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The development of regional collaboration for resource efficiency: A network perspective on industrial symbiosis

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ABSTRACT

Industrial symbiosis (IS) improves regional sustainability through inter-firm collaboration for more efficient use of materials and energy. Drawing on the literature of IS and complex networks, this paper proposes three forming processes of IS networks corresponding to different institutional settings – preferential growth under self-organization, homogeneous growth under coordination and facilitation, and random pairing under planning and policy promotion. We examine the growth of IS networks and the impact of promotional institutions by analyzing a diverse sample of 15 IS networks including 204 firms. Additional illustrations of by-product and utility networks are provided for the cases of Kalundborg (Denmark) and Kwinana (Australia). The results suggest that preferential growth is a dominant process widely held in self-organized IS networks, indicating an enduring disparity of firms' capabilities in building IS. Firm-organized coordination as well as government facilitation and promotion tend to change the preferential growth to a more homogeneous one, by improving the capabilities of previously disadvantaged firms. The improvement of disadvantaged firms and non-preferential growth under facilitation and promotion call for the overall symbiotic opportunities to be explored more thoroughly, and render the IS system more resilient in a region. This effect of policy promotion, however, may take time to change the IS system, and may be diminished in utility exchanges and in areas with fewer, undiversified firms, due to technical difficulties and lack of opportunities to expand an existing IS network. Policy-making and planning should take into consideration the local industry composition and context, as well as other cost associated with the policies to determine the appropriate extent of promotion and incentives.

1. Introduction

Sustainable development has become a common emphasis in policy-making and planning during the recent decades. A particular approach to bring environmental benefits in agreement with local economic development is industrial symbiosis (IS) – the exchange and sharing in the management of materials, energy, water, and by-products between geographically proximate firms (Chertow, 2000, 2007). IS improves resource efficiency, reduces pollution, waste, and landfill use, and strengthens economic competitiveness collectively for a region. It was uncovered as self-organized efforts between firms, originally in the industrial town of Kalundborg, Denmark (Ehrenfeld & Gertler, 1997) and later in many other places across the world, with quantified environmental and economic benefits to the local areas (Chertow & Lombardi, 2005; Jacobsen, 2006; Chertow & Miyata, 2011) and globally (Mattila, Pakarinen, & Sokka, 2010). IS has also been intentionally facilitated as a key initiative in the development of eco-industrial parks (EIPs) to integrate economic competitiveness and environmental sustainability in the US, Europe and Asia (Heeres, Vermeulen, & Walle, 2004; Chertow, 2007; Park, Rene, Choi, & Chiu, 2008; Shi, Chertow, & Song, 2010).

Given the apparent benefits of IS to a region and the recognition that policy can help facilitate IS, there is a need to understand the formation and development of such inter-firm collaborations, and to guide planning and policy making for IS. The formation of a symbiotic relation is influenced, among others, by the cultural and natural environment, formal and informal social ties, managerial perception, technical feasibility, economic and investment decision-making, and information dissemination. Their collective impact leads to the emergence of a symbiotic exchange and corresponding contract and management, which in turn lead to the emergence of an IS system. While the literature of IS development is expanding (for example: Baas & Boons, 2004; Jacobsen & Anderberg, 2004; Howard-Grenville & Paquin, 2008; Ashton,

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2008; Doménech & Davies, 2011; Chertow & Ehrenfeld, 2012; Paquin & Howard-Grenville, 2012), a remaining challenge is to explore patterns behind the complexity of IS development that may inform policy making and planning. An IS system, with autonomous industrial actors and bilateral symbiotic relations between them, has been considered as a complex adaptive self-organizing system (Kay, 2002; Ehrenfeld, 2007; Chertow, 2009; Kempener, Cohen, Basson, & Petrie, 2009). Such systems with complex dynamics at lower levels sometimes produce simple emergent features at higher levels (Ottino, 2004; Sawyer, 2005), insensitive to detailed variations of the elements of a system.

A dynamic network representation of firms and symbiotic relations between them can link the micro-interactions of firms with macro-behaviors of IS systems. Regarding the growth of IS networks, Chertow (2009) observes that "linkages beget linkages" based on a temporal observation of Kalundborg and other cases. Paquin and Howard-Grenville (2009) report that a "rich get richer scenario" might have been true in a UK's symbiosis network including all initiated and fulfilled projects, but the expertise support from the National Industrial Symbiosis Programme (NISP) changed the network's structure and evolution pattern by making some previously less connected firms highly connected and central in the network. The observations suggest that the existing symbiotic relationships affect the further development of new IS, while this development processes may also be influenced by facilitating institutions of IS, such as the NISP. However, more empirical evidence is needed to confirm and elaborate the process.

It is not easy to examine the growth patterns of IS networks empirically: on the one hand, most identified IS networks, except the entire network facilitated by the NISP in the UK, have exclusively small sizes with few firms, suggesting that an analysis of a single case is not statistically reliable; on the other hand, complete timeline data of IS networks are not readily available, making regression analysis of a step-by-step network growth (like Powell, White, Koput, & Owen-Smith, 2005) not feasible. Alternatively, the posterior probability that an existing network G is generated by a hypothesized process H, i.e. $P(H|G)$, can be inferred from the likelihood of observing G given H, i.e. $P(G|H)$, and the prior probability of H, i.e. $P(H)$, via Bayes' Theorem:

$$P(H|G) \propto P(G|H) \times P(H). \quad (1)$$

Under such a framework, promising hypotheses can be derived from the observations in complex network and IS research, and the compatibility of the evidence with the hypotheses can be determined by producing networks from the hypotheses through Monte Carlo simulations and matching them with the increasing number of case studies of IS.

This paper reveals general growth patterns of IS networks within different institutional settings based on a comprehensive pool of IS cases and dynamic network simulations. Without detailed discussion about building a single symbiotic exchange, such a parsimonious description of the evolution of IS networks helps to understand more systematically and generally how an IS system is developed. The paper identifies institutional effects on IS development, and thereby informs policy making, planning and management to improve firms' symbiotic capabilities and to explore regional resource efficiency. Because the growth patterns of IS affect the network structure, which in turn affects system operation (Zhu & Ruth, 2013), the paper also informs management for long-term sustainability of IS systems.

The remainder of the paper is organized as follows. Section two reviews the literature of IS development and complex networks, leading to three hypotheses about the growth patterns of IS networks. Section three explains the criteria for selecting cases and the methods for analyzing them. The results are demonstrated in Section four, and discussed alongside their policy implications, in Section five. We close the paper in Section six with a brief synopsis and conclusions.

2. Hypotheses of IS growth processes

In recent years, conceptual models of the evolution of regional IS have been developed. For example, Baas and Boons (2004) propose three stages of regional industrial ecology, from regional efficiency based on firms' autonomous decision-making, to regional learning based on mutual recognition, trust and knowledge exchange, to sustainable industrial districts based on actors' strategic vision on sustainability. Doménech and Davies (2011) summarize three phases of IS development as emergence, probation, and development and expansion, with firms having increasingly more knowledge and experience of IS. Chertow and Ehrenfeld (2012) propose a three-stage model including sprouting, uncovering, and embeddedness and institutionalization, with later stages having more intentional and institutional realization of positive environmental externality, but suggest that the progress across stages are discontinuous and nonlinear. Specifically, Paquin and Howard-Grenville (2009, 2012) examine empirically the NISP's facilitating role in shaping the evolution of an IS network.

The literature of IS leads to the basic assumption of this paper: IS networks have common growth patterns, because a network builds on and strengthens the disparity of firms' capabilities to develop IS as individual agents; by improving disadvantaged firms' capability on building symbiotic relations, institutional arrangement can change the growth process of IS networks. This assumption is elaborated and substantiated into three hypotheses below – preferential growth, homogeneous growth, and random pairing, based on the literature of IS and complex networks.

2.1. Preferential growth

Industrial symbiosis development is perceived as a process that requires a set of special expertise of firms involved. Boons, Spekkink, and Mouzakitis (2011) state that "(the coming about of industrial symbiosis) depends on specific knowledge that actors acquire through experience and learning of the specific potential for industrial symbiosis in their system, as well as about the process of realizing that potential." Doménech and Davies (2011) argue for the need for frequent interaction, the transfer of tacit knowledge and learning by doing to deliver customized solutions. Chertow and Ehrenfeld (2012) stress the importance to lower transaction cost and to "push by-product issues higher up in the management hierarchy". In addition, Chertow (2000) considers anchor tenants, which are large resource-intensive firms like power plants, as important actors for subsequent IS building. Following the observations and discussions, it can be argued that existing IS reflects that firms involved have certain advantages in building IS than firms not involved. Such advantages may include the availability of resources, technical knowledge, information about other firms, social ties, management structure and decision-making process, and managerial perception of IS. Because these capabilities for building IS are acquired and accumulated in a learning-by-doing process, firms with more IS relations are likely to be more advantaged than those with fewer IS relations. This disparity of firms' capabilities on building IS, whether present at the very beginning or not, will emerge and be strengthened through the IS development.

This proposition of cumulative advantage and disparity of firms as individual agents in developing IS matches "the rich get richer" and "linkages beget linkages" notions of IS developments. It is also a common mechanism in the growth of complex networks, known as preferential attachment – nodes' with higher degree, k, have