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Optimization of Ecological Industrial Chain design based on reliability theory – a case study

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ABSTRACT

The stability requirement for node enterprises within Ecological Industrial Chain (*EIC*) has a high degree of functional similarity with the reliability of engineering components. Thus, a methodology for *EIC* design optimization is established in this study based on the reliability theory. Results showed that series structure had weaker stability than parallel structure. The stability of entire system is reduced with the increase of the number of series, and node enterprises with smaller reliability showed greater contribution to the system stability. On contrary, for the parallel structure, node enterprises with higher reliability had greater contribution to the system stability. To improve the system stability, it is crucial to maintain the weak parts of system or to introduce an appropriate number of “spare parts”, i.e. to adopt parallel structure and reduce the number of enterprises series. For the parallel structure, priority must be given to those enterprises with higher reliability. Similarly, other constraints (e.g. economic costs and resource constraints) should also be taken into consideration. The redundant design of *EIC* becomes nonlinear planning decision problems. Novel nonlinear programming model for redundant *EIC* design is proposed in this study based on the reliability theory, and is effectively verified by means of MATLAB software programming and empirical analysis. Results provide a theoretical basis and practical reference for decision making process of optimizing the design and management of *EIC*.

1. Introduction

Since the industrial revolution, social economy has gained a rapid development with the assistance of advanced science and technology. There has been a growing public concern on the massive demand of natural resources as well as environmental impacts associated with such rapid economic development (Geiser, 2001; Wang et al., 2014). In late 1980s, the concept of industrial ecology was proposed. Since then, the discipline of industrial ecology was gradually emerging (Frosch and Gallopoulos, 1989; Jouni, 2001). The principles of industrial ecology are substantially different from those of the traditional industry development models. The end treatment of open loop becomes the whole process control of closed-loop, in order to resolve the conflicts amongst economy, society and environment (Chu and Zhou, 2003). This theory is well recognized, and the Eco-Industrial Parks (*EIPs*) have been developed. *EIPs* are a new type of industrial park, which is based on the concepts of circular economy, industrial ecology and cleaner production. The cycle mode of “producer–consumer–decomposer” is established by means of forming the industrial symbiosis system, sharing resources and exchanging by-products between various enterprises (Ministry of Environmental Protection of China, 2012). The natural ecological laws are applied in ecological industry chain (*EIC*) to establish the symbiotic relationship by linking waste and by-products between enterprises in the industrial park. China is facing great challenge in the fields of energy, resource and environment (Mu et al., 2015; Yuan et al., 2015). *EIC* helps to achieve the recycle of resources and energy, which consequently leads to the maximum benefits of economy, environment and society of the industrial ecosystem (Wang et al., 2003). Planning and construction of *EIPs* started in 2000 in China (Jin et al., 2003). At present, 51 state-level *EIPs* have been built, and

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construction of 82 more national *EIPs* are in progress in China (Ministry of Environmental Protection of China, 2015). *EIPs* have become an effective way for China to transform the economic development mode and adjust the industrial structure towards sustainable development. However, the development of national *EIPs* in China is obviously lagging behind that of its economic development while the operation of national or provincial *EIPs* are unsatisfactory (Chang et al., 2015; Zhu et al., 2015). This is arguably due to various issues associated with the process of actively planning new parks or promoting the ecological transformation of existing industrial parks. During the early stage of *EIPs* development in China, researches mainly focuses on the concepts, theories and lessons learnt from experiences of overseas (Xue et al., 2003). Recent years saw studies extended to the theory of material metabolism, cleaner production, and eco-economic efficiency (Yang and Feng, 2008). Compared with developed countries, the researches in China are limited in the contents and methods of *EIPs*. There is lack of theoretical support for the development of *EIPs* in China (Mao et al., 2010). In general, the theoretical research of *EIPs* lagged far behind of practice in China. As a result, there is lack of theoretical guidance for *EIPs* development. Many issues emerge, e.g. lack of coordination between enterprises in the park, low symbiotic efficiency, and unstable *EIC*. A big gap exists between the current practices and ideal *EIPs* (Wang and Wang, 2010). Therefore, attention should be paid to the stability issues of *EIPs*.

Extensive literature review showed that instability presents a significant challenge in eco-industrial systems all over the world, such as United States, Denmark, Finland, Italy, and China. Even those *EIPs* which were called "model" have suffered from various degrees of instability, such as Denmark's Kalundborg (Baldwin and Ridway, 2004), Lubei and Guitang of China (Cai et al., 2007). Broken link occurred in *EIC* is one of main reasons for the instability of *EIPs*. As a result, the optimization of ecological chain and the stability of *EIPs* have attracted wide attention from scholars all over the world. Some researchers examined the stability of *EIC* according to natural ecology theory (Raymond and Hall, 1995; Baldwin and Ridway, 2004; Raffaella et al., 2012). However, most of these methods are qualitative, lack of quantitative measures. Similarly, methodology is a popular topic where some researches attempted to solve the problem of *EIC* optimization by means of modeling (Ostrom, 2007; Deutz and Lyons, 2008). For example, Ma et al. (2006) employed the Simulink toolbox to establish the industry ecosystem model, consequently put forward the impact factor method for the analysis and improvement of flexibility. Li et al. (2009) utilized the linear programming model to optimize of the recycling economy industrial chain of the coal industry. Chae et al. (2010) established the *EIC* optimization model for harvesting the waste heat. Cimren et al. (2011) proposed *EIC* optimization design by establishing the mixed integer programming model of byproduct stream. Taskhiri et al. (2011) examined the water reuse issues by setting up a fuzzy optimization model. Li et al. (2011) established a robust optimization model for the development of *EIC* so that maximum profits can be achieved.

In summary, the current research efforts for the optimization of *EIC* are based on the improvement of the economic benefits, system stability, material flow and energy flow of system. These previous studies provided useful insights that help to understand the dynamics of *EIC* while the framework has been developed to specify basic relationships between variables. The theory of natural ecology is mostly commonly adopted in *EIC* related studies, since the development of industrial ecology is based on imitation associated with natural ecosystems (Raymond and Hall, 1995; Raffaella et al., 2012). Vast majority of these studies are qualitative oriented under the principles of imitation ecology. Further research is required to define variables more precisely, and consequently quantify the relationships among them (Boons et al., 2011). The system reliability theory provides an innovative method for the *EIC* optimization. System reliability theory is conventional research methods of traditional engineering. This theory has been successfully employed in various fields of research such as urban transportation (Albert et al., 1999; Lida, 1999; Strogatz, 2001), power grid design (Billinton, 1969), software design (Scheneeweiss and Gmbh, 2001), and logistics design (Yin and Leda, 2001). Similarly, some studies have been undertaken to analyze the structural model and the optimization design of the supply chain (Chen and Hu, 2006; Wang and Fan, 2009; Chen et al., 2009; Zhang and Zhang, 2006) based on the reliability theory. However, to date, the reliability theory has not been employed to study the stability of *EIC*. Therefore, the paper aims to apply the analytical method of reliability theory to investigate the stability of *EIC*. This offers a new research perspective for the optimization design of *EIC*.

2. Methodology

The optimization procedure of *EIC* based on the reliability theory mainly includes two aspects, namely "Timely fill" concept and nonlinear programming decision (see Fig. 1). "Timely fill" concept is the foundation of nonlinear programming decision. It is well recognized that the series structure has weaker stability than the parallel structure. To improve the stability of *EIC*, it is imperative to maintain the key parts of system, i.e. node enterprises with smaller reliability for the series structure; node enterprises with higher reliability for the parallel structure. Alternatively, an appropriate number of "spare parts" should be introduced to the parallel structure as much as possible. These design concepts and methods should take other constraints into consideration such as the costs of economy, environment, and resources. As a result, the redundant design of *EIC* becomes a nonlinear planning decision problem. Based on reliability theory, a novel nonlinear programming model is proposed for the redundant *EIC* design.

2.1. Feasibility analysis of reliability theory applied to ecological industries

The stability of supply chain has drawn a growing concern. As a result, the reliability theory has been widely employed in various fields of research such as social sciences and engineering (Nelson, 1982). It is well recognized that supply chain is a dynamic and complex system, and its normal function can be affected by a large number of uncertainties. If error occurs to any link, it will spread to other sectors and even the entire supply chain (Chen et al., 2004; Thomas, 2002; Liu et al., 2003).

(1) Functional similarity

Reliability is the ability of product or system to work. It is an index to measure quality, so it is determined by the quality of each component. Stability is an index to measure the ability of *EIPs* to resist interference for normal operation. The stability of entire system is directly influenced by stability of each node enterprise. From the system perspective, the node enterprises in *EIPs* are similar to engineering components in the field of engineering. Both of them could be used to measure the ability of system to complete the task. Therefore, the functional analysis of node enterprises and engineering components shows a high degree of similarity.

(2) Concept of sustainable development

Sustainable development is defined as development model that fulfills the needs of the current generation, and does not affect the