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Study on the construction and optimization of a resource-based industrial ecosystem

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ABSTRACT

In China, developing industries based on the regional resource endowment is an important approach to increase GDP in many regions in the past few decades. However, the extensive development pattern results in excessive consumption of natural resources and severe environmental pollution. Therefore, the concept of eco-industry and the theory of system engineering are combined and applied in this study. A new interactive inference method to construct industrial ecosystems is proposed. Firstly, a node information database is set up, and a material group is established according to the resource endowments in the selected region, and the construction rules are defined, such as the termination conditions. Then the structure of the ecosystem is obtained by an interactive inference process between the node information database and all possible combinations in the material group. After the supplement and elimination of nodes, an industrial ecosystem containing 34 nodes is obtained in a certain western region in China. After the industrial ecosystem constructed, a mathematical model is established to optimize the industrial ecosystem, and four aspects of objective functions, including resource efficiency, economic profit, environmental effect and comprehensive benefit, are optimized. After that, four scenarios are analyzed, and the indexes in each scenario are analyzed comparatively. Policy implications for China are proposed.

1. Introduction

The rapid industrial development caused serious damage to the environment and tremendous consumption of resources. Since the 1930s, all types of environmental pollution caused by industrial development constantly occurred worldwide (Lao and Geng, 2003). In China, the severe problems can be reflected in two aspects. First, the water, air and soil are severely contaminated. More than 400 Chinese cities are suffering from water shortages; the water quality of 22.9% of the total river length and 29.2% of the total lake area is grade V or worse, and other pollutant indexes, such as the COD, ammonia nitrogen and permanganate, are serious (The Ministry of Water Resources of the People's Republic of China, 2012). More than 11% of the city's air quality is grade III or worse; the phenomena, such as haze, have received extensive attention (Ministry of Environmental Protection of the People's Republic of China, 2012). In terms of soil, more than 10% of the arable land has been polluted by heavy metals (Xinhua News Agency, 2012). On the other hand, the consumption of natural resources increased dramatically. In 2014, the apparent consumption of oil reached 519 million tons, and the external dependence exceeded 59% (Xinhua News Agency, 2013). China's coal reserves and production are among the highest in the world, but according to the present situation of exploitation, the coal reserve-production ratio is only approximately 40 years, even lower than one-third of the world average (Yu and Kong, 2011). Due to the huge production of cement, limestone reserves are only enough to last for a few decades. Because of the backwardness of production technology and the lack of supervision, there are many small and medium-sized mines that only gather rich ores and discard lean ores. In consequence, residual resources in the lean ore cannot be used, enormous waste has been caused and environmental pollution has been aggravated.

Industry is the main source of environmental pollution; thus, people take the management of industrial systems very seriously. At the beginning, people mainly used the method of end-of-pipe control, but this method could not solve the problem thoroughly, so the concept of cleaner production, which still has bottlenecks, was developed. Finally, the concept of eco-industry was proposed. Eco-industry is an industrial pattern that imitates natural ecological processes to plan an industrial ecosystem; it is planned to maximize the utilization of resources and energy and to minimize the waste emissions to achieve a win–win of economy and environment by linking every production process with material flow, energy flow and information flow.

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The concept of eco-industry is gradually being applied in practice around the world. The most famous eco-industrial park (EIP) is Kalundborg EIP in Denmark (Erkman, 1997), which has provided significant economic benefits and achieved a balance between the economy and the environment. In China, the number of EIPs is developing rapidly. For instance, Shandong Lubei EIP, with phosphoric acid and alkali as its core industries, and Guangxi Guigang EIP, with sugar, alcohol and papermaking as its core industries. These EIPs have formed a thorough material and energy cycle.

Currently, research on eco-industry mainly focuses on four aspects: discipline principle, system mechanism, analytical method and integrated computation. The concept of eco-industry was first proposed in the 1980s; in the following decades, researchers proposed definitions of eco-industry from different perspectives (Harper and Graedel, 2004; Lowe and Evans, 1995). The original concept of eco-industry comes from system engineering and aims to reduce the environmental impact of the production process by the design of industrial systems. Eco-industry is a multi-field discipline, which includes system engineering, mathematics, economics, management and ecology. The ultimate goal is to change the whole industrial system into a closed system, with all of the material and energy cycle inside the system (Cote and Cohen-Rosenthal, 1998; Lowe, 1997; Lowe et al., 1997; Pellenbarg, 2002). The main approaches to constructing stable industrial ecosystems are: improve the production efficiency by using advanced technology, analyze the material flow and energy flow in the system thoroughly and program the system with interdisciplinary knowledge, strengthen the internal flow circulation and develop the extension and coupling of the industrial chain (Allenby, 2006; Andrews, 1999; Carr, 1998; Geng et al., 2007; Heeres et al., 2004; Roberts, 2004; Zhu and Cote, 2004). The industrial ecosystem is complicated, and the stability of the system is important. Agent-based modelling is a common method to analyze the complexity of the system (Axtell et al., 2011). The necessary conditions for stability are discussed mainly based on the network structure and the supply-demand relationship among every unit in the system. Without contracts, fluctuations in the external conditions may result in the collapse of the symbiotic relationship between enterprises; small and medium-size enterprises can unite or innovate at both the enterprise level and policy level to solve this problem (Li and Wang, 2012; Wang and Li, 2006). System innovation, economic benefits, social responsibility, environmental capacity and government orientation actuate the development of the industrial ecosystem (Chai and Huo, 2007), and good interactions between the industrial ecosystem and the government, the public and the market maintain sound development (Shi et al., 2010). Sendra, Gabarrell and Vicent analyzed the material flows in the industrial system in Catalonia and proposed strategies for the enterprises (Sendra et al., 2007). The sulfur flow in Shangyu EIP was analyzed, and 35% of the sulfur was found to be subjected to various forms of loss (Tian et al., 2012). Yang and Hu analyzed the material and energy flows in Lubei EIP and summarized the experience in development (Yang et al., 2004). Index analysis has become a primary method to evaluate EIPs. Resource productivity, energy consumption per unit output value and other indexes are widely used in the planning of EIPs. Several index systems have been set up, such as the production capacity index and network structure index (Dewulf and Langenhove, 2005; Domenech and Davies, 2011; Huppes and Ishikawa, 2005; Maxime et al., 2006; Morioka et al., 2005; Shonnard et al., 2003). Integrated computation is frequently used to analyze and optimize industrial ecosystems. Chae and Kim used the industrial ecosystem in Yeosu area as an example and set up a waste heat comprehensive utilization model, which decreased more than 82% of the waste heat by optimization (Chae et al., 2010). Boix and Montastruc set up a mixed integer linear programming model to analyze the water network in an EIP (Boix et al., 2012). Aviso and Tan set up a double layer fuzzy programming model to balance the relation between a building wastewater reuse network and purchasing fresh water (Aviso et al., 2010).

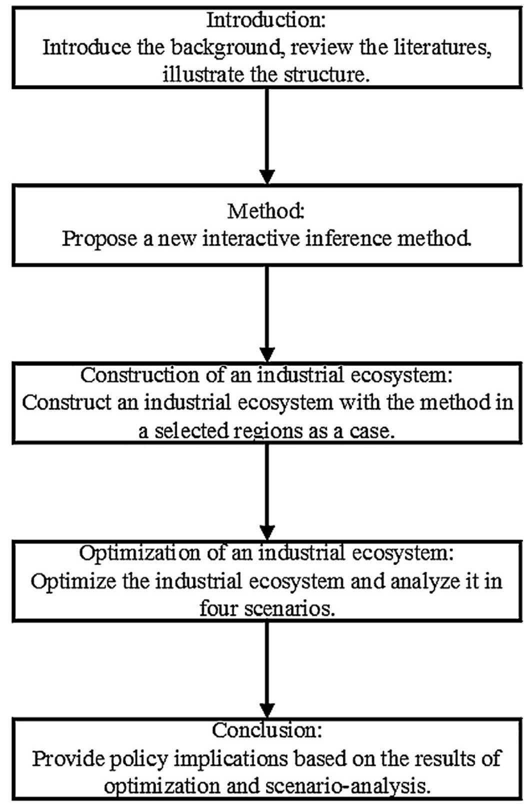

Fig. 1. The structure of the paper.

In this study, a new interactive inference method to construct industrial ecosystems is proposed and applied to construct an industrial ecosystem in the selected region. Optimization and scenario analysis are performed to study this industrial ecosystem. The structure of this study is shown in Fig. 1.

2. Interactive inference method

The construction of industrial ecosystems is based on experience and subjective judgment and is accomplished by literature research and expert discussion, which has poor repeatability and cannot achieve the global optimal value because of its randomness. Therefore, an interactive inference method is proposed in this study. This method includes three steps: set up node information database, establish material group and interactive inference process. The overall method framework is shown in Fig. 2.

2.1. Set up node information database

First, investigate the resource endowment of the selected region and the industrial types that will be developed in priority according to the national and regional policies. Then, list all of the relevant industrial processes as optional nodes and gather the information of nodes into the database, such as node classification, input materials, and output materials.

In this study, all nodes are classified as four categories:

(a) Enrichment and separation: The nodes that extract or purify the important components of the resources, and most of these nodes are preparation processes. For example, the coal preparation and the concentration of salt lake brine.