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# Integrated Stability Analysis of Industrial Symbiosis Networks

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The concept of industrial symbiosis network (ISN) has progressed in recent years. There are lots of stability problems in the eco-industrial practices. A major challenge in stability analysis is to effectively deal with different kinds of exogenous and endogenous attributes. To promote and manage stability of ISN, this work focuses on the methodology of integrated stability analysis based on information fusion technology. This work provides an introduction of classification and characterization for stability attributes. Then, we classified into a total of 9 kinds of attributes according to the exogenous and endogenous contribution. Two-level information fusion model is proposed. A real-world ISN as a case study is presented. We consider this ISN with five plants (i.e. a combined heat and power plant, a pulp mill, a paper mill, an alkali recovery plant, and a cement plant). We use the integrated stability analysis to evaluate the stability performance of this ISN case.

## 1. Introduction

Industrial ecology (IE) considers principles of biological ecosystems when designing and redesigning industrial systems to create more efficient interactions both within industrial systems and between industrial natural systems (Lombardi and Laybourn, 2012). Industrial Symbiosis (IS) is about identifying and using such synergies and linkages between members. It engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by products (Wang et al., 2017). An IS can also involve sharing assets, logistics and knowledge.

A central aspect of IS is a systems approach: entire systems (e.g. firm and process networks) are examined in addition to individual system components. This way problem transfer between different system components can better be avoided. In each IS system, it must be determined who collects data, who maintains it, and who owns it. Focusing on collection, three choices have been identified: government mandated surrender of data; facilitators collecting data directly from companies; and companies entering data into a common database themselves. A framework which embraces IE and IS integration within the context of supply chain environmental sustainability development is desirable (Leigh and Li, 2015).

There is increasing evidence that throughout the world, firms, governmental agencies and non-governmental organizations are seeking to stimulate industrial symbiosis. This concept and its application have also been the topic of extensive research. But Boons et al. propose the framework conceptualizes industrial symbiosis as a process at two levels: (1) the level of the regional industrial system, and (2) the societal level where the concept and routines of industrial symbiosis diffuse. They link the dynamics at these levels to changes in ecological impact and increase in institutional capacity. Boons et al. conclude with a research agenda based on the variables and their basic relationships specified in the framework. The main line of research they propose is to systematically investigate how institutional capacity evolves over time in regional industrial systems and how it affects the ecological impact of such systems (Boons et al., 2011). Mirata and Emtairah (2005) discuss industrial symbiosis networks from the perspective of innovation studies. They argue that industrial symbiosis networks can contribute to fostering environmental innovation at the local or regional level by stimulating the collective definition of problems, providing inter-sectoral interfaces, and promoting a culture of inter-organisational collaboration oriented towards environmental challenges. Lambert and Boons (2002) describe the sustainable development (including industrial symbiosis) of industrial parks as a social process based on ecological, social, and economic aspects and emphasise the importance of learning processes among social actors. They describe two main difficulties in the development towards sustainability. First, it is relatively easy to achieve superficial, short-term social changes, but social actors have a tendency to fall back into their old patterns of behaviour on the long term due to their embeddedness in an institutional context. Second, to ensure system change rather than system optimization, it needs to emerge from the existing system (Lambert and Boons, 2002; ).

In recent years, attention to eco-industrial parks (EIPs) development projects has been attracting at a good pace both in developing and developed countries worldwide. EIPs have emerged with the focus on efficiently sharing resources in a similar fashion to natural ecosystem in the pursuit of reduced ecological impact and maximized economic benefits (Liwarska-Bizukojc et al., 2009).

In China, sustainability and effective environmental protection have become a vital issue for the long-term development of industries, apparently, because of two factors: (1) increasing awareness that there are limits to the availability of non-renewable resources; and (2) increasing awareness that there are limits to the biosphere's ability to absorb wastes. China has rapidly developed a number of EIPs in recent years (Shi et al., 2012). Yuan and Shi (2009) reported that ISN can effectively improve the competitive advantage of the enterprise in terms of decreasing production cost and improving environmental performance. The Ministry of Environmental Protection and the National Development and Reform Commission are currently engaged in promoting national pilot EIPs programs (Zhang et al., 2010). As a result, some initiatives have been launched to establish EIPs. EIPs have been a major national policy tool to promote resource efficiency in the context of the Circular Economy policy in China (Yong and Zhao, 2009). The state of eco-industrial development in China is examined (Yu et al., 2015b). The problems encountered in program implementation (Yu et al., 2015a).

There has been widespread interest amongst park management in promoting resource efficiency and other environmental activities in response to targets imposed upon them (Chertow and Ehrenfeld, 2012).

The stability of industrial system is the prerequisite for the existence and sound development of eco-industrial chain, including five dimensions: structure stability, adequate technology and innovation, economic benefits stability, policies and regulations adaptability and public support, among which structure stability is an important factor to decide the linkage of internal components of industrial system.

The instability of an IS system may emerge due to its special characteristics in ecological connections and developing environment. The instability would become severe barriers to the successful development and evolution of IS systems. Some problems have been noticed in the development of eco-industrial parks (EIPs), in which the notable ones are the instability and poor symbiosis in EIPs (Zhu et al., 2010). The stability of an IS system can be defined in two different ways. First, the stability of a system indicates its resistibility and affordability to the external changes. This ability can be denoted as 'resistance'. Second, the stability of a system shows its ability to recover from external disturbance and its capacity to repair the damage caused by the external force, which can be expressed as 'resilience' (Wang et al., 2013). The Cape Charles Sustainable Technologies Industrial Park is reported to stop waste recycling and came to a deadlock in substance because of unclear geographical location, low level of manpower and declined economic support. The scattered small enterprises are attempted to integrate in theirs surrounding regions and promote the regional competitiveness on the basis of the existing IS system, but the plan failed due to the occurrence of some conflicting interests (Korhonen et al., 2002). These studies suggest that stability analysis of ISN is an important area of research (Wang et al., 2013).

Different types of technical barriers in the operation of an eco-industrial system have been identified theoretically as a result of the exploration and implementation of ecological industrial parks since the 1990s. However, the vulnerability of these systems is amplified by inadequate management. In this paper, we describe the indicators of stability in an eco-industrial system based on complex network theory to build a cascading failure model for the system. We discuss how two types of node enterprises impact the stability of the eco-industrial system. The results show how various node enterprises with different mechanisms affect the systematic stability of the eco-industrial network and how the removal of core node enterprises can lead to greater damage to the network. Managers of eco-industrial systems should focus on structural core enterprises and core industrial chains. In this paper, the managerial implications can provide reliable guidance for stable operations in an eco-industrial system(Xiao et al., 2016).

## 2. Problem statement

Based on the stability problems of industrial symbiosis, we analysis these elements by Hall three dimensions structure. The Hall three dimensions structure embodies the characteristics of systematization, integration, optimization, programming and standardization of system engineering method, which is an important part of system engineering methodology. Inspired by the hall three dimensions structure, it discussed the necessity and feasibility of the hall system method combined with the industrial symbiosis. Based on the characteristics of IS, it briefly analysed industrial design system models from the perspective of process dimension, organization dimension, knowledge dimension three dimensions. The Hall three dimensions structure for IS are shown in Figure1.

Based on the Hall three dimensions structure for IS and integration of information from all aspects to the classification, we classify the stability problems of industrial symbiosis. The influence factors of stability are divided into two types: the exogenous and the endogenous attributes. All of these factors are summarized according the literature review, as shown in Introduction section.

- The exogenous attributes include the Social factor (X1), Resources supply factor (X2), Environmental factor (X3) and Market risk factor (X4).
- The endogenous attributes include the Incentive contract factor (X5), Credit-risk factor (X6), Co-operation flexibility factor (X7), Waste synergy factor (X8) and Profit allocation factor (X9).

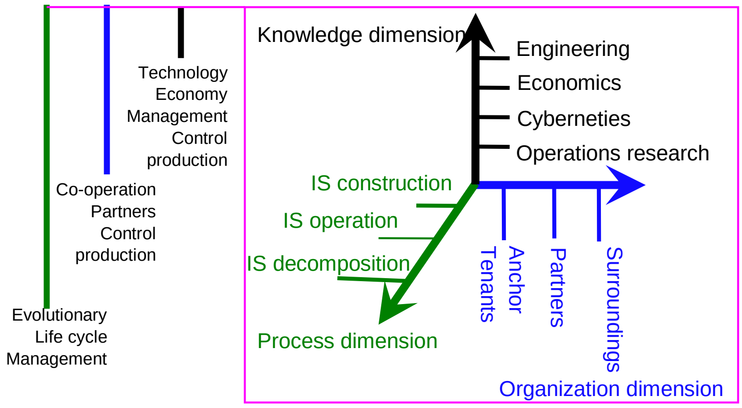


*Figure 1: Hall three dimensions structure for IS*

## 3. Methodology

### 3.1 Integrated analysis method

This method attempts to use the data from multi-sources under various spatial-temporal conditions. Two-level information fusion model is proposed. This proposed methodology will facilitate the representation, the inner relation and working mechanism of multi-sources information among the member entities in the ISN. The integrated stability analysis method includes several parts as follows:

- First step: data collection. Data are collected from multi-sources under various spatial-temporal conditions, dynamic events.
- Second step: classification. Based on the influence factors, stability are divided into two types: the exogenous and the endogenous attributes.
- Third step: quantification. The main methods to get quantitative data include the expert scoring, Monte Carlo simulation, risk reward and accounting approaches.
- Fourth step: information fusion. Modular artificial neural network is built to integrate multiple resource data.

### 3.2 Modular artificial neural network

Based on the thoughts of integration and according to the characteristics of the modular structure and function modules, the neural network system in large neural network is divided into several sub modules. To minimize the interconnection of the sub module, the network module network within the scale of neuron shrinkage kid all connected, so that each module of network regularization.

The whole neural network system is readable and easy to understand, which makes the system more flexible and open. Based on the above ideas, this paper constructs a universal modular neural network system model, and uses it to solve the problem of feature level fusion (Xu, 2004). The modular artificial neural network is shown in Figure 2.

General modular neural network system (MNN) consists of decomposition sub-module (DSM), function sub-module (FSM) and combination sub-net module (CSNM).

- The DSM is responsible for decomposing the input variable *X* into the input variables *K* FSM function modules P1, P2... Pk, whose function is equivalent to a switch of a matrix.
- The CSNM is responsible for synthesizing the output variables of the *K* FSM function modules into the final output of MNN.

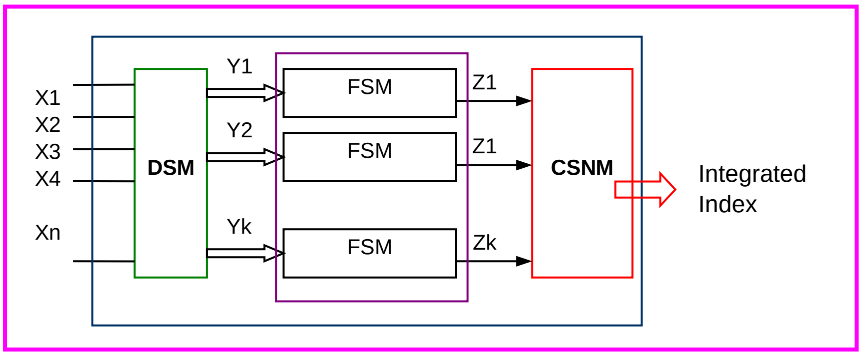


*Figure 2: Modular artificial neural network*

## 4. Illustrative example

A certain number of medium and small-sized enterprises centered around a large core enterprise to operate, thus forming a single core enterprise of an ISN model. In such kind of model, the two kinds of enterprises cooperate closely and can profit from each other. One party (the large core enterprise, the anchor tenant) survive independently and the other side (a number of medium and small enterprises) dependent on it. Around the core business, many medium and small enterprises are joined in together to make full use of a variety of by-products and raw materials. Then, the formation of industrial symbiosis system is constructed.

In the illustrative example with five plants is shown in Figure 3. It is a part of the Shouguang EIP, Shandong province, China. The anchor tenant is a combined heat and power (CHP) plant; 4 members are a pulp mill, a paper mill, an alkali recovery plant, and a cement plant. Water resource is conserved by direct and indirect recycle network. A water reuse project of the total annual processing capacity of 130 kt is constructed. Water reuse rate is up to 90 %. Cement plant uses the slag and fly ash from the CHP. "Coal - electricity - building materials" recycling chain is established according to lots of industrial projects. The by-products (coal ash and cinder) from the CHP plant can support the construction of an annual output of 300 kt of cement plant and 80,000 $m^3$ of new building materials plant.

The exogenous and the endogenous attributes for its stability are identified and listed in Table 1. In this case study experts are invited to visit the park site and give the score assessment of the attributes. Monte Carlo simulation, risk reward approach and accounting are performed based on the investigated data. The integrated index is calculated based on the proposed integrated analysis method.

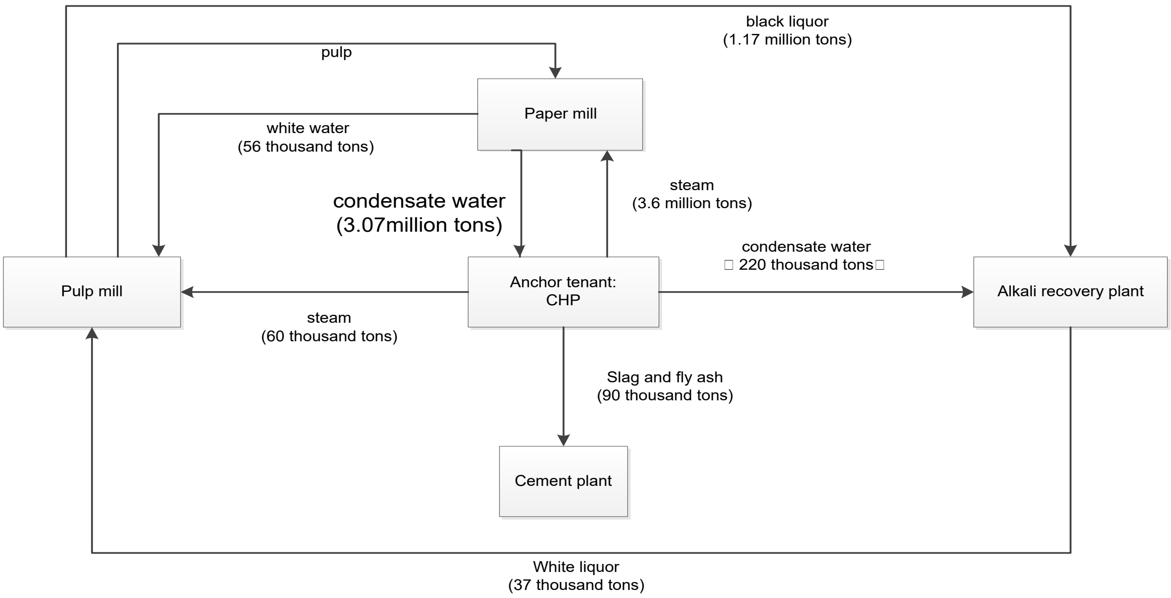


*Figure 3: Illustrative example*

*Table 1: The exogenous and the endogenous attributes and integrated index*

| Attribute | Quantitative Method | Anchor | Member 1 | Member 2 | Member 3 | Member 4 |
|---|---|---|---|---|---|---|
| X1 | Experts Scoring | 3 | 3 | 3 | 3 | 4 |
| X2 | Experts Scoring | 3 | 2 | 4 | 3 | 5 |
| X3 | Experts Scoring | 1 | 2 | 6 | 3 | 2 |
| X4 | Monte Carlo | 0.15 | 0.12 | 0.58 | 0.3 | 0.2 |
| X5 | Risk Reward Approach(k$) | 800 | 625 | 365 | 80 | 250 |
| X6 | Experts Scoring | 5 | 3 | 3 | 0 | 0 |
| X7 | Experts Scoring | 4 | 5 | 6 | 4 | 5 |
| X8 | Experts Scoring | 4 | 5 | 6 | 2 | 5 |
| X9 | Accounting(k$) | 1200 | 560 | 200 | 350 | 300 |
| Fusion | ———— | 0.1935 | 0.2985 | 0.5125 | 0.4218 | 0.176 |
| Integrated | | | 0.1798 | | | |

## 5. Conclusions

This proposed methodology tries to facilitate the representation, the inner relation and working mechanism of multi-sources information among the member entities in the ISN. An integrated analysis method is based on information fusion. Integrated analysis for stability attributes is based on Hall three dimensions structure. The integrated index for the ISN and the indicators of each member is identified and quantified according to the exogenous and the endogenous attributes. This method attempts to use the data from different sources under various spatial-temporal conditions. Based on the integrated indices, the decision-maker can rank the design scenarios. In fact, there are lots of uncertainty problems for these stability attributes in the ISN practices. The future work will focus on the ISN-wide uncertainty management based on the perspective of life cycle thinking for the ISN.

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