Stability Assessment of an Eco-Industrial System Based on Entropy Analysis Method

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Abstract: Eco-industrial system is a typical kind of dissipative structure system, and its stability is influenced by industrial metabolism of materials as well as the degree of industrial symbiosis. Based on entropy analysis method, function entropy and structure entropy of the eco-industrial system are put forward to express the chaos of an eco-industrial system, and to evaluate the system stability and evolution direction. This method is implemented on a case study of Xinfa industrial park in China. According to the results, the function entropy showed a trend of decline. Improving of water reuse efficiency and material use efficiency was the main cause, while energy use efficiency constrained the development of Xinfa eco-industrial system. The addition of new node enterprises resulted in an increase of the structure entropy, and at the same time improved the utilization efficiency of upstream enterprises by coupling. Industrial symbiosis and cleaner production were the main ways for Xinfa industrial park to enhance its stability. Entropy analysis method offers an evaluation method with comprehensive consideration for quantifying the stability of eco-industrial system, and lays a ground work for conducting evolution of industrial clusters.

1. Introduction

Industrial ecology has been a study subject since 1980s for minimizing pollutants or wastes and maximizing utilization efficiencies of materials and energy [1-3]. Absorbing from experience of the Kalundborg Symbiosis in Denmark, many countries have also made progress in building thousands of eco-industrial parks to mitigate environmental risks and achieve economic benefits, such as the United States, Japan, and some developing countries [4, 5]. Eco-industrial systems have brought significant benefits for the local economy and environment, while problems are also surfacing through the years. To remain stable is a basic condition for well operation of an eco-industrial system.

Many researchers have paid attention to studies on the stability of eco-industrial systems. The views of research include environmental economics, structural analysis, and system optimization. Wang et al. [6] defined two parameters of symbiosis profit and symbiosis cost to analyze the stability of the IS system. Ashton [7] provided a framework to assess the structure, function, and evolution of a regional industrial ecosystem. Some researchers analyzed the importance of core node enterprises in the eco-industrial system, and found that the removal or disruption of critical nodes would greatly impact the stability and systematic efficiency [5, 8-10]. In system optimization perspective, Zhou et al. [11] used scenario optimization and linear programming methods to analyze the behaviors and optimal industrial structures of a coal-chemical eco-industrial system.

Eco-industrial system is a typical kind of dissipative structure system, and the order degree of system
structure can be expressed by entropy [12]. The changes of system entropy can reflect the stability of eco-industrial system, but little research has been done from entropy analysis perspective. Lowenthal and Kastenberg [13] first took entropy into consideration when analyzing the industrial ecology of energy system. Xu et al. [12] proposed the concept of industrial ecological entropy to explore the stability and evolution mechanism of eco-industrial system, considering recycle and reuse rate of materials as the only measurement. However, energy flows and system structure are also important factors in maintaining stability of eco-industrial system [14, 15]. Based on entropy theory, Wang et al. [16] used relational entropy model and structural entropy model to theoretically calculate the stability of ecological industry chain, and found that the system stability can be enhanced by developing of the supplemented chain around the core enterprise.

The literature review shows that (1) helpful attempts have been made by researchers to study the stability of eco-industrial system, especially in economics and structural perspective; (2) factors are not synthetically considered, and so far no unified standards have been provided to evaluate the system stability; (3) entropy as an effective indicator to assess system stability, has not been well considered by previous studies; (4) empirical studies remain scarce on the stability research in eco-industrial system.

With such circumstance, the present study aims to provide an entropy-based method to evaluate the stability of an eco-industrial system. A case study of Xinfa eco-industrial park in China is analyzed based on data from 2006 to 2014. This study also discussed ways to improve system stability.

2. Methods

2.1 Entropy and its description in eco-industrial system

As a measure of disorder, entropy has been widely used to describe the system state [17, 18]. The lower entropy production is, the more stable the system will be. In an eco-industrial system, enterprises and their connections make up the IS network. Each enterprise is presented by a node. Both the operation condition and chaining intensity of enterprises will influence the system stability.

The research boundary and main factors are defined and presented in Figure 1. Water reuse efficiency, material use efficiency, energy use efficiency, and inter-node links are considered as main factors that influence system stability. The stability of the eco-industrial system is measured by employing the concept of entropy from both functional and structural aspects. Function entropy reflects the utilization level of materials and energy, and structure entropy reflects the organization degree of system structure. These two indicators are used to make a concerted evaluation on the stability of an eco-industrial system. Increasing and decreasing of entropy indicate the fluctuation of system stability.

![Figure 1. The research boundary of the eco-industrial system](image_url)

**Figure 1.** The research boundary of the eco-industrial system

2.2 Function entropy

Function entropy refers to a state function of an eco-industrial system, which depends on industrial metabolism level of each enterprise. Assuming within the enterprise \( i \) \((1 \leq i \leq n)\), there are \( j \) \((1 \leq j \leq k)\) factors that affect system stability. In this research, three factors including water reuse efficiency, material use efficiency and energy use efficiency are considered: (1) water reuse efficiency \( R_{water} \),
which is the ratio of reused water to the total water consumption in a certain time, specific calculation of \( R_i(water) \) is represented in Equation 1; (2) material use efficiency \( (R_i(material)) \), which is the ratio of effectively used material to the total material consumption, specific calculation of \( R_i(material) \) is represented in Equation 2; and (3) energy use efficiency \( (R_i(energy)) \), which is the ratio of effective energy to the total energy consumption, specific calculation of \( R_i(energy) \) is represented in Equation 3. These three indices can indirectly reflect the discharge of wastes and dissipation of energy.

\[
R_i(water) = \frac{V_r}{(V_r + V)} \times 100\% \quad (1)
\]

where \( V_r \) is the volume of reused water, and \( V \) is the volume of fresh water consumption.

\[
R_i(material) = \frac{(P + \sum[B_i])}{\sum[f_{io}]} \times 100\% \quad (2)
\]

where \( P \) is the production volume of enterprise \( i \), \( \sum[B_i] \) is the yield of by-products, and \( \sum[f_{io}] \) is the total material inflows (excluding water).

\[
R_i(energy) = \frac{D_o}{D_i} \times 100\% \quad (3)
\]

where \( D_o \) is the theoretical energy consumption per unit product, and \( D_i \) is the comprehensive energy consumption per unit product.

Function entropy of the eco-industrial system in a certain year \( t \) is defined as Equation 4.

\[
H(t) = \sum_{i,j=1}^{n} \begin{cases} 
2/e + R_i(j) \ln R_i(j), & 0 < R_i(j) \leq 1/e \\
-R_i(j) \ln R_i(j), & 1/e < R_i(j) \leq 1 
\end{cases} 
\]

in which \( U \) is a set of factors that affect system stability, and \( U = \{water, material, energy\} \). \( H(t) \) is a decreasing function and segmented at the inflection point \( R_i(j) = 1/e \). It is observed that function entropy reaches the minimum when \( R_i(j) \) is at high level (close to 1). Under this condition, water, materials, and energy are effectively utilized within the eco-industrial system. Wastewater is reused directly or after advanced treatment; solid waste is used by venous industry enterprises as raw materials; energy is cascading utilized through reusing of energy-carrying materials. Less discharge of wastes implies less entropy production. And when \( R_i(j) \) is close to 0, all inputs are transformed into wastes. Function entropy increases rapidly and the system becomes paralyzed.

When comparing the function entropies from the dimension of time, e.g. \( H(t+1) \) and \( H(t) \), change of function entropy reflects the evolution direction of the eco-industrial system. The change of function entropy is defined as Equation 5. \( \Delta H < 0 \), which means the function entropy decreases over time, represents that the eco-industrial system is in stable progress, and vice versa.

\[
\Delta H = H(t+1) - H(t) \quad (5)
\]

2.3 Structure entropy

Structure entropy is used to reflect the order degree of the system structure, which is affected by the intensity of inter-node links. Industrial symbiosis is a typical character in an eco-industrial system. Products, by-products, solid waste, reclaimed water, and even waste heat of an enterprise can be utilized in another enterprise. These relations comprise the symbiotic structure of the eco-industrial system. Structure entropy takes the chaining intensity of each node as the independent variable. For node \( i \), the chaining intensity \( (I(i)) \) is calculated by Equation 6.

\[
I(i) = \frac{L(i)}{\sum_{i=1}^{n} L(i)} 
\]

where \( L(i) \) is the number of links for node \( i \).

The structure entropy of the eco-industrial system is calculated by Eq. 7. Similar to the function entropy, \( \Delta S \) also reflects the evolution of system structure.
\[ S(t) = -\sum_{i=2}^{n} I(i) \ln I(i) \] (7)

2.4 Case study

2.4.1 Overview of Xinfa eco-industrial park. Xinfa eco-industrial park is an under construction eco-industrial system. After ten years of development, this park has evolved into an IS network covering cogeneration, aluminum-electricity joint operation, aluminum deep processing, and chemical processing industries. The IS system expansion of Xinfa industrial park is shown in Figure 2. The numbers are given according to the industrial chains and addition sequence of enterprises. In 2006, there were only seven key enterprises in the industrial park. In order to build an IS network with high-efficiency utilization of materials and strong environmental awareness, Xinfa Group introduced six enterprises to enrich the industrial chains in 2008. In 2011, another four enterprises were introduced into Xinfa industrial park, including PVC deep processing plant, scrap aluminum refining plant, eco-cement plant, and fertilizer plant. Newly added nodes extended the industrial chains and made the eco-industrial system tend to be mature.

![Figure 2. IS network and system expansion of Xinfa eco-industrial park](image)

2.4.2 Data acquisition. Data from 2006 to 2014 were collected to analyze the stability of the Xinfa eco-industrial system. Field investigation was the main method of data acquisition. Questionnaires, annual reports on material consumption, energy consumption, and production, as well as cleaner production auditing reports were gathered to ensure the data integrity. Interviews with experts and stakeholders were also conducted to grasp the data accuracy. Data of 2006, 2008, 2011, and 2014 were selected and analyzed to study the stability of the Xinfa eco-industrial system. These four years could reflect the initial, developing, mature, and stable stages of the system, respectively.

3. Results

3.1 Function entropy of Xinfa eco-industrial system

Figure 3 shows the changes of function entropy from 2006 to 2014. Function entropy showed a trend of decline except for the year 2008 and 2011. In 2006, Xinfa eco-industrial system was in an early stage of construction. Low number of nodes made the function entropy stayed at a low value. With the addition of six new nodes in 2008, the IS was enriched, but the industrial metabolism remained at a low level. Discharging of waste water, stockpiling of solid waste, and dissipation of heat energy resulted in a sharp increase of function entropy. In 2011, four more nodes were added to the Xinfa industrial park. New nodes could improve the material use efficiency of upstream enterprises by consuming their wastes, and increased productivity of node enterprises cut wastage of materials. The improvement of utilization efficiency led to a decrease of function entropy, which indicated that the stability of the Xinfa eco-industrial system was enhanced in recent years.
The constituent of function entropy for each node in Xinfa eco-industrial system is shown in Figure 4. There were only seven node enterprises in 2006, however, the constituent of function entropy for each node was higher than that in other years. In terms of a single node, node 1, 2, 3, 5, and 7 were prominent compared to other nodes. The corresponding enterprises of cogeneration plant, aluminum plant, electrolytic aluminum plant, lime plant, and carbon plant were all plants with primary processing of materials. The constituent of function entropies for node 4 and node 14 were lower than others. These two nodes both belonged to deep processing enterprises which were with higher utilization efficiency of materials and energy. From 2006 to 2014, the constituent of function entropy for each node presented a trend of decrease. This phenomenon indicated that with the development of Xinfa eco-industrial system, enterprises improved their industrial metabolisms of materials and energy.

Energy use efficiency was the most significant factor that influenced function entropy of the Xinfa eco-industrial park. As shown in Figure 5, the contributions of water and material have been depleted since 2008. Energy use efficiency towards becoming a restraining factor for the system to obtain lower function entropy. This phenomenon demonstrated that, in order to avoid sharp fluctuations of function entropy and maintain stability, the eco-industrial system should enhance its requirements on the level of industrial metabolism in controlling new enterprises access.
3.2 Structure entropy of Xinfa eco-industrial system

Structure entropy of Xinfa eco-industrial system in 2014 was 2.61, which was higher than that in 2006 and 2008. Figure 6 shows the structure entropy of Xinfa eco-industrial system from 2006 to 2014. The structure entropy increased with the addition of node enterprises, while the average structure entropy of each node decreased. As described in Figure 2, node 1 owned the most connections with other nodes. Being one of the core enterprises of Xinfa eco-industrial system, the cogeneration plant provided other plants with energy and steam, and at the same time supplied materials to node 12 and node 13. Node 2, 3, and 9 also owned many linkages with other nodes. These linkages made it more efficient for utilizing of material and energy. The highly connected nodes maintained the structure entropy of Xinfa eco-industrial system at a low value, and kept a strong ability of anti risk.

![Figure 6. Structure entropy of Xinfa eco-industrial system](image_url)

4. Discussion

4.1 Ways to improve system stability

4.1.1 Enrich the IS network. The enhancement of system stability has benefited greatly from the accession of venous industries including node 11, 12, 13, 15, 16, and 17. They coupled with the core industrial chain and enriched the IS network. Meanwhile, venous industries reused most of the wastes generated by the cogeneration plant and the aluminum plant, and contributed to the overall improvement of material utilization efficiency in Xinfa eco-industrial system. Besides, from the perspective of system structure, newly added nodes improved the structural flexibility, and enhanced the system adaptability.

4.1.2 Raise cleaner production level of enterprises. The advancement of cleaner production level in node enterprises was also one of the dominant factors in decreasing function entropy of the system. Embodiments included the increasing of water efficiency, the upgrading of process technology, and the improvement of management. Therefore, under the circumstance that the system structure maintained unchanged, improving the cleaner production level can minimize the emissions of wastes, and enhance the function stability of Xinfa eco-industrial system. In addition, improving research input on products made of renewable resources was necessary. Lack of quality standard of renewable products limited the recognition and consumption in the market.

4.2 Limitations and future research directions

In this study, the research scope was confined to the internal factors. In addition to functional and structural ones, there are also many external factors that would have effects, such as reliability of raw material supply, fluctuation of the market, implementation of environmental policies and so on. These factors tend to be crucial for the stability of the eco-industrial system, but are difficult to predict or quantify. Another limitation lies in the difficulty to access data of other eco-industrial systems. The calculation of function entropy needs large amount of basic data on single enterprises as well as the
overall system. Therefore, in future research, the authors will seek to collect the data of other eco-industrial systems, so as to scientifically determine stability standards for eco-industrial systems.

5. Conclusions
This study applied entropy analysis method to evaluate the stability of an eco-industrial system. Function entropy and structure entropy were proposed respectively to analyze the operation status and system structure. Xinfa eco-industrial park, as an eco-industrial system that has been developed for the past ten years, was selected as a case study. The results show that function entropy of the Xinfa eco-industrial system has shown a downward trend since 2008, which indicates the improving stability of the system. The main cause was the lifting of water reuse efficiency and material use efficiency. While energy use efficiency constrained further decreasing of function entropy. Structure entropy of the Xinfa eco-industrial system had a slight increase due to the addition of new enterprises.

Changes of function entropy and structure entropy can reflect the annual variation tendency of stability in an eco-industrial system, and help to make the judgment of system development state. The results of this work can serve as references for decision makers in planning the future of Xinfa eco-industrial system. The entropy analysis method provided in this research can also be applied to evaluate the stability of other eco-industrial systems.

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