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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.

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)

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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. Goh 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 prospective 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)

$$Q = \frac{R}{N_0} \tag{1}$$

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