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Industrial ecosystem and its resilience: towards a resilient society

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Abstract

A prerequisite to achieve sustainable society is the resilience of various social systems. The concept of industrial ecosystems derives from industrial ecology upon the call of sustainability. The resilience of industrial ecosystems play an important role in the resilience of the society given it relates to natural resources, environment, commerce etc many fields. Up to now, many scholars have introduced various methods and tools to model industrial ecosystems. The resilience or stability of them also attracts increasing attention among industrial ecologist in recent years. This article provides a literature review as to modeling and the resilience of industrial ecosystems.

Keywords

Industrial ecosystems; resilience; tools; modeling; sustainability

1. Resilience and stability of society and industrial ecosystems

Upon the call of sustainability, one systemic dynamic attribute-resilience has become an important topic to cater for changes and uncertainties, especially the unexpected potential risks. There are different definitions of resilience in literature.

According to Holling's definition (1996), resilience can be classified as ecological resilience and engineering resilience, which reflect two different aspects of stability. Resistance (The ability to resist and avoid destroy and disturbance) and resilience (the ability to recover from outer disturbance to its initial state) are in fact the two aspects of stability of ecosystems in ecology. According to Holling's(1996), engineering resilience focuses on efficiency, constancy, and predictability. It is measured by resistance to disturbance and speed of return to the equilibrium (Pimm 1984; Tilman and Downing,1994); Ecological resilience focus on persistence, change and unpredictability , which are studied from evolutionary perspective by biologist. The measurement of ecological resilience is the magnitude of disturbance that the system can absorb before changing the structures by variables and processes that control behavior (Walker et al., 1969). Allenby and Fink (2005) defined resilience as the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must. The centre for resilience defines resilience, is the capacity of a system to survive, adapt, and grow in the face of unforeseen changes, even catastrophic incidents. Although the definitions of resilience are seemingly different, they are more or less the same emphasizing robustness /persistence/ staying within thresholds etc. to guarantee the existence and healthy development of the system temporally and spatially.

Except in ecology, resilience has also become a research topic in social-ecological systems (Walker et al, 2002), supply chains as well as enterprises. A resilient enterprise, as argued by the centre for resilience, continues to grow and evolve in order to meet the needs and expectations of its shareholders and stakeholders. It adapts successfully to disruptive changes by anticipating risks, recognizing opportunities, and designing robust products and processes. Sustainability is an attribute of dynamic, adaptive systems that are able to flourish and grow in the face of uncertainty and constant change. Korhonen and Seager (2008) mentioned in pursuing sustainability for enterprises, that eco-efficiency optimization rarely results in improved adaptability and consequently may have perverse consequences to sustainability by eroding the resilience of production systems .Industries play a central role in achieving sustainability as well as a resilient society since it is also the industries that caused serious resource and environmental problems.

As the concept of industrial ecology introduced and popularized by Frosch and Gallopoulos (1989), one way to achieve sustainability among industries is via the implementation of the industrial ecology principles. They proposed to redesign and refurbish industrial systems so as to behave like ecosystems. This led to the concept of the industrial ecosystem (IES), mimicking natural systems. The industrial ecology community envisages industrial systems in which industries optimize their interaction by means of closed-loop use of materials and energy flows, in order to reduce by-product and waste production and negative environmental impact at system level. In reality, the IESs are in form of eco-industrial parks (EIPs), industrial symbiosis (IS) or just industrial clusters. The defining property of an IES could be a collective inter-firm approach to achieve competitive advantage, involving the physical exchange of materials, energy, water, and by-products (Chertow, 2000).

How come the resilience (or stability) concept in industrial ecosystems? In recent years, industrial ecosystems are developing fast worldwide for sake of sustainability no matter in the form of industrial transformation or newly built ones or identified symbiotic phenomenon. Although industrial ecology, as the theoretical support of IESs , develops fast these years, it is still not mature enough to guide us. In reality, not all of IES efforts are paid as expected. David Gibbs et al.(2005) once said, "despite a growing interest in EIPs, there have been few empirically informed studies that seek to explore the potential contribution such EIPs may make to sustainable development". In the Netherlands (Janet and Walter,2004) , yet only a limited number of local projects are actually designed to bring about symbiosis and utility sharing. Macheon Industrial Park (MIP) (Kim, 2007) in South Korea project unsuccessfully deals with the needs of the stakeholders because of technical, economic, and social obstacles, support from the public sector for the project seems quite inadequate. In the USA, key features of EIPs, like inter-firm networking and collaboration of materials and energy are absent or are still at early planning stage. Of the 15 projects, three had failed including Cape Charles, which represents early USA EIPs ; Baldwin and Ridgway(2004) once mentioned even as to Kalundborg symbiosis, potential problems brought by new evolutions of technical change or renovation /external pressure (e.g. law and public, new energy and raw materials) /film mergers may result in collapse of the whole system.

Given Industrial ecosystems are normally studied in a regional level, and it relates to infrastructure building, community, resource exchange network, and land use etc. many aspects. Thus, resilience or stability of IESs is the bridge to achieve sustainability; a resilient or stable IES could also help build a locally resilient society; the theoretical models or frameworks to show the pathways of IES are the first steps for us to further explore the stability of industrial ecosystems. In this article, we will offer a literature review of existing frameworks modeling the industrial ecosystems and research methods that mentioned the resilience of industrial ecosystems.

2. An overview on methods modeling industrial ecosystems

2.1 Tools from system dynamics and complex systems theory

Industrial ecosystems are normally seen as complex adaptive systems. Various tools from systems dynamic and complex systems theory are widely investigated in analyzing or modeling IESs. Bailey et al. (2000) used response surfaces in system dynamics studies with the simulation of a case study of Kalundborg symbiosis. The focus is on the regions within the design space of the original simulation with the most desirable performance. Recommended changes to a system are based directly on the simulation model, not on response surfaces. A similar research is conducted by Wang et al.(2005) simulating the thermal plant EIPs with system dynamics.The subsystems of the EIPs are consisted of industries,population,resources, ecological environment where the industries are the core of the thermal plant EIPs ; the population provide labor; technology innovation offer new products ;the investment ratio directly affect the evolution model of the EIPs. The industries are mainly made up of industry, agriculture, service, environmental protection agencies. The author employed Cobb- Douglas function to get the input-output relations of the industries. In the system dynamic model, productivity, investment ration of the industries, technology factor, the recycling rate of resources are setup as control parameters.

An important tool from complex systems theory, agent-based modeling**,** is also widely applied in industrial ecosystems. Batten (2009) applied agent-based simulation to “identify those potential elements and simulate alternative future scenarios of an industrial ecosystem to seek how could they work together to achieve more eco-efficient outcomes” for it can explore various “what-if” scenarios under different eco-efficient goals. Then the author argued that eco-industrial development is co-evolutionary learning systems to gain mutual economic and ecological benefits and this co-evolutionary learning process could be aided by participatory modeling for it can help build trust and reduce conflict among sharing resources. Cao et al. (2009) also used ABM to see the evolution of IES by simulating flows using the mechanism for determining the price of every product, calculating the inventory and profits of the factory (agent) and the mechanism for determining the demand. They designed some important interaction mechanisms between agents and studied the sustainability evolution with emergy theory and use “internal-flow emergy” to indicate the evolution direction of an IES. Andrews and DeVault (2009) introduced a multi-agent simulation framework for investigating the emergence of niche markets for environmentally innovative products. They investigated how consumer preferences, business strategy, and government policy interact during market development. The framework allows investigation of the effects of uncertainty and agents‟ corresponding coping strategies.

2.2 Tools from ecology

Industrial ecology principles come from the metaphor from ecosystems. A group of scholars attempted to apply ecological theories in IESs. Zhang (2006) applied ecological theories to analyze how to build industrial symbiotic systems in EIPs. Applied theories include key species, food webs, niche, ecological diversity and tolerance. From an ecosystem perspective, an eco-industrial park is actually a biological community with raw materials processing, manufacturer, supplier, waste treatment, recycling materials. Basin on these theories, the author built EIPs structure model that consists of four subsystems, namely natural environment, public infrastructures including information/technology/environmental centers and infrastructure, ecological chains including producer/consumer/decomposer companies, supportive service system including the government/park manager/market/law and financial service sectors . The four systems exchange physical, energy and information and coevolved into a self-adaptive system. Wang (2005) built synergistic evolvement model of industrial cluster companies basing on niche theory .The function relation between regional cluster enterprises and resource elements is researched based on niche theory. The ecology foundation of coordination and competition of cluster enterprises is analyzed and the models of niche breadth, niche overlapping and niche coordination evolution of cluster enterprises are set up. Via analysis, the author got a conclusion that, if cluster enterprises are laid in the different niche, the resource competition can be avoided between enterprises, and coordination symbiosis between cluster enterprises will be realized.

2.3 Tools from mathematics

Many mathematical tools are applied by scholars to conduct quantitative analysis of IESs. Chen et al. (2001) introduced logical expression equations in modeling the EIPs. The authors considered the EIPs as member and connection blocks. These blocks form a modular architecture, by which EIP scenarios with different topological structure are represented. The member block has unified interface, and mainly express the relations of raw materials, products, byproducts, waste, water, electricity and investment relationship. The connection block, except expressing the material balance, also express the connection constraints among members of EIP via introducing logical expression equations. Logical proposition expressions are introduced into the model, so that the decision in the course of EIP design and management can be formulated as a mixed integer nonlinear programming (MINLP) problem. It is easy to expand, modify, reuse the EIP model, and can be used as the kernel model in EIP decision making. Fuzzy mathematics, gray theory analysis, analysis hierarch process method, the distance function model are also proposed to quantitatively evaluate the eco-industrial parks. Zhang (2011) applied multi-level fuzzy comprehensive evaluation mathematical model considering economic index(growth rate of industrial added value and proportion of leading industry output in the parks' gross value), social index(employment and technology innovation), environment index(the use of resources and pollution control) and management index(policy and law; public recognition; management and consciousness). Singh and Lou (2006) provide a systematic and flexible framework of Hierarchical Pareto Optimization Methodology to solve multi-scale, multidimensional problems for the sustainable development of industrial ecosystems. The methodology decomposes a complicated multi-objective optimization problem into multiple levels. The upper level constitutes the overall objectives for the entire system, and the lower level resembles individual subsystems that are interconnected with interaction variables. A recursive Pareto optimization algorithm is deployed to identify the optimum solution for the overall system. Sustainability indices are proposed by emergy analysis for industrial systems.

2.4 Exploration of the evolution of industrial ecosystems

Since resilience is a capacity that can be tested from long term perspective, the evolution of IESs then becomes an important topic. As to this aspect, Gradel et al.(1994) argued there are basically three phases from Type I to Type III with the different degree of maturity of industrial systems. Type I system is almost linear, raw materials are exploited and manufactured by the industries and then leftovers are taken as waste into the environment. In contrast, in Type III systems, materials are fully recycled and no waste is piped into the environment. Baldwin and Ridgway (2004) in their article also explored the simulation of the evolution of industrial ecosystems. They applied the evolutionary framework developed by Allen (2001) with urban modeling as well as industrial ecosystems. They also argued that simulations of future scenarios of IESs and the consequences of particular decisions can be explored with respect to normal systemic and environmental events such as the introduction of innovative (and sustainable) technology, policy and legislative changes, new actors emerging, mergers and takeovers. Especially, human factors such as human preferences and relationships, interests, and values, may also be represented in the model. Thus, in this way of modeling, it not only represents a visual representation of industrial structure but also a dynamic unfolding of potential future scenarios of the sources, movement and sinks of materials (and energy). The models can therefore serve as decision support tools to lessen or manage the risk and uncertainty of future evolutionary trajectories. In analyzing the evolution and control of EIPs, Qin (2007) simulated the EIPs and applied genetic algorithms, evolutionary game theory, neural networks, and the complex network approach to analyze potential problems. Scattered structure theory is also applied in analyzing the evolution of IESs(Xu et al. ,2004).

3. An overview of research methods on the resilience of industrial ecosystems

3.1 Stability of industrial ecosystems among scholars in China

As to the capacity of industrial ecosystems to deal with possible risks, the stability issue of IESs becomes a popular topic among Chinese scholars during the last few years. The stability of industrial ecosystems, as defined by Deng Hua (2006) is that the capacity for an IES to maintain its original equilibrium in case of interference. Ye Xun (2006) also emphasized the eternal equilibrium of material and energy demand and supply chains and the capacity of the IES to adapt to changes. Given that, the stability of IESs among Chinese scholars has similar meanings with resilience, we offer a review of them in the article.

Some research aims quantitatively to explore the stability from conditions and measurement or assessment. For instance, Cai (2006) applied a benefit-allocation model basing on cooperative game theory and Sharpley value method. They got the prerequisites for IES to stay stable, which are the overall benefits in the system should be added due to a new organization entering the network; expected benefits of each member equals its contribution value multiplied its success rate. Besides, each member company is supposed to gain the biggest benefits within the IES. Similarly, Guoli et al.(2005) also attempted to compute the equilibrium point for IES to maintain stable, whereas she described the interactions among companies with Logistic Equation and mathematics models. Interestingly, Ye Xun (2006) applied a tool from thermodynamics- enthopy to examine the stability of IES ,taking EIPs as dissipative structured. He computed the internal and external entropy‘s effect on the stability of the IES via equations. He got a conclusion that the key to maintain the park‘s stability is to coordinate the relation among various stakeholders to reduce the park’s entropy. Tong (2006) ,basing on ecology and IES theories, built Eco-Industry System Stability Assessment Index (ESSAI) to assess it from degree of dominance, circular , adjustment indicators and series of sub-indicators. And its calculation includes five steps:①basic data collection and processing according to indicator system ② Standardizing the data with Z-score method.③Using SPSS for Windows software, principal component analysis, factors analysis to variables of the system④ the calculation the systemic value ⑤calculate the comprehensive value of stability of industrial ecosystems . Li (2007) proposed an assessment that includes external impact (including environmental policies, relevant sector policies, financial policy, and market environment), internal aspects (competitive ability, response to changes, economic benefits), and network aspects (degree of networking and information level, flexibility of the system). Tong (2006) assessed stability from the points of view of sector-dominant capacity (which consists of economic productivity, strength of keystone companies, and ecological advantages), the extent of circulation (which consists of material and energy recycling, water reuse, and the capital flows pyramid), and adjustment capacity (which includes the capacity to adapt to policy and capital as well as environmental disturbances). Zhou et al.(2007)applied predator-prey mathematic model from ecology to calculate the quantity of the enterprise populations with predator-prey relations in the hi-tech industrial ecosystem. The competitiveness of enterprises and the stability of hi-tech industrial clusters are also analyzed.

3.2 Resilience of industrial ecosystems in English literature

Resilience of IESs attracts increasingly attention among English literature. In fact, Frosch and Gallopoulos (1989) also mentioned: an IES should be resilient in order to absorb and recover from unexpected shocks. Ashton (2009) illustrated that external forces and interactions among actors at multiple levels can cause permanent changes—but not necessarily system collapse. She got this conclusion via developing a framework to assess the structure, function, and evolution of a regional industrial ecosystem that integrates insights from industrial ecology and economic geography dimensions with complex systems theory. Liang et al. (2010) proposed Structural Analysis Method for Industrial Ecosystems (SAMIE) according to two valuation indices, species index and rigidity and concluded that “it is the species with the highest system rigidity that dominates the stable level of whole industrial ecosystem, because the system rigidity is a synthetic indicator under the consideration of the absolute rigidity and source relative rigidity to the dominant nodal point species”. In SAMIE, a set of indicators is developed to evaluate the industrial system, in order to explore the problems of structural complexity, identify the limiting factors of industrial ecosystem evolution, and strengthen the capacity of adaptation and self-organization.

There is also other literature that mentioned the problem of resilience of IESs; however, most of them are qualitatively analysis, resilience of IESs has not been systematically quantitatively investigated .Here, we will not unfold other literature that mentioned one or two words related to resilience of IESs. Instead, we will offer some efforts or organizations that attempt to quantitatively study the resilience of IESs. One of them is the Centre for Resilience, which explores the risks, resilience and sustainability in complex industrial systems. The centre developed the tool of SCRAM™ (Supply Chain Resilience Assessment & Management) that can be used to analyze the vulnerabilities and capabilities of supply chain operations and is applicable to both manufacturing and service industries. IESs, as complex systems, are different from supply chains; still, it is a useful tool to analyze the resilience of the supply and demand chains in an IES. Another organization is Resilience alliance. One of their research programme is the urban resilience basing on metabolic flows, social dynamics, governance networks, and built environment. The scale of an IES is normally geographically defined , the resilience of IESs may contribute or can be studied from the same perspective as urban resilience.Another research programme that is being conducted in University of Surrey is the evolution and resilience of industrial ecosystems programme , which aims to embed complexity science methods and techniques within prototype computational tools that will provide policymakers with realistic and reliable platforms. Meanwhile, they will also examine and measures the resilience (the ability to recover from external shocks).

4. Summary and discussion

Resilience is an important property or capacity of complex systems. A resilient society is a prerequisite to sustainability. Among greening industrial systems, an IES is normally geographically defined. An IES as a newer promising concept in our horizon needs much attention and investment in reality for sake of long term sustainability. Mature IESs are very few in current literature though; the resilience of these systems in operation can not be neglected. The resilience (or stability) of an IESs also directly affect the belief of the IE and IES. As Lambert and Boons (2002) pointed that, there has been a growing concern that EIPs are not stable in the situation where the members of the EIPs change. Many companies regard liability as a major concern when it comes to decisions about getting involved in IES projects (Lowe , 2001).

From the literature review of this article, we can see that IESs are studied from different perspectives with various methods and tools introduced in modeling IESs. Resilience of IESs also attracts interests among industrial ecologists. Despite of this, we can see that research on the resilience or stability of IESs is still in a very preliminary stage; a more convincing systemic analytical framework to quantify it is urgently needed. The introduced methods and tools as well as the mentioned resilience organizations have provided many possibilities to build a systematic framework.

Research into the resilience(or stability) of IESs is also one effort to examine industrial ecology in the real world, in order to further perfect the concept and reduce the gap between theory and practice. Given the scope of an IES is very wide, including agriculture, industries, and commerce etc aspects. Its resilience is an important impetus to the resilience of the local society.

References

Allen, P.M. (2001) “A complex systems approach to learning, adaptive networks”, *International Journal of Innovation Management,* 5(2):149–180.

Allenby,B. and Fink,Jonathan. (2005)” toward Inherently Secure and Resilient Societies” , *Science* 309(5737):*1034-1036.*

Andrews, C., DeVault,D. (2009).”Green Niche Market Development A Model With Heterogeneous Agents” .*Journal of Industrial Ecology* 13(2), 326–345.

Ashton, W. S. (2009) ‘The structure, function, and evolution of a regional industrial ecosystem’, *Journal of Industrial Ecology* , 13 (2):228–246.

Batten,D.F.(2009).”Fostering Industrial Symbiosis with Agent-Based Simulation and Participatory Modeling “.*Journal of Industrial Ecology*13(2),197-213.

Baldwin,J.S., K.Ridgway, B. Winder, R. Murray. (2004) “Modelling industrial ecosystems and the problem" of evolution “, *Progress in Industrial Ecology,* 1(1-3): 39-60.

Bailey,R. Bras,B. *Allen,J.K.* (2000)“Using response surfaces to improve the search for

satisfactory behavior in system dynamics models" *Business &Manageme*nt 16(2):75-90
Chen,D. Li,Y .2001 "A MINLP Model of Eco-Industrial Parks". The Chinese journal of process engineering:1-7.
Chertow, M.R. (2000) 'Industrial Symbiosis: Literature and Taxonomy', *Annual Review of Energy and Environment* , 25:313-337.
Cai X., L. Shuangjie,L. Qihao. (2006) 'The forming mechanism of industrial linkages in EIPs and its stability analysis(in Chinese) ', *Soft Science*, 20(3): 12 - 14.
Cao, K., Feng,X., Wan,H.(2009). "Applying agent-based modeling to the evolution of eco-industrial systems" . *Ecological Economics* 68(11), 2868-2876.
Deng, H. (2006). "Research on the influential factors of industrial ecosystem stability in China (in Chinese)", Ph.D. thesis, Dalian University of Technology, Dalian, China.
Frosch, R.A. and N. Gallopoulos. (1989) 'Strategies for Manufacturing', *Scientific American*, 261 (3): 144–152.
Gibbs, D., and P. Deutz. (2005) 'Implementing industrial ecology? Planning for eco-industrial parks in the USA', *Geoforum* , 36 (4): 452-464.
Guo,L., S. Jingqin. (2005) "Stability analysis of symbiotic industries based on logistic model", *Forcast* 24 (1): 25 - 29.
Holling,C.S.(1996) "Engineering resilience versus ecological resilience". *Engineering within ecological constraints*, 31-43.
Janet A.M. Eilering; Walter J.V. Vermeulen .(2004). Eco-industrial parks: toward industrial symbiosis and utility sharing in practice. *Progress in Industrial Ecology* 11(1), 245 – 270.
Kim. H.(2007). Building an Eco-Industrial Park as a Public Project in South Korea: The Stakeholders‟ Understanding of and Involvement in the Project. *Sustainable Development* 15(6), 357-369.
Korhonen, J.,T. P. Seager . (2008) "Beyond eco-efficiency: a resilience perspective", *Business Strategy and the Environment* , 17 (7):411-419.
Korhonen ,J. Snakin,J(2005) "Analysing the evolution of industrial ecosystems: concepts and application", *Ecological Economics* 52: 169– 186.
Lowe, E. A. (2001) "Eco-industrial Park Handbook for Asian Developing Countries", A Report to Asian Development Bank, Environment Department, Indigo Development, Oakland, CA.
Liang, C., W. Rusong, Y. Jianxin and S. Yongliang. (2010) "Structural complexity analysis for industrial ecosystems: a case study on LuBei industrial ecosystem in China", *Ecological Complexity*, 7 (2): 179-187.
Lambert, A.J.D., Boons, F.A. (2002). Eco-industrial parks: stimulating sustainable development in mixed industrial parks. *Technovation, 22(8), 471-484.*
Pimm,S.L.(1984)"The complexity and stability of ecosystems", *Nature* 307:321-326.
Tilman,D.,and J.A.Downing.(1994)" Biodiversity and stability in grasslands",*Nature 367:363-365.*
Qin,S.(2007) "The evolution and control of eco-industrial parks". PhD thesis. Hehai University, China
Singh ,A and Lou,H.H. (2006)" Hierarchical Pareto Optimization for Sustainable

Industrial Ecosystems*” Ind. Eng. Chem. Res.* 2006(45): 3265-3279.

Tong, L. (2006) “ Studies on the design of the eco-industry chains and on the assessment index system of its stability (in Chinese) “, Ph.D. thesis, Beijing University of Chemical Technology, Beijing, China.

Wang,L.2007. Simulation and Adjustment of System Dynamics on Power Plant Eco-Industrial Park.*Chinese journal of applied ecology* 7 (2005):117-124

Walker,B.H.,D.Ludwig,C.S.Holling,and R.M.Peterman,(1969)”stability of semi-arid savanna grazing systems”*,Ecology* 69:473-498.

Walker, B., S. Carpenter, J. Anderies, N. Abel, G. S. Cumming, M. Janssen, L. Lebel, J. Norberg, G. D. Peterson, and R. Pritchard. (2002). “Resilience management in social-ecological systems: a working hypothesis for a participatory approach”. *ConservationEcology* 6(1): 14.

Wang,Z,T*an,Q*.”research on the evolution model of industrial clusters basing on nic*he theory” Scientific management research,* 23(5):34-37.

Ye, X. (2006) ‘Study on the stability of eco-industrial parks (EIP) (in Chinese) ’,Master’s thesis, Beijing University of Technology, Beijing, China.

Zhang,C. *(2006).”*Research on modeling eco-industrial parks basing on ecological theories”.*Industrial technology and economy*”25(3):84-87.

Zhang,X.(2009).“Modeling building of eco-industrial parks basing on scattered structure theory”. Commerce era 2009(30):30-42.

Zhang,H. (2011).”Study on the fuzzy analytic hierarchy integrated evaluation method of Eco-Industrial Parks”, *Energy Procedia*, 5 (2011):1944–1948.