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Unified network analysis on the organization of an industrial metabolic system

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ABSTRACT

Industrial parks have been playing a crucial role on driving regional economic development, but also been posing threats to local environment due to intensive resource consumption and waste emission. To analyze the trade-off between economic development and environmental pollution, we use an approach based on social and ecologic network analysis to survey the industrial metabolic network and explore their functional characteristics. We conduct a case study in Hefei economic and technological development area, whose components (environment/industrial sectors) are treated as nodes and the relationships (material/energy flows) between nodes are seen as links in this network. Results show that the relationships distribution between components in the entire network basically shows a feature of decentralization. Environment controls the relationships in the network with the greatest advantage. Other industry and fast moving consumer goods industry have considerable ability to build relationships with other components, and are very important for constructing the network. The whole network shows mutualism and synergism based on the ecological relationships between components. In addition the park had a network stability of 0.70, indicating it was in an evolutionary phase, and most material/energy flows are used to improve operational efficiency rather than maintain network stability. This study could provide scientific basis for optimizing industrial park management, thereby reducing environmental pollution and promoting resources conservation.

1. Introduction

Enterprises cannot develop individually. They created various relations based on resource supply, market trade or social connection, and thus formed the industrial systems with the network structure, among which industrial parks are common examples. In the past 30 years, China established more than 2000 industrial parks, which accounted for > 60% of gross national industrial output value and > 50% of GDP (Bao, 2013). In 2014, the GDP growth rate of industrial parks, 29.1%, prominently exceeded that of the national average, 7.4% (CADZ, 2014). Meanwhile, various environmental issues brought by industrial parks have come to the fore (Yune et al., 2016; Liu et al., 2016). It is therefore urgent that industrial metabolic system should be studied deeply and systematically in order to solve the serious industrial pollution and relieve conflicts between regional economic development and resources supply.

In the last 20 years researchers have started considering economic systems as network structures, where independent entities interact with each other (Low, 1997; Håkansson, 1997; Nasini et al., 2015). According to the classical definition, the industrial system can be defined as a network where sectors represent the nodes and the inter-sectoral relationship are the edges (Håkansson,1997). As a social-ecological system, the industrial system has both social and natural attributes. Material and energy flows are fundamental to the discussion of environmental issues in industrial systems (Andersen et al., 2007; Nandy et al., 2015). We can examine the network characteristics using methods from both social network analysis (SNA) and ecological network analysis (ENA).

SNA is a collection of theories and methods that assumes that the behavior of actors (individuals, groups, organizations, etc.) is profoundly affected by their ties to others and the networks in which they are embedded (Furht, 2010). SNA provides both a visual and a mathematical analysis of social relationships (Scott, 2012). Most studies about SNA have been conducted to investigate research relationships and trends (Ghafouri et al., 2014; Patterson et al., 2013), inter-organizational collaborations in the study of mental health systems (Provan and Milward, 1995), tourism research (Erkus-Ozturk and Eraydin, 2010; Scott et al., 2011), sport research (Quatman and

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Chelladurai, 2008; Love and Andrew, 2012), construction project management research (Chinowsky and Taylor, 2012), and industrial ecology research (Kim and Perez, 2015).

Similarly, ENA provides methods for analyzing the interactions between ecosystem's structures and functions, revealing the integrity and complexity of ecosystem behaviors (Jørgensen and Fath, 2006; Fath, 2007). ENA can identify and quantify the direct and indirect interactions within a system, which determines the system's overall status of operation (Patten and Higashi, 1995; Fath and Patten, 1999a,b). It therefore can be used to quantify the path structure of a system (Fath and Patten, 1999a,b; Borrett and Patten, 2003; Fath, 2007), the patterns of the ecological flows (Finn, 1976; Fath and Patten, 1999a,b), and the relationships between the components of the system (Ulanowicz, 2004; Fath, 2007). ENA has been widely applied to study natural ecosystems (Baird et al., 2008; Schaubroeck et al., 2012; Small et al., 2014), and its applications in the metabolism of artificial systems have recently become popular (Zhang and Wang, 2006; Yang et al., 2012), but there are only very few such studies for industrial metabolism in Chinese industrial systems.

There are some studies using SNA to analyze networks for industrial symbiosis systems (Schiller et al., 2014; Zhang et al., 2013; Zhang et al., 2016). In this paper, we performed a study combining SNA and ENA to explore a deep insight into the whole industrial metabolic system, not only the industrial symbiosis system. We try to answer one scientific question: Will the energy and material flows lead to more or less harmonious relationships between the diverse components of the industrial system? The aim of combining SNA and ENA methods in our study is to better understand complex systems of material or energy flows in industrial systems. We attempt to integrate the unified network theory with information about resource flows to understand operation patterns and stability in industrial system networks. Based on this model, we examined the functional and structural traits of the system to provide a theoretical and practical basis for optimizing and managing industrial metabolism of industrial parks. We conducted a case study of Hefei economic and technological development area (HFETA) to display how this model can be used. Section 2 details the method of social network analysis and ecological network analysis, and describes the industrial metabolic network in a typical industrial park-Hefei economic and technological development area. Section 3 presents the results of this case study, including the nodes centralities, the ecological relationships between nodes, and the stability of the network. A discussion of the results is in Section 4, and a main summary of our study is in Section 5.

2. Methodology

2.1. Network modelling of industrial metabolism

In this study we construct a network to describe the industrial metabolism of industrial park. A network is a structure amounting to a set of objects in which some pairs of the objects are in some sense "related". The objects correspond to mathematical abstractions called vertices (also called nodes or points) and each of the related pairs of vertices is called an edge (also called an arc or line) (Balakrishnan, 1997). A industrial metabolic network consists of a set of nodes (industrial and other sectors, defined as n_1, n_2, ……), and links (material/energy flows, defined as l_1, l_2, ……) between nodes. The industrial metabolic system could be portrayed by mimicking natural ecosystems. Firstly, energy and raw materials suppliers such as power plant play the role of producers, secondly, industrial enterprises are the consumers consuming energy and materials, and thirdly the industrial wastes including solid wastes and wastewater enter the decomposers, such as, wastewater treatment plant, or solid waste disposal department. Moreover the waste/byproduct exchanges between industrial sectors are taken into account. The ecological flows between components are divided into several parts: the energy provided from environment to industrial enterprises for industrial production, such as coal, gasoline, diesel fuel, natural gas, electricity; raw materials input, including steel and iron, copper, aluminum, glass, rubber and plastic, etc.; waste/byproducts and residue heat generated from one component are delivered to other components; solid waste and wastewater flow into the waste treatment facilities; and the products flow into the ambient environment. For the convenience of analysis, the material and energy flows in the industrial metabolic system should be converted into a unified unit of measurement—emergy, based on the corresponding transformities (Odum, 1988, 1996; Odum et al., 2000; Brown and Bardi, 2001).

2.2. Social network analysis

SNA, a method that involves descriptive and structure-based analysis, is akin to structural analysis (Scott, 2012). It is significant if one wants to understand the structure of the network in order to obtain insights about how the network "works" and make decisions upon it by either inspecting characteristics of node/link (e.g. centrality) or by investigating metrics at the whole network cohesion (e.g. density) (Sapountzi and Psannis, 2016; Vicari et al., 2014). Seeking to disclose the effects that structural features may have on the actors, social-network analysis uses some metrics, which will be briefly introduced below (Borgatti et al., 2002).

Three actor-level network measures are used to survey key nodes in the network: degree centrality, betweenness centrality and closeness centrality. Degree centrality gauges how connected a node is within a network and is simply measured by counting the number of direct connections each node has with other nodes in the network (Freeman, 1997). An actor with a high degree centrality in the network can communicate directly with many other actors and is highly apparent and prominent (Wasserman and Faust, 1994). Betweenness centrality surveys the number of times that an actor is on the shortest path between other pairs of actors (Freeman, 1997). Hence it symbolizes the ability of some nodes to control (or "broker") the flow of connectivity (information, resources etc.) within the network; or to connect other disconnected nodes. Closeness centrality stresses the distance of a node to all others in the network. The geodesic distance, between pairs of nodes, is the most usually used measure of closeness, which calculates the distance from a node to the others and reflects the availability, health and security of nodes. In network analysis, a node has high closeness centrality if it is connected to the others directly or through a few intermediaries. Nodes with high closeness probably receive resources faster than the others since fewer intermediaries exist among them.

With the help of specialized SNA software packages, social networks has been able to comprehend and depict a broad range of network characteristics. In our study, we use UCINET 6, a procedure developed by Borgatti and his colleagues for the social sciences (Borgatti et al., 2002), to analyze the above metrics. UCINET 6 was picked out from a series of available instruments due to its relative ease-of-use and a wide range of analysis options (Huisman and Van Duijn, 2005). NetDraw software was applied to draw the relationships among the nodes in the network (Borgatti 2002). NetDraw's multidimensional scaling algorithms were used to place actors according to the similarity in their geodesic distances (shortest path lengths) to other actors (Hanneman and Riddle 2005).

2.3. Ecological network analysis

2.3.1. Network utility analysis (NUA)

NUA is applied to assess the mutual relationships between nodes in the industrial metabolic network. The mutual benefit between nodes is assessed through a matrix of mutualism (Fath and Borrett, 2006; Fath, 2007). The direct relationship between components was appraised by a direct utility matrix D, whose element d_{ij} is defined as