dimension of a giant component can be an important variable to measure structural stability for the network structure. A giant component is a subgraph that includes more nodes than other subgraphs. There are connections between any two nodes in a giant component, which indicates the integrity of the network after being disturbed and the anti-interference ability of the network from the perspective of structure.

Material flow in the network has certain effects on its topology, which makes the traditional indicators for structural stability such as giant components invalid due to significant deviations. Considering the transmission characteristic in the cascading failure model, the cascading failure process is repeated until the load of the remaining nodes in the network does not exceed its capacity. After the expiration of the cascading failure process, the proportion of the remaining network, Q, can be used to present the structural stability of the network (Xia et al., 2010; Yin et al., 2014), as calculated in Equation (1)

\[
Q = \frac{R}{N_0}
\]  

(1)

where Q refers to the structural stability, \(N_0\) is the number of initial network nodes, and \(R\) is the remaining network nodes after the expiration of the cascading failure process. A smaller structural stability, \(Q\), indicates that there is a large cascading failure with greater damage to network connectivity, and vice versa.

2.2. Indicator for functional stability

The network functionality is the ability of a network to transmit material. In the cascading failure model, the network's functional stability means that the network can maintain an efficient exchange of material after interference by a cascading failure. As the actual physical flow of the network has already been considered, network functional stability indicators should relate to the network material flow. For a brief and somewhat simpler...
comparision, let $P$ denote the proportion of the remaining flow (Zhao et al., 2013) in the network to represent the network functional stability. This can be defined as Equation (2)

$$P = \frac{W_{\text{remain}}}{W_0}$$

(2)

where $P$ refers to the dynamic functional stability after the network is interfered with by other factors, $W_0$ is the total material flow in the initial network, and $W_{\text{remain}}$ is the remaining flow after the network is disturbed and is equivalent to the total inflow or total outflow of material in the network.

3. Cascading failure model in the eco-industrial network

In a real network, a malfunction occurring in one or more nodes would induce the other nodes to break down through a coupling relationship, which is an immediate linkage effect that ultimately leads to the collapse of a large number of nodes or possibly the whole system. This phenomenon is called a cascading failure. To describe this phenomenon in an eco-industrial network based on the ‘capacity-loading’ model, the cascading failure model of an eco-industrial network is developed to analyze the dynamic stability of the network.

We assume that the potential of cascading failure within the eco-industrial network has arisen due to the removal of a node, and our research emphasis is based on the dynamic performance of an eco-industrial network. In the initial phase, because the material flow capacity of each node, i.e., the actual material processing capacity, is greater than the node's economic capacity limit, i.e., the break-even point, the network is in a steady state. Removing nodes makes other adjacent nodes’ material inflows or outflows immediately decrease, which results in a decrease in the actual material processing capacity of the adjacent nodes. Here, the inventory of the node enterprises is not taken into account. When the adjacent nodes cannot process the existing material economically, the adjacent nodes will fail, and the cascading failure phenomenon is triggered.

In view of the above ideas and assumptions, a simple description of the model is as follows.

On the basis of the directed network, $W_i$ refers to the material exchange capacity between the node enterprises. A parameter, $n_i$, also known as the enhancement coefficient for material flow, will be adopted to denote the fact that node enterprises within the network exchange material with the outside world and is computed as Equation (3).

$$n_i = \frac{W_{i\text{out}}}{W_{i\text{in}}}$$

(3)

When $n_i$ is greater than 1, there is material input for node enterprises, and when $n_i$ is less than 1, there is material output for node enterprises. When $n_i$ is equal to 1, node enterprises have no material exchange with the outside and function completely within the eco-industrial network.

(1) Positive proportional relationship between the prescribed minimum material flow for the nodes and the initial flow

In reality, the enterprises have their own break-even points. When the yield of an enterprise is lower than the break-even point, its production will be uneconomical, and the firms will go out of business. Here, we set $k$ as the coefficient of the break-even point for node enterprises. If $n_i$ is less than the coefficient of the break-even point, the firms will be shut down following a cascading failure.

According to field research in the Qinghai Salt Lake Industrial Park, some large companies possess a high proportion of fixed asset investment in the Industrial Park, and if they experience a capacity reduction of 40%–50%, they will suffer serious losses. Small and medium enterprises with a low proportion of fixed asset investment in the Industrial Park have strong adaptability with regard to operation costs, so they can bear a higher market risk and tolerate a capacity drawdown as low as 30%–50%, or even lower.

To facilitate the model calculation, the minimum acceptable capacity for the enterprises in the network is assumed to be 40% of the original production, so $k = 0.4$.

(2) Flow balance principle of the collapsed nodes

The nodes in an enterprise network must maintain a material flow balance (Liu et al., 2003), i.e., $W_{i\text{out}} = W_{i\text{in}}$, which is an external and cardinal principle in failure propagation and can be described as Equation (4).

$$\sum_{i=1}^{n} w_{i\text{out}} = \sum_{j=1}^{n} w_{i\text{in}}$$

(4)

This formula denotes that the ratio between the nodes’ input flow at present, $\sum_{i=1}^{n} w_{i\text{in}}$, and the initial input flow, $\sum_{j=1}^{n} w_{i\text{in}}$, is always equal to the ratio between the nodes’ output flow at present, $\sum_{j=1}^{n} w_{i\text{out}}$, and the initial output flow, $\sum_{j=1}^{n} w_{i\text{out}}$. If one of the nodes in a network collapses, the value on one side of the above equation will be changed, and the value on the other side of the above equation must be changed to match the material flow ratio of the simultaneously collapsed nodes to meet the flow balance principle.

Due to the accumulation of failures, if $\sum_{i=1}^{n} w_{i\text{in}} / \sum_{i=1}^{n} w_{i\text{in}} > k_s$, the node enterprises will be shut down while the failure spreads, and a cascading failure will occur in the eco-industrial system.

4. Simulation

A real case from the Qinghai Salt Lake Ecological Industrial Park is introduced to construct a network topological structure and simulation to support the network cascading failure transmission theory.

4.1. Brief introduction to the Qinghai Salt Lake Ecological Industrial Park

The Qinghai Salt Lake Ecological Industrial Park is located in the largest dry inland salt lake of China, i.e., Qarhan Salt Lake, which is rich in mineral resources, including potassium, magnesium, sodium, lithium, and boron, with a potential economic value of about RMB ¥ 12 trillion. A schematic map of the Qinghai Salt Lake Ecological Industrial Park is drawn in Fig. 1. The Industrial Park is the largest potash industry production base in China and uses the key technologies of recycling potassium, sodium, and magnesium as the base of industrial research, forming five highly relevant circular economy industrial chains.

Each node enterprise in this eco-industrial park works together to form an industrial symbiosis network. Fig. 2 presents the industrial symbiosis network diagram of the Qinghai Salt Lake Ecological Industrial Park.
4.1.1. Industrial chain A

After extracting bromine (A5) from brine (A1), part of the saturated brine (A3) after extracting the bromine is used to dry crude salt (A7), while the waste salt is transported to a soda plant (C4) to produce soda via the ammonia-soda process, and gypsum salt (A6) is transported to a cement plant (C2) to produce cement. The other part of the saturated brine is transported to a chlor-alkali plant (B1) to produce chlorine, alkali, and hydrogen. Finally, the leftover brine is refined, dehydrated and electrolyzed into chlorine, potassium, and magnesium (A8) and part of the leftover brine is dynamically calcined to generate hydrogen chloride, magnesium hydroxide and magnesium oxide, while the hydrogen generated from the chlor alkali plant (B1), chlorine and potassium are conveyed to a potash fertilizer plant (C1) to produce potash.

4.1.2. Industrial chain B

Without the traditional technology to make salt, the brine (A3) in the saltern is input into the chlor alkali production facility (B1) through self-provided power, which can reduce the cost of production and transport for the crude salt. A coking plant (B3) cokes coal to produce coke oven gas and coke. With raw coal, coal gangue and carbide furnace gas as fuel, the thermal power plant (B2) generates the electricity and steam for the other plants, while the by-product, lime ash, is conveyed to the cement plant (C2) as a raw material for cement production.

4.1.3. Industrial chain C

The potassium gypsum from the potash fertilizer plant (C1) is transported to the cement plant (C2) for cement production. The cement kiln gas rich in SO₂ is transmitted to a sulfate plant (C3) for sulfate and liquid SO₂ production. Part of the sulfate acts as the raw material in the potash fertilizer plant (C1), and the other part of the sulfate is transported to the soda plant (C4). The liquid SO₂ is delivered to a bromide plant (A5) as a raw material.

4.1.4. Industrial chain D

After gasifying raw coal into methyl alcohol (D1), the methyl alcohol is decomposed into propylene and ethylene by MTO technology commercialization. A propylene plant (D3) produces polypropylene directly. When mixed with chlorine extracted from leftover brine (A4), an ethylene plant (D2) produces polyvinyl chloride via EDC technology.

4.1.5. Industrial chain E

Calcereous stone is transported to a calcium carbide plant (E1) and calcined into calcilime. Calcilime and charred coal from the coking plant (B3) are used to produce calcium carbide and carbide.
Using calcium carbide in a chemical reaction with water, an acetylene plant (E2) generates acetylene that is involved in a chemical reaction with hydrogen chloride from calcining leftover brine (A4) that dynamically produces polyvinyl chloride. Part of the carbide slag is slated as a raw material for the cement plant (C2), and the other part is transported to the soda plant (C4) to produce calcium chloride.

4.2. Design for the simulation of a real network

A real eco-industrial network including 27 node enterprises from the Qinghai Salt Lake Ecological Industrial Park is built and the simulation framework is developed using a Java platform.

4.2.1. Real eco-industrial network

In actuality, there are about 180 enterprises in the Qinghai Salt Lake Ecological Industrial Park. The enterprises have an annual output value of over RMB ¥ 3 million and a certain scale of production, which indicates that those with a certain degree of production stability can affect the eco-industrial network, and therefore they were added into the network topology map. Another rule that was established for the simulation is that the enterprises involved in the network topology map must have an actual exchange of material or energy with other enterprises in the eco-industrial park. Based on the above principles, 54 enterprises have been selected for the network topology map. The edge of the network topological structure chart is used to denote the exchange behavior between enterprises, and the edge’s direction denotes the direction of the material or energy exchange.

The network adjacency matrix and the network topological structure chart of the Qinghai Salt Lake Ecological Industrial Park were created using the software UCINET (UCINET is a social network analysis program developed by Steve Borgatti, Martin Everett and Lin Freeman. The program is distributed by Analytic Technologies. UCINET works in tandem with freeware program called NETDRAW for visualizing networks. NETDRAW is installed automatically with UCINET. UCINET can be downloaded from http://www.analytictech.com/ucinet/download.htm and used free for 60 days). The resulting chart is shown as follows in Fig. 3.

When the data pertaining to the material flow based on the weighted flows of the physical units in the Qinghai Salt Lake Ecological Industrial Park are sorted into respective industry networks and adapted to the cascading failure model, because the collection process of the actual material flow data is both complex and difficult, a network data model including only 27 node enterprises is shown in Fig. 4.

4.2.2. Simulation framework

Based on the Java platform, a network dynamic stability simulation experiment is developed to solve the aforementioned simulation problem and the simulation framework is presented as follows in Fig. 5.

4.3. Discussion of the real network

Based on the above simulation experiment, the structural and functional stabilities of the network of the Qinghai Salt Lake Ecological Industrial Park (including 27 node enterprises) are
analyzed as follows, and the flow-removed calibration of a network topology has been done simultaneously.

4.3.1. Structural stability

By analyzing each deleted node on the actual network map, we are able to obtain the distribution of network core nodes, and the results are presented in Table 1.

Table 1 shows three levels of network fission under a cascading failure: (1) The nodes of the first level, i.e., nodes 1, 2, 3, 10, 15, 25, 26, are deleted, so that the remaining node ratio is 14.8%. Obviously, the cascading failure will spread to the whole network after these seven nodes are deleted. As a result, there are only four node enterprises that can maintain connectivity and maintain the state of operation in the network when the failure occurs, which is the result of rapid network failure transmission. Based on the location of the nodes of the first level in the network, these seven nodes connect with each other and form a pathway for supplying material, and thus damage to any node on this pathway will lead to a network collapse. (2) The nodes of the second level, i.e., nodes 4, 5, 6, 16, 17, are deleted, so that the remaining node ratio is 40.7%. The material flow among these five nodes accounts for a large proportion of the material processing on each node, and the interconnected relationship is fairly strong, which results in a cascading failure and indicates that it is an integrated link. (3) The remaining
nodes, i.e., the nodes of the third level, are deleted, so that the remaining node ratio with a small scale of failure transmission is greater than 85%.

4.3.2. Functional stability

By analyzing each deleted node in the actual network map, we are able to create Table 2.

Because the network is the carrier of material flow, the remaining network scale is inevitably positive with the remaining network flow. The distribution rule of the functional stability coefficient is the same as that of the structural stability coefficient and can be divided into three levels, with inter-nodes as strong ties composing an integrated link at the same level.

4.3.3. Preliminary analysis of the results

The indicator of structural stability for the first six nodes on the network degree and betweenness is presented in Tables 3 and 4.

For the first two nodes in terms of degree, i.e., node 5 and node 6, their remaining network scales are far larger than those of the nodes with a non-maximal degree, such as node 25. The remaining network scale of the nodes with the betweenness ranked fourth and fifth is 23 and 24, and these two nodes are entirely made up of non-core nodes. Therefore, the degree and betweenness are no longer the key indicators for us to identify the core nodes in the dynamic stability of an ecological industrial network. After the material flow is added into the network model, the network topology structure will be changed with the distribution of the material flow. Thus, it is not possible to respond to the information of the overall network by only considering the degree and betweenness. Flow-removed calibration is a technique that can be used to analyze the network structure and develop the judgment criteria of core nodes in accordance with the network structural property.

4.3.4. Flow-removed calibration of a network topology

Through filtering the “active edge of failure transmission”, a network diagram of fault transmission is set up. If the ratio defined as the flow value between node i and node j divided by the material flow of node j is greater than 0.6, there will be an active failure transmission from node i to node j, and the directed edge from node i to node j is appended. If the ratio defined as the flow value between node i and node j divided by the material flow of node i is greater than 0.6, the directed edge from node j to node i will be appended. The network diagram of fault transmission in Fig. 6 is plotted based on the calculation of the entire diagram.

Fig. 6 reveals that the whole network can be separated into two sub-networks from node 9, which is the same as the simulation result from the cascading failure and implies that the two sub-networks that do not affect each other are comprised of various industry clusters. The influence from the “node-reachable region” of the nodes on network stability has been deeply explored. The nodes with a maximal reachable region, i.e., nodes 1, 2, 3, 10, 15, 25, and 26, are the core nodes, and the reachable region scale is 22. If any failure occurs with these core nodes, there will be only four nodes remaining in the whole network graph. Nodes 4, 5, 6, 16, and 17 are regional core nodes with a reachable region scale of 13, and if any failure occurs with these regional core nodes, there will be only eleven nodes retained in the entire network graph. The results are exactly in accordance with the simulation analysis, so the reachable region scale of network nodes in failure transmission can be employed in estimating the importance degree of various nodes on network stability.

Furthermore, the core material link of the network can be recognized from Fig. 6, and the link from node 25 to node 3 is comprised of core nodes that possess a strongly mutual reachable interrelationship, so that any fluctuation of this link could cause disastrous consequences to the whole network.

4.4. Discussion on a random network

A random network including 200 node enterprises is generated stochastically to compensate the effectiveness of the results obtained from the real network only including 27 node enterprises, which is regarded as a control group and compared with the real network data model.

### Table 1

<table>
<thead>
<tr>
<th>Node</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
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<td>4</td>
<td>4</td>
<td>11</td>
<td>11</td>
<td>11</td>
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<td>0.148</td>
<td>0.407</td>
<td>0.407</td>
<td>0.407</td>
<td>0.926</td>
<td>0.926</td>
<td>0.852</td>
</tr>
<tr>
<td>Node</td>
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<td>11</td>
<td>12</td>
<td>13</td>
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<td>Remaining scale</td>
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<tr>
<td>Remaining node ratio</td>
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<td>0.889</td>
<td>0.852</td>
<td>0.852</td>
<td>0.963</td>
<td>0.148</td>
<td>0.407</td>
<td>0.407</td>
<td>0.926</td>
</tr>
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<tr>
<td>Remaining node ratio</td>
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<td>0.963</td>
<td>0.148</td>
<td>0.148</td>
<td>0.926</td>
</tr>
</tbody>
</table>
The solution process for the evolution of eco-industrial systems (Xiao et al., 2012) is employed in this paper to generate a random network including 200 node enterprises. This random network is the same as the real network from the Qinghai Salt Lake Ecological Industrial Park on the property of a small world and scale-free network. 60% of the non-boundary nodes (with in-degree and out-degree) are chosen stochastically and defined with a value of 1 as their enhancement factor of material flow, and the rest of the nodes, i.e., the remaining 40 percent, are defined with a random value between 0.3 and 4.0 as their enhancement factor of material flow. The random network is assigned with a prescribed limit by analyzing the distribution rule of the real network material flow in the Qinghai Salt Lake Ecological Industrial Park, and finally, a balancing network is generated after circulation.

The following network topological structure chart in Fig. 7 is designed based on the procedure described above.

4.4.2. Validating the effectiveness of the conclusions

After the flow-removed calibration in Fig. 7, we have Fig. 8.

The reachable region scale, degree, and the number of nodes deleted out of the first fourteen nodes are shown in Table 5. Based on this, we can determine that the correlation between the reachable region scale and the number of nodes deleted is larger than that between the reachable region scale and node degree.

The results indicate that there is a high correlation between the reachable region scale and the number of nodes deleted, with a correlation coefficient of 0.934. Thus, the reachable region scale of a network node with failure transmission can be adopted to verify the importance of nodes to the systematic stability. Meanwhile, the directed edges of the failure transmission network can be the direction of failure transmission. By searching for the link circuit of a two-way junction, the core node enterprises can be identified. If the core nodes are involved in the link circuit, this link circuit will be the core circuit, which must be the focus of attention for the whole network.

4.5. Results analysis

We use two indicators to show that the damage caused by removing core nodes is greater than that by removing non-core nodes in the network. To make an intuitive comparison of the impacts to the network imposed by core nodes and non-core nodes, we select a core node (node 8) and a non-core node (node 24) discretionarily from the random network to demonstrate the failure diffusion process and scale, as illustrated as follows in Figs. 9 and 10, respectively.

Based on a comparison of the two figures, over 70 percent of the nodes in Figs. 9 and 10 are affected when core node 8 is removed, leading to a shutdown of 14 nodes and having a great degree of influence on the systematic stability. None of the nodes are closed if non-core node 24 is removed, which only has an effect on 20 percent of the nodes, while the systematic structure and function continue to function normally.

In terms of the velocity of failure transmission, core node 8 takes six steps to reach the remotest node, while non-core node 24 takes four steps. Although nodes 8 and 24 are both in the center position of the random network, it is notable that we cannot confirm that the velocity of the failure transmission of a non-core node is immediately larger than that of a core node due to the different failure transmission scales of the two nodes. According to an analysis of the transmission process of the two nodes, it is obvious that both nodes 8 and 24 can reach the peak of failure transmission in step 3 and affect the largest scale of whole nodes in the random network. This result matches the average minimum path length in the network graph, which proves that the velocity of failure transmission is affected by the position of the nodes, the average minimum path length and the scale of failure transmission. Without loss of generality, the velocity of the failure transmission of core nodes is faster than that of non-core nodes considering the scale of failure transmission.

This also shows that the withdrawal of most enterprises does not have a significant impact on the stability of the eco-industrial network. When one of the network’s core node enterprises withdraws, the eco-industrial network will experience paralysis over a fairly large area, with a large number of enterprises in the network withdrawing in succession. Ultimately, the structure and function of the system are severely damaged. The operational stability of the ecological industrial network depends on the stability of the core node enterprises.
After the flow-removed calibration of the network, the reachable region scale of nodes can be a more accurate indicator for identifying the core nodes in a network. Obviously, the nodes with a larger reachable region scale have a significant effect on the stability of the network, and these types of nodes need to be a focus of concern.

5. Managerial implications

The case from the Qinghai Salt Lake Ecological Industrial Park has been introduced to construct the network topological structure and perform a simulation on the network cascading failure transmission. After discussing how two types of node enterprises impact the stability of the eco-industrial system, some managerial implications can be concluded to provide reliable guidance for stable operations in an eco-industrial system.

5.1. Core node enterprises become the key to maintaining the stability of the eco-industrial network

The Qinghai Salt Lake Ecological Industrial Network has been found to show a small world and scale-free feature. From the perspective of network topology characteristics, the Ecological Industrial Network is formed based on a fraction of core nodes as the network center. From the two points of the fault transmission scale and failure transmission velocity, the core nodes have been proven to be of crucial importance for the structural and functional stability of the ecological industrial network by the dynamic stability simulation model. If the core nodes are damaged, the fault will quickly spread to the majority of the whole network. Due to the small world feature of the network, the velocity of the failure transmission is too fast to take precautions against.

From both qualitative and quantitative analyses, the core nodes can be regarded as the ‘heart’ of the ecological industrial network. When the function of the ‘heart’ is insufficient, the production activity of the network will be affected, postponed and lose efficiency. When the function of the ‘heart’ is broken, the network will be seriously damaged and even paralyzed. While the normal production and operation of the network depends on the key resources, to enhance the stability of the network, the ability of anti-interference and the adaptive capacity of the network have to be increased.

The first task for the administrators of eco-industrial systems is to consider the appropriate industrial scale. Theoretically, the larger the network, the more stable the system, but the cost and difficulty of managing the network will increase as well. Therefore, the scale of the eco-industrial system must be within an appropriate range. Furthermore, the administrators must identify the structural core enterprises and the functional core enterprises. Structural core enterprises are defined as enterprises (core nodes) holding a comparable advantage of the node degree in the ecological industrial system that are able to sustain the stability of the eco-industrial system. Functional core enterprises refer to the enterprises (core link circuits) that are able to maximize the efficiency of their exchange of material in an eco-industrial system. To handle the unstable factors of production and operation for core enterprises and issue warnings for other enterprises to take emergency measures in advance when faults exist in the system, the managers of an eco-industrial system must constantly monitor the production status of the core enterprises. Additionally, the system administrators must guarantee the raw material and energy supply for the core enterprises as described earlier, and maintain the stability of the system for some time by using the inventory and spare capacity of the enterprises when the system encounters severe interference.

<table>
<thead>
<tr>
<th>Node</th>
<th>Remaining network scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
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<td>12</td>
<td>23</td>
</tr>
<tr>
<td>11</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 4. Remaining network scale of nodes on maximal betweenness.

Fig. 6. Network diagram of fault transmission.
5.2. Identifying the core nodes and core links is critical to managing stability in the eco-industrial system

In the management of a real ecological industrial network, although some network administrators have realized the importance of core node enterprises to the stability of the network and provide supervision and support for these core node enterprises, large-scale faults still occur and are transmitted in the network, and cannot be completely eradicated. In the ex post analysis of a fault, core enterprises are not always revealed to be the source that triggers a large-scale fault in the network, but rather enterprises hidden behind the core enterprises that are easily ignored, which are defined as 'hidden core enterprises'.

In the analysis of dynamic stability for an ecological industrial network, a cascading failure model considering network material flow was built. The model reveals that some node enterprises with a small degree and betweenness may have a significant impact on the network stability, and this type of node enterprise is named 'hidden core enterprises'. Hidden core enterprises that possess unique resources or technologies have a direct or indirect relationship with core node enterprises in supplying or adopting raw material, energy or waste and have an effect on the production of core node enterprises, but only connect with a small number of nodes. Therefore, the administrators of an eco-industrial system often ignore hidden core enterprises with a small degree and betweenness, which presents hidden trouble to the stability of the ecological industrial network.

Fig. 7. Random network topological structure chart.

Fig. 8. Network graph of random network failure transmission.
In addition, from the fault transmission path of network fault transmission graph, we find that some mutual reachable nodes consist of a link circuit. In the process of cascading failure transmission, if any node of this link circuit has been shut down, all nodes of this link circuit will be shut down correspondingly, so all nodes of this link circuit are regional core nodes. If this link circuit includes core node enterprises, it will form a core link circuit of the network. Thus, we must pay particular attention to this core link circuit because any fluctuation of this core link circuit will impact the whole network.

The cascading failure model of this article can be employed in effectively identifying the core nodes and core link circuit of the network and comprehensively show the administrators the characteristics of the eco-industrial system. The hidden core nodes are different from the general core nodes, and their presence is not required. The management tool can be used to reduce the hidden core nodes and core link circuits. First, the system administrators can introduce multiple substitution enterprises to prevent some small enterprises from becoming hidden core nodes and core link circuits with critical resources and technologies, which allows the system to reduce its reliance on such hidden core node enterprises. In addition, to avoid the formation of network core link circuits or long link circuits, it is necessary to introduce the right amount of complementary enterprises in appropriate positions and to disperse the material input and output of link circuits. The objective is to make each section more independent, thus improving the overall stability. Last, for non-substitution hidden core node enterprises, administrators must realize their importance and increase support to them to prevent them from becoming the source of a cascading failure.

Table 5
Simulation results for partial nodes in a random network.

<table>
<thead>
<tr>
<th>Node ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reachable region scale</td>
<td>6</td>
<td>3</td>
<td>10</td>
<td>11</td>
<td>9</td>
<td>9</td>
<td>1</td>
<td>12</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sum of degree</td>
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<td>19</td>
<td>25</td>
<td>13</td>
<td>22</td>
<td>24</td>
<td>6</td>
<td>8</td>
<td>1</td>
<td>5</td>
<td>9</td>
<td>10</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Number of nodes deleted</td>
<td>6</td>
<td>3</td>
<td>10</td>
<td>11</td>
<td>14</td>
<td>9</td>
<td>2</td>
<td>14</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

5.3. Reasonably planned industry clusters can increase the network stability

During the formation of an eco-industrial system, some enterprises and relative departments engaged in the same or related industry create a strongly correlated network around certain local core nodes, also known as subnets, which represents the branches of the system’s “industry cluster”.

The analysis of the dynamic stability for the ecological industrial network indicates that the network fault transmission graph is divided into sub-networks after the flow-removed calibration of network topology is implemented in the original network. Therefore, the real network including 27 nodes splits into 2 sub-networks, and the random network including 200 nodes is divided into 4 sub-networks. The simulation results prove that the fault of a certain node enterprise in a certain sub-network will impose a slight effect on the node enterprises of other sub-networks, which cannot result in the shutdown of node enterprises for other sub-networks, while the fault of global core nodes may lead to a devastating impact on the whole network. These dispersive sub-networks are a natural barrier to network failure expansion, and the impact scope of faults is restricted to a small scale.

The administrators of eco-industrial systems should realize that the industry cluster sub-networks make confinement of fault transmission. Eco-industrial system administrators should reasonably plan the relevancy between industry clusters to reduce external dependence of industrial clusters, such as reducing the impact of the nodes outside the industry cluster on the core nodes in the industry cluster, reducing the input of external faults and the...
output of internal faults. For the core enterprises of the industry cluster sub-networks, the anti-interference capability of these core enterprises should be advanced, as it can have a significant impact on improving the stability of running the eco-industrial system because these core enterprises are the first defending line to restrict fault transmission.

6. Conclusions

This paper confirms the stability of a network evaluation based on the fundamental structure of an eco-industrial network topology. Through this process, an eco-industrial system network cascading failure model was built. The simulation results proved that the removal of core nodes and core link circuits will lead to node faults spreading quickly in the network, causing dramatic fluctuations in the network, which affects the entire industry network and cause node closures on a large scale. Thus, the impact of faults from core nodes and core link circuits on the network stability will be significant, and these core nodes and core link circuits are obviously the key to network stability.

The identification of core nodes and core link circuits will be more complicated if material flow is added into the network topology structure. Therefore, flow-removed calibration is a new way to accurately identify the core nodes and core link circuits. In the static stability analysis of the ecological industrial network, the degree and betweenness of the network nodes are effective indicators to identify core nodes in the network, and shutting the nodes with a high degree or betweenness will have a dramatic influence on the network. However, the way to identify core nodes in static stability analysis cannot work well in the dynamic stability analysis of an ecological industrial network, so we need to perform a flow-removed calibration for the network, so a reachable region scale can be used to judge the core nodes of the network and also the core link circuits of the network. The way to identify core nodes and core link circuits in static stability analysis is different from that in dynamic stability analysis, which indicates that the change of the identification method is closer to the actual situation.

The conclusions in this paper contribute to the learning of management techniques for eco-industrial systems and suggest that core node enterprises and core link circuits are absolutely crucial to the stable operation of the overall system. Within the analysis of the industrial network dynamic stability, we established a cascading failure model, which provides a new perspective for network stability analysis. It also provides a method that can be used for related research in industry networks.

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