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Short communication

Analyzing network topological characteristics of eco-industrial parks from the perspective of resilience: A case study

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ABSTRACT

Realizing the stable operation of an eco-industrial park (EIP) as a complex system consisting of a variety of the enterprises and embedded relations is challenging. The topological structure plays an important role to understand the balance of network resilience and eco-efficiency in the operation process of a given EIP. In this paper, Ningdong Coal Chemical Eco-industrial Park (Ningdong CCEIP) is used as a case study in Ningxia Hui Autonomous Region of China. Based on complex network theory, we focus on topological characteristics analysis of symbiotic network from the perspective of resilience. Results reveal that Ningdong CCEIP has scale-free characteristics as well as the small world ones. Compared with the node-level metrics, the important degree of node considering ecological factor is a more crucial index measuring the importance of a particular node in the network. The removal of top 10% node contributes to 60% decrease of network efficiency, which indicates the decline of resilience in the studied case. Protecting the most important nodes is critical to safeguard the potential "vulnerability" in the development of EIPs. This study can help us better understand the strategies for avoiding disruptions, improving the resilience of EIP and safeguarding the stable operation.

1. Introduction

The expansion of resources consumption and the aggravation of environmental decay, coupled with increasing urbanization, rising population size and accelerating economic development have imposed a considerable impact on the planet (UNEP, 2000). Tammemagi (1999) contended that a "*mere 1.5 ha of space will be available to each individual for housing, food production, waste disposal and other needs*" by 2020. In the context, there have been increasing calls for eco-efficiency, aiming at reducing material and energy throughput without influencing goods and services supplied (Gibbs and Krueger, 2005; Zhu and Ruth, 2013).

In 1989, the term "industrial ecosystems", firstly introduced by Frosch and Gallopoulos (1989) in *Scientific American*, has served as one of the important solutions to achieve productive use of waste and by-products and minimize environmental degradation. Meanwhile, a cluster of companies from different industries, were intensively sharing resources to competitive advantage involving physical exchange of materials, energy, water, and by-products, which was defined as industrial symbiosis (IS) by Chertow (2000). A variety of companies and embedded symbiosis relations among the companies forms industrial symbiosis networks (ISNs), which often was expressed as eco-industrial park (EIP) in the research literature (Côté and Cohen-Rosenthal, 1998). EIP has coemerged with the focus on efficiently sharing resources in a similar fashion to natural ecosystem in the pursuit of reduced ecological impact and maximized economic benefits (Liwarska-Bizukojc et al., 2009).

In recent years, attention to EIP development projects has been attracting at a good pace both in developing and developed countries worldwide, including USA (Chertow and Lombardi, 2005), Australia (Van Beers et al., 2007), Canada (Venta and Nisbet, 1997), Finland (Korhonen et al., 1999), India (Patel et al., 2001), Korea (Behera et al., 2012), and China (Zhu et al., 2007). Meanwhile, many researchers have been studying ISNs (Wright et al., 2009; Boons et al., 2011; Behera et al. 2012), in order to provide new implications on the design and improvement of EIPs. To develop cost-effective strategies to conserve resources and reduce wastes, Tan et al. (2008) applied systematic approaches to find optimal designs of industrial material reuse/recycle networks. Wright et al. (2009) quantitatively interpreted industrial parks as ecosystems, by translating ecological tools, such as diversity and connection, to an industrial context, and presented a theoretical platform to explore how the ecological concepts affect the sustainability of industrial ecosystems.

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However, the outstanding problems are the instability and poor symbiosis confronted by many national EIP projects (Zhu et al., 2010; Behera et al. 2012), in spite of the fact that EIP can maximize resource efficiency and minimize pollutant emissions (Park and Behera, 2014). Resilience, as a property of complex systems, refers to industrial system's ability to sustain in an instable market environment in response to unanticipated perturbations (Korhonen and Seager, 2008). Its ecological meaning has been extended to provide guidelines for design and management in the industrial ecosystems increasing firm and system level adaptability to disruptions (Zhu and Ruth, 2013). Among a range of limitations, the structure of the network is very important factor that is influenced by perturbation, and further affects a system's resilience (Gao et al., 2016).

The introduction of network theory opened a new way for many scholars to study the topological structure in the EIS as a complex network (Korhonen and Snä kin, 2005). It was applied on Kalundborg industrial network to understand its organizational framework, i.e. the structural characteristics of industrial symbiosis and the role that different actors play (Domenech and Daviesa, 2011). Based on the intrinsic properties of EIS, Xiao et al. (2012) proposed a modified Barabaísi and Albert (BA) model to design the green logistic supplying network to accurately interpret the formation mechanism of an eco-industrial network. To help EIP managers understanding the importance of stability and identify sustainable strategies, several researchers have been working on resilience in the eco-industrial networking under disruptive scenarios (Chopra and Khanna 2014; Zeng et al., 2013; Zhu and Ruth, 2013), to provide effective support for industrial ecology. Zhu and Ruth (2013) proposed the concept of resilience for industrial ecosystems and explored the influencing factors of resilience to removal of firms from networks by employing a network model of inter-firm dependency. Chopra and Khanna (2014) applied extensively network analysis to enhance understanding the resilience based on the network metrics in response to partial (untargeted disruption on a node) and complete (targeted attack) disruptions, from 2002 snapshot and evolution analysis during 1960–2010. Zeng et al. (2013) put forward the critical threshold to quantitatively assess the resilience of EIPs. Xiao et al. (2016) simulated the network cascading failure to show how the node enterprises impact the stability of EIP. However, the available related studies had not provided us an effective assessment of resilience characterizing the integrated feature of EIP. The ecological relationships among members should be gained important insights in EIPs, which results from direct and indirect exchange of byproducts and wastes (Zhang et al., 2015; Zeng et al., 2013). And mutual dependence among nodes (Hu et al., 2015) and node attributes (Chen et al., 2016; Liu et al., 2015) may provide useful information for structural exploration. Therefore, network topological characteristics, with ecological attributes, different from other general complex system, should be considered to study the important node and the resilience of highly interconnected and symbiotic industrial network.

In this paper, complex network theory is applied to focus on network topological characteristics from the perspective of resilience. Using a case study of Ningdong Coal Chemical Eco-industrial Park (Ningdong CCEIP), one of EIPs in Ningxia Hui Autonomous Region, this paper has three specific objectives to obtain: (1) to calculate the statistical parameters of EIP and to identify the topological characteristics of the case study; (2) based on node-level metrics and ecological factor, to quantitatively determine the important enterprises by a novel evaluation model; (3) to explore the change of resilience in response to targeted disruptions. The study relies on complex network theory to provide a systematic overall view of the structure and function based on topological structure and ecological features in EIP, which will contribute to further expand the theoretical framework for developing resilience of EIP.

2. Methods

2.1. Research background

In this paper, Ningdong CCEIP is used as a case study, which is one of the three industrial parks in Ningdong of Ningxia Hui Autonomous Region in northwestern China. The chemical industrial park combines traditional coal chemical industry (such as coal to methanol) with new coal chemical industry (such as coal to olefin), and produces many kinds of products, such assyngas (SNG), polyacrylonitrile, polyethylene, poly trimethylene terephthalate (PTT), poly ethylene terephthalate (PET), poly oxy methylene (POM), γ-butyrolactone, tetrahydrofuran, naphtha, diesel oil, coal tar, etc. In particular, polyethylene accounts for the largest amount of synthetic resin, which is mainly applied in hollow products, plastic products, wire, etc. PTT is a kind of new polyester polymer material, which has broad application prospects in many areas. POM is one of the five big engineering plastics in the world and also called 'super steel', which can substitute metallic materials (or metals) such as steel, copper, zinc and aluminum in many parts of the industry. SNG is a high-quality and clean energy, which can be used in power generation, chemical raw materials, natural gas cars, etc.

Ningdong CCEIP consists of four industrial systems: coal-fired power, coal chemical industry, salt chemical and glass building materials, based on the principles of 'development plan focusing on the keys, advancing eco-industrial construction step by step, coal-fired electricity industry as the foundation, resources in situ conversion, deep processing and comprehensive utilization system'. Its main chains are as follows: (1) Coalmine → SNG, semi-coke, tar, methanol, coal gangue → all kinds of chemical products (such as naphtha, POM, etc.). (2) Coalmine → thermal power plant → electricity. And at the same time, the thermal power plants provide steam for chemicals. (3) Coalmine → polyvinyl chloride (PVC) → various chemical products (such as ammonia, etc.) and instrument components (such as bellows). In addition, the exchange of 'by-product to raw material' can reduce the resources consumption and environmental pollution, and generating considerable economic benefits. The schematic diagram of system network of Ningdong CCEIP is shown as Fig. 1.

2.2. Network metrics

Complex network can be considered as an approach to characterize complex systems in the real world (Strogatz, 2001). In a network, nodes identify the elements of the system and the set of connecting links (edges) represent the presence of a relation among those elements (Barrat et al., 2008). Network theory (also called graph theory) can be traced back to 1730s thanks to Leonhard Euler (1736) in solving the Ǩonigsberg seven bridges problem. In 1998, Watts and Strogatz released a paper named "*Collective Dynamics of Small-world Networks*" in *Nature* and established a small world model. Besides, Professor Barabasi and Dr. Albert published a paper named "*Emergence of Scaling in Random Networks*" in *Nature* and established a scale-free networks model. So far, complex network has become a hot spot of complexity science, which is widely applied in food web, WWW, electric power grids, railway networks etc. (Strogatz, 2001; Albert and Barabási, 2002; Hong et al., 2015).

Because structure always affects function (Xu, 2000), the differences in topology of the network would bring about the diversity of system functions. For instance, the topology of social networks affects the diffusion of information and diseases, and the topology of the power grid affects the robustness and stability of power transmission (Strogatz, 2001). To describe the topological characteristics of network, the paper mainly pay close attention to