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Uncovering key factors influencing one industrial park's sustainability: a combined evaluation method of emergy analysis and index decomposition analysis

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A B S T R A C T

Industrial parks have been adopted as one way to promote industrial development in China since the early 1980s. However, most of current performance evaluation indicators highlight the maximization of industrial yield, leading to both ecological degradation and environmental pollution due to intensive industrial activities. Therefore, it is critical to develop appropriate evaluation indicators so that industrial parks can move toward sustainable development. This paper aims to fill such a research gap by developing innovative emergy indicators. Kaya formula and index decomposition analysis (IDA) were integrated together in order to quantify the key factors influencing the sustainability of an industrial park. Tianjin Economic Development area (TEDA), the largest industrial park in terms of its economic scale in China, was chosen as one case study area for testing the related methods. The results show that during the period of 2006–2010 the sustainability of TEDA experienced a declining trend. From the Kaya formula and IDA analysis, indicators on economic efficiency of process, economic return on investment, renewable empower density and nonrenewable empower density were calculated. Such research findings provide valuable policy insights to the industrial park managers so that they can prepare appropriate development strategies for achieving sustainable development of their industrial parks by considering the local realities.

1. Introduction

The United Nations Industrial Development Organization (UNIDO, 1997) defined an industrial park as a tract of land that is developed and subdivided into plots according to a comprehensive plan that makes provision for roads, transport and public utilities for the use of a group of firms and industrial business oriented activities carried out in the park. Generally, government-developed industrial parks are characterized by a government intervention mode, which may involve comprehensive legislation, establishing organizations and institutes, offering a competitive production environment and management services, creating clusters that integrate each other, etc (Lin and Ben, 2009). In China, the central government planned and developed economic and technological development zones as one way to stimulate economic development nationwide since the 1980s (Geng and Zhao, 2009). Through nearly 30 years' development, there are 215 industrial parks at the national level and over 1000 industrial parks at the provincial level (Geng et al., 2014).

However, rapid development of these industrial parks also generated several problems, such as excessive resource consumption and increasing environmental pollution caused by industrial activities in the industrial parks. In order to respond these problems and boost the sustainable development of industrial parks, the

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Ministry of Environmental Protection (MEP, the former State Environmental Protection Administration) initiated eco-industrial parks (EIP) project in 2001. By the end of 2014, 85 eco-industrial park projects had been approved by MEP, among which 23 EIPs had met with all the criteria of national EIP released in 2007 (Geng et al., 2009). Meanwhile, the National Development and Reform Commission (NDRC) released national circular economy industrial park indicators in 2007 in order to further promote industrial symbiosis at the industrial park level, leading to 33 industrial parks approved as national circular economy demonstration industrial parks (Geng et al., 2012). Moreover, Ministry of Industry and Information Technology (MIIT) released national low-carbon industrial park indicators in 2013 in order to address the increasing concerns on climate change (Geng et al., 2014). However, all of these indicators have certain problems and cannot really promote the sustainable development of industrial parks. Typical issues include the lack of absolute emission reduction indicators, the lack of industrial symbiosis indicators, the lack of consideration of China's imbalanced development and the lack of preventative indicators, etc (Geng et al., 2009, 2012, 2013, 2014; Li et al., 2015). Particularly, industrial park development cannot be achieved without the provision of ecosystem service. But such a contribution from natural ecosystem has not been recognized by any published literatures. Consequently, it is crucial to develop a new evaluation method on the sustainable level of one industrial park so that the above issues can be addressed in a scientific way.

Sustainability is a multi-dimensional concept, in which economic, social and environmental aspects must be equally considered and integrated (Pope et al., 2004). An appropriate tool for a multi-dimensional representation must be a suitable set of indicators developed as an integral part of an assessment methodology to be used for the purposes of measuring sustainability (Ness et al., 2007; Moffat et al., 2001; Boggia and Cortina, 2010). In recent years, the development of sustainability evaluation methods to monitor industrial park performances made great progresses. There are some effective methods for evaluating the overall eco-efficiency of an industrial park, such as life cycle analysis (LCA), material flow analysis (MFA), ecological footprint (EF), emergy analysis and the system of environmental economic accounting (SEEA), among others. For instance, Wesley (2011) analyzed the waste emission during mineral ore exploitation in Peru based on LCA. Zhao et al. (2005) applied ecological footprint and carrying capacity methods to uncover the problems of sustainable development for an industrial park in northeastern region of China. Zhang (2010) evaluated the eco-efficiency optimization of an industrial park by means of MFA. Each method has certain advantages and disadvantages. Among them, emergy analysis receives more attention and has been gradually applied. In this regard, Wang et al. (2005) employed emergy analysis to evaluate a power plant based industrial park in Shanxi province. Taskhiri et al. (2011) studied water reuse in an eco-industrial park by applying emergy-based fuzzy optimization approach. Further, Geng and his colleagues presented their emergy analysis approach on evaluating the overall eco-efficiency of an industrial park (Geng et al., 2010) and detailed how to evaluate industrial symbiosis by employing emergy analysis (Geng et al., 2014), in which they addressed the main problems existed in the current official EIP indicators.

Nevertheless, in order to promote sustainable development of industrial parks, it is of vital importance to know what factors affect the sustainable development of an industrial park so that appropriate development strategies can be raised. However, to the best of our knowledge, no thorough studies focus on identifying key factors and quantitatively calculating their impacts on the sustainability of industrial parks. Under such a circumstance, the objective of this study is to analyze the key factors affecting the sustainability of an industrial park in China by combining the emergy and index decomposition analysis (IDA) approaches. A case study approach is employed in order to test the feasibility of such an approach. The case study park is Tianjin Economic Development Area (TEDA), the largest industrial park in China according to its economic scale. The whole paper is organized as below: after this introduction section, Section 2 presents research methods, including the accounting procedures, data collection and treatment and a short description of the case study park. Research results and policy implications are discussed in Section 3. Finally, Section 4 summarizes the research conclusions.

2. Methods

2.1. Emergy indicators

Emergy, specifically solar emergy, is "the available energy of one kind (usually solar) used up directly and indirectly to generate a service or product" (Odum, 1996). This concept was first proposed in the late 1980s. The emergy accounting approach, as a system method, can be used to evaluate the interplay of industry and environment. It deals with an integrated evaluation of ecological-economic systems, and was successfully applied to systems at different scales (Brown and Ulgiati, 2004). In recent years, emergy analysis was applied to individual industrial systems and industrial parks. Geng et al. (2010) applied emergy analysis to evaluate Dalian Economic Development Zone, especially with a detailed method of accounting transformities of various wastes by considering their physical and chemical properties. Further, Geng et al. (2014) and Liu et al. (2015a) evaluated the industrial symbiosis performance at industrial park level by employing emergy-based analysis. Zhang et al. (2011) applied emergy analysis to evaluate the impact of waste recovery and exchange on the sustainability of sulfuric acid and titanium dioxide production in the Chinese industrial systems and found that waste exchange improved the sustainability of the interacting systems. Liu et al. (2014) applied the emergy method at the Shenyang economic development area to uncover the efficiencies among different industrial clusters. Liu et al. (2015b) further developed an emergy-ecological footprint hybrid model to study on both the energy metabolism of industrial parks' activities and the ecological capacity of the local areas at Shenyang economic development area and Fuzhou Qingkou investment zone.

Generally, emergy analysis indicators can be categorized as structural indicators, functional indicators and systemic indicators. Structural indicators, including the emergy amounts of renewable resources (R), non-renewable (N), and imported resources (F), as well as the emergy supporting labor and services ($L\&S$) converge to the total emergy (U, the production cost of the yield), expressed as ($U = R + N + \mathrm{F}$), can be used to reflect the components of one industrial ecosystem so that the rational structure of such a system can be recognized. Functional indicators can be applied to demonstrate the targeted system's functions, such as the emergy yield ratio (EYR), the environmental loading ratio (ELR), the emergy exchange ratio (EER), the emergy investment ratio (EIR), the emergy self-sufficient ratio (ESR), among others. Moreover, a systemic indicator, namely the Emergy Sustainability Index, provides an assessment of the overall economic (self-reliance) and environmental performance of the system. In this study, we apply EYR (Equation (1)), ELR (Equation (2)) and ESI (Equation (3)) to evaluate the overall eco-efficiency of an industrial park. All of these indicators (including U and emergy per unit values ($UEVs$)) can be calculated with and without adding the emergy value of Labor and Services ($L\&S$). Since $L\&S$ are always purchased from outside process, they can be considered as an integral part of imported resource (F). For the sake of simplicity, we assume F as the emergy