Industrial Symbiosis: Testing the Boundaries and Advancing Knowledge

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[Pull-quote: [Industrial symbiosis] … has graduated from academic curiosity to practical tool supported by policy makers, business organizations and environmental NGOs alike – to address a broad policy agenda encompassing innovation, green growth and economic development in addition to the traditional resource efficiency]

The idea of industry finding uses for non-product outputs (by-products and waste) is not a new one (Desrochers 2000). Local context and incentives changed in the 20th century, however, and the practice fell out of favor due to cheap and abundant energy, resources and disposal options, subsidies that discouraged recycling, and regulations preventing re-use (Desrochers 2004). As the sustainable development agenda gained ground, other concerns led firms and governments to reconsider their strategies: increasing waste disposal costs, concerns over environmental degradation accompanied by stricter environmental regulations, and a growing awareness of the potential profits from by-product and waste utilization. The practical example of resource cycling between industrial facilities in Kalundborg, Denmark, came to the attention of the academic community (Ehrenfeld and Gertler 1997), generating substantial interest in what has become known as 'industrial symbiosis' (IS). In the intervening fifteen years, examples in which two or more otherwise unrelated industries develop a mutually beneficial relationship making productive use of otherwise underutilized resources (including materials, water and energy)[i] continue to be a topic of study. The phenomenon, and the research on it, is emblematic of the broader field of industrial ecology.

IS has now been documented in six continents. It has been incorporated at all levels of policy——local, regional, national, and international——as a strategic tool for economic development, green growth, innovation, and resource efficiency. In Europe for example, the Roadmap for a Resource Efficient Europe recommends IS as a priority for all member states to exploit resource efficiency gains, citing the UK's National Industrial Symbiosis Programme (NISP) as exemplar; and the strategy document 'Sustainable Industry: Going for Growth and Resource Efficiency' advocates IS as a policy instrument, citing Kalundborg as a practical example. Similarly, in 2010, the OECD recognized IS as systemic innovation vital for green growth (OECD 2010)[ii]. To reconcile economic growth and environmental management, China launched its National Demonstration Eco-industrial Park Program in 2001, which has expanded to a network of 60 national eco-industrial parks[iii]. The development of eco-industrial parks has become one of the primary approaches for realizing China's circular economy strategy that promotes resource efficiency and reduces pollution intensity (Yuan et al. 2006). As part of its Green Growth strategy, South Korea initiated the first phase of the National Plan for Eco-Industrial Park Development in 2005 to develop resource cycling in existing industrial parks (Park and Won 2007).

From the early 1990s, there have been calls for better integration of social sciences into what started, in the early days, largely as a technical field (Lifset 1998). The research presented in this special issue evidences a growing breadth and increasing pace of integration between social and natural sciences' approaches and literature. Analyses herein range from dimensions of social embeddedness drawing on organization, institutional capacity, and network literature (Boons and Spekkink 2012; Ashton and Bain 2012; Paquin and Howard-Grenville 2012), to an evolutionary theory of IS that draws on biology, ecology, and organizational behavior (Chertow and Ehrenfeld 2012) and the elaboration of a definition of IS from a practitioner's point of view that adds to the list the business literature (Lombardi and Laybourn 2012). In addition, issues of flow modeling and technological innovation (Kovacs 2012; Brent et al 2012;Ludwig et al 2012; Zhou et al 2012), quantifying the specific environmental and economic benefits for IS (Matilla et al 2012; Chen et al 2012) and the role of policy (Salmi 2012) are all addressed.

Testing the Boundaries of IS [heading level 1]

IS has manifested itself in various forms internationally, from top-down government mandates to bottom-up independent programs, from self-initiated synergies to facilitated and coordinated IS networks. Unsurprisingly, given the diversity of IS models in practice, there have been continuing debates among researchers concerning the nature and definition of IS. The role of geographic proximity has long been considered an essential component for IS (Chertow 2000), perhaps deriving from the central role played by Kalundborg in shaping expectations of IS, or the presumed low value of the by-product or waste involved. For some synergies (steam sharing, for example), the "spatial extent" of geographic proximity depends upon the nature of the resource; however, recent work has shown that the distance traveled by a resource in a synergy does not statistically correlate with the resource value or mass (Jensen et al 2010), which raises the question of exactly what is meant by geographic proximity. The traditional perception that the IS relationship between participants is somehow more collaborative or altruistic is also being questioned, and support is growing for Ehrenfeld and Gertler's (1997) observation that many synergies are 'business as usual' to the organizations involved (see Lombardi and Laybourn 2012, Chertow and Ehrenfeld 2012; Ashton and Bain 2012, in this issue). Both Chertow and Ehrenfeld (2012) and Lombardi and Laybourn (2012) tackle the essential issue of how we bound the concept of IS and separate the theory of IS from other forms of industrial ecology. Chertow and Ehrenfeld set themselves the ambitious task of establishing a unified theory of IS, while Lombardi and Laybourn confront the issue of how best to define IS from the practitioners' perspective.

Chertow and Ehrenfeld (2012) draw on the complexity literature to develop a 3-stage theory of IS evolution beginning with a random formative stage in which actors begin to engage in synergies for any number of reasons. For Chertow and Ehrenfeld, such synergies are characterized along two dimensions: first they pass a market test, and second the interaction is dynamic. As such, in a manner comparable to other local and regional industrial patterns where new firms appear, disappear or merge together, even successful synergies may not lead to further synergies. Indeed, neither the number of synergies, nor the regulatory environment, nor reduction in costs nor increases in profits are sufficient to ensure the establishment of an IS network. For the network to evolve to the second stage, the net benefits must become known and advocated in the public sphere, leading to the emergence of an incipient institution and further institutionalization that facilitates additions to the network as the new norms and beliefs about IS emerge. For Stage 3 to emerge, the evolving institutions and general awareness identified in Stage 2 must deepen and extend across a region. Important elements of this longer-term institutionalization include embeddedness of network actors, the role of locational factors, and the ways in which social capital comes into play. However, while the authors do not privilege any specific means (social conditions, information, serendipity, facilitation), they do stress the recognition of benefits as an emergent property characteristic of these self-organized systems that moves the process beyond the initial stage.

Lombardi and Laybourn's (2012) provocative redefinition of IS challenges us to think about the diverse interpretations of the elements of IS, at the synergy and network level. After exploring the development of terms associated with IS in the literature, the authors contest the use of commonplace terms (such as exchange for synergy) and concepts (such as the need for geographic proximity, equitable distribution of economic gains, or focus on materials and energy). Building on the OECD definition of eco-innovation as actions taken by business that *result in* environmental benefit (as opposed to seeking it), the authors propose a new definition of IS rooted in eco-innovation and networks for knowledge sharing, intended to communicate the essence of IS as a tool for innovative green growth. The authors close with three challenges about the boundaries of IS: first, reference is made to firms, organizations, industries and facilities participating in IS — is there a 'right' answer for the entity boundary? Second, synergies are generally written about as involving materials, energy and water; although sometimes information and expertise are included — where is the resource boundary? Third, researchers refer to IS as companies engaging with non-traditional partners, yet some synergies have continued for years — where is the temporal boundary of IS?

Role of information and other social factors [heading level 1]

Any model of IS will have to account for the diversity found in practice since industry conventions, expectations and general business milieu are often culturally and regionally specific (Gertler 1995), and these variations must be considered in building a comprehensive theory of IS. Much of this special issue examines the role of access to information and social embeddedness. The concept of embeddedness is concerned with the role of concrete personal relations and networks of such relations in generating trust and discouraging malfeasance during formal and informal interfirm economic interactions (Granovetter, 1985). This has led to interesting tensions between accounts of how the different aspects of social embeddedness vary in importance in different models of IS. The hypothesis that social dimensions may be predictors of IS engagement plays a central role in the papers presented here, as authors explore the interface between social factors at the individual actor level, and outcomes at the industrial system level.

Boons and Spekkink (2012) test the correlation between three dimensions of institutional capacity (relational, knowledge and mobilizational) against an identified opportunity set via analysis of 233 projects initiated under the Dutch stimulation programme for eco-industrial parks from 1999-2004. Results indicate that only the ability to mobilize actors crucial for the synergy is strongly correlated with the outcome. The lack of correlation between knowledge capacity (access to information) and the formation of synergies raises a number of questions regarding the enabling ability of information. For example, Web-based waste exchanges have been implemented widely throughout the world to provide information on resources available for synergies, but there is no evidence that they lead to substantial completed synergies. While Boons and Spekkink operate at the level of a national dataset, Ashton and Bain (2012) examine the role of social factors at the case study level by combining quantitative and qualitative measures of the influence of social relationships and shared norms among actors in an IS network. Their Indian case study assesses short mental distance and communication (which governs the flow of information) among participants in an industrial zone, some of whom are engaged in self-organized synergies. The results support only a weak correlation between communication (structure and content) and the development of synergies—providing further support that information is not the constraining factor in synergy development.

Given that the availability of information has been shown to be insufficient to advance IS, the research then turns to the role of coordination and facilitation in advancing those synergy opportunities for which information on technical and economic criteria is known. This aspect is explored via large data sets (Paquin and Howard Grenville 2012; Boons and Spekkink 2012) complementing case study work (Ferrer 2012; Ashton and Bain 2012) to give a comprehensive assessment. Paquin and Howard-Grenville present analysis of 8 years of the UK's National Industrial Symbiosis Programme (NISP), starting when NISP was only operating regionally. Their analysis indicates a role for embeddedness and serendipity within a facilitated IS network. For example, by seeking out a wide set of firms that may have had interest in IS, and by creating interaction spaces where firm members could meet and share ideas, NISP staff created conditions that facilitated both serendipitous and goal directed synergies from the earliest stages of the program. However, they observe that the role of serendipity in the NISP program apparently differs from that in a self-organizing system, in that NISP staff identify and introduce organizations that might be most receptive to IS and that, in the case of NISP, the facilitation process became increasingly goal-oriented over time.

Complementing the earlier work by Hewes and Lyons (2008), Ferrer (2012) documents the role of a champion in advancing (facilitating) a cooperative approach to resource management in the Brazilian shoemaking industrial cluster of Três Coroas. Because most of the companies in the region are involved in the same production sector (shoes), most face the same waste disposal challenges making symbiotic relationships based on waste or by-products unlikely. Changes in the regulatory regime for waste management forced Brazilian industrial companies to rethink their waste disposal strategies. While many cities build dedicated landfills to deal with their wastes, the community of Três Coroas, under the leadership of a trade association leader and his wife, decided on a long-term solution requiring the proper separation of the industrial waste at its source, thus facilitating potential recycling opportunities and reducing the need for waste disposal. While a number of hurdles needed to be overcome to change existing practices from landfilling or burning to sorting waste at source and transporting it to the recycling center, the cooperation hurdle was more readily overcome in Três Coroas because of 1) an established trade association where much cooperation already occurred, 2) the effective leadership that built the trust to find a joint solution 3) and the transparent method in which the recycling operation was organized (free-riding was not possible).

Designing IS Networks [heading level 1]

Designing IS networks for a particular objective is technically challenging. In this issue, examples are presented for waste heat reuse among SMEs, for carbon emissions reduction, and for resource efficiency. IS network design is also constrained by a series of economic and political realities within which the network must operate.

For example, thermal pinch analysis, a technique to optimize process integration in large chemical plants has been applied for decades by large companies to reduce costs by optimizing reuse of process heat. It is generally not used by SMEs because of the low volume and number of energy flows. However, co-located SMEs with complementary heat demands and waste heat supplies may achieve the critical size necessary for economic heat reuse. Ludwig and colleagues (2012) present an example from pulp and woody biomass energy carriers to illustrate how thermal pinch analysis can be applied to co-located firms in an eco-industrial park. They argue that an extension of process integration to multiple independent companies creates a whole spectrum of technical and organizational challenges to planning and optimization: considering piping distances between individual plants; risk of interruptions when linking independent production processes across plants; and including the reliability of streams in the pinch analysis. In the case where fair distribution of costs and savings among participants is relevant (which does not extend to IS more generally), Ludwig and colleagues suggest cooperative game theory as a solution. They regard both partners of a synergy as equally important for total savings, and thus argue for an approach to allocation that generates results different from those based on actual prices of energy. Further work in this area should focus on the acceptance of such allocation schemes, as well as on customizing general process integration approaches to specific conditions found in practice.

Carbon capture and storage or sequestration (CCS) strategies are now widely viewed as necessary to reduce global emissions of carbon dioxide (CO_2). Brent and colleagues (2012) explore the potential of forming an IS network by situating a mineral carbonation plant as a carbon sink at the heart of a minerals and energy complex. They present a hypothetical case study of such a system within New South Wales, Australia, based on material and energy flows derived from Aspen modeling of a serpentine carbonation process. They demonstrate how several resource-intensive industries can be integrated synergistically to enable a complex producing energy and mineral products with low net CO_2 emissions. Such a system has the potential to significantly offset the energy and emission penalties and direct costs of CO_2 capture and storage. This suggests that greenfield minerals beneficiation (i.e., processes whereby extracted ore from mining is separated into mineral and gangue) and metals refining plants should consider closer integration with the power production and energy provision plants on which they depend, together with a carbon solution, such as mineral carbonation, as a critical element of such integration.

Zhou and colleagues (2012) apply the principles of industrial ecology to a coal-chemical eco-industrial complex using multi-objective and linear programming to compare the behaviors of industrial structures under different scenarios. Models yield a marked (15%) decrease in coal use for coking compared to the actual system. Research results show that the coal-chemical eco-industrial system can achieve a high-value-added utilization of coal and an update of the product structure. According to Zhou and colleagues, such systems will constitute the main development direction for China’s coal utilization in the future.

Technical and economical feasibility, while necessary, are not sufficient for the development of individual synergies or the development of IS networks. This point is taken up by Salmi and colleagues

(2012) who model a technically feasible IS network in the Gulf of Bothnia between Sweden and Finland encompassing 4 carbon steel mills, 1 stainless steel and 1 zinc plant, and a novel iron regeneration plant exchanging 3 by-products/wastes (scales and sludge, jarosite and manganese dregs) that would both improve industry performance and create a number of new synergies. However, current governance structures severely impede the potential success of the network. On the regulatory front, the central issue lies in how regulatory bodies define wastes and by-products. Using the EU Waste Framework Directive Article 3 definition of the boundaries between wastes and by-products, the authors argue that the "binary" quality of the Gulf of Bothnia by-product streams present some unique challenges to the establishment of an IS network: relatively few resource streams; of very large magnitude; not clearly classified as by-products or wastes; subject to fluctuations in market price; and whose potentially hazardous nature may preclude trans-border shipment. The authors draw from the work of economics Nobel laureate Elinor Ostrom to call for the formation of a common pool resource (CPR) system. Under such a system, each party reaps the benefits of having its by-products re-used and its wastes managed within the IS network, while the parties share the risks posed by global markets and waste management. If it can be shown that the benefits (i.e., reliability of flows, costs, and clear definitions) of a CPR system are indeed greater than dependence upon open market systems, CPR may become another useful tool for the IS community to employ.

Implementation of IS [heading level 1]

Research continues to explore technical and other barriers to individual synergies, and the quantification of their impact at the level of both the individual synergies and the broader IS network. Research on the technical implementation and quantitative evaluation of the benefits of individual synergies and IS networks is presented by Kovacs, and Chen and colleagues. The article by Kovacs (2012) tackles the important issue of bio-fuels production at the farm, or small and medium enterprise (SME) scale to boost production capacity and improve product quality and reliability. This article sets the context by introducing the basic chemistry of bio-fuels production and the usual cost drivers therein, explaining why small-scale production is often uneconomic. The author then develops a farm-scale analysis to consider the economic and environmental consequences of a systems approach to small-scale production. By specifically addressing the farm as the system boundary and seeking to reuse flows within that boundary (including refuse and secondary oil sources for feedstock to generate additional revenues), the author introduces important new ideas to improve the small-scale processes to produce bio-diesel, as well as providing advice on enhancements to the production process.

The impact of size of operation, geographic scale, and waste types on the performances of firms engaged in IS, are still unclear (Lyons, 2005, 2007; Van Berkel et al 2000). Using two proxy indicators, (1) the amount of virgin material saved as an indicator for environmental benefits and (2) the operating rate (ratio of wastes treated to the planned amount to be treated) as an indicator for operational performance, Chen and colleagues (2012) analyzed data from 88 sample recycling operations in 23 eco-towns in Japan, to explore how these factors impact environmental and operational performance. First developed in the late 1990s, Japanese Eco-towns are areas where urban planning and environmental management tools are applied to pursue collaborations in resource utilization, waste management, environmental preservation, and the promotion of industrial and economic development. Their initial finding that larger eco-towns achieved proportionally more savings of virgin materials than smaller eco-towns and had a higher degree of stability in operation, is similar to experiences of other types of manufacturing firms that operate under scale economy conditions. Similarly, just as more specialized supplier firms often locate close to their major customers, recycling firms producing products for special users (e.g., industrial inputs) tended to locate closer to their customers. Interestingly, the authors did not find evidence of agglomeration economies (cost savings that firms accrue from locating close to other firms) operating among the firms. Rather, they found that many of the same types of facilities were located in the same eco-town, suggesting that the relationships between the firms are more competitive than collaborative. This important finding will need more investigation since the absence of agglomerative benefits could be a key weakness for eco-town developments going forward.

Following earlier work by Chertow and Lombardi (2005), the issue of accurately quantifying the environmental and economic benefits of synergies is taken up by Matilla and colleagues (2012). They argue for an IS evaluation approach on the basis of the recent life cycle assessment guidelines[iv] developed by the Institute for Environment and Sustainability in the European Union's Joint Research Centre. The authors provide a methodology to extend assessment of the environmental performance of synergies within IS networks to the entire supply chain, thus reducing the risk of transferring emissions from the local synergy to elsewhere in the supply chain, and the risk of overestimating the benefits of IS. In addition, their paper contributes a methodology to determine accurate reference cases from which to empirically evaluate the environmental and economic benefits from IS. They recommend an environmentally extended input-output analysis (EEIOA) to streamline the analysis and provide an industry average baseline for comparison for individual synergies and IS networks. However, they caution that when large scale changes are applied to the system such as the adoption of circular economy in China, more sophisticated tools (e.g., general equilibrium modeling) are necessary but remain to be developed in the IS literature.

Research agenda: Advancing knowledge [heading level 1]

Considerable effort has been invested in developing models for IS, looking for insights that will facilitate the development of more, and more resilient, IS networks. In spite of the debates over definition and scope, IS has graduated from academic curiosity to practical tool supported by policy makers, business organizations, and environmental advocates alike – to address a broad policy agenda encompassing innovation, green growth and economic development in addition to the traditional resource efficiency. Despite the increasing number of academic papers being published on industrial symbiosis, as well as the recent recognition of IS as a key resource efficiency tool by the European Commission, there is much to be done to make IS more theoretically structured and practically enlightening. To this end, we prioritize the following research topics. First, it may be counter-productive to standardize the definition and scope of IS when its diversity and novelty should be encouraged. Nonetheless, it remains constructive to facilitate and advance the debate about the nature, scope, and valuation of IS. Making underlying assumptions of different IS research more explicit will be of great value. The theoretical and practical strengths and weaknesses associated with different definitions and boundaries of IS can then be assessed against growing empirical research. This will help academic debates shift from assertions and exhortations to more productive directions.

Second, to substantially advance theory-building for IS, and inform (if not structure) the discussion of its nature and definition, core IS hypotheses must continue to be challenged and qualified with empirical research, via both large data sets (where possible) and case studies. Such hypotheses include the following:

- IS results in enhanced and shared economic and environmental benefits.
- The IS supplier-customer relationship is fundamentally the same as a traditional supplier-customer relationship
- Social embeddedness is a precursor to the emergence of IS networks.
- The critical dimensions of social embeddedness are culturally independent and vary with IS model
- More extensive and more diverse IS networks are associated with higher stability and resilience
- IS is an effective means to create space for innovation

Third, while more individual case studies remain indispensable to reveal the patterns of IS, comparative research using a common analytical framework covering more than one country or continent will cast more light on the similarities and differences in IS in varying economic, institutional, and cultural contexts. These types of studies deserve further attention, particularly the ones that cross continental boundaries, as they may considerably enhance the generality of the fledging IS theory and policy transfer and replication.

In the spirit of an old Chinese proverb, we "throw a brick to attract jade" and wish the papers in this special issue will bring about challenging and productive academic discussions and debates on the emerging theory of IS, and provide insights that lead to greater impact.

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[i] Complete consensus regarding use of the term industrial symbiosis (IS) has not yet emerged in the literature (see Chertow and Enhrenfeld; Lombardi and Laybourn, this issue). Here we refer to IS as the phenomenon where organisations engage in non-traditional transactions to find beneficial uses for underutilized resources (particularly materials, water, and energy) with environmental and/or economic benefit. When referring to a single transaction between two organizations we use the term 'synergy', whereas the term 'IS network' is used to describe all organizations engaged in synergies with the associated resource transactions.

[ii] For further information on recent developments in European policy, see Laybourn and Lombardi, this issue.
[iii] For further information on recent developments in China, see Shi and colleagues 2012, in this issue.
[iv] The ILCD Handbook. *See http://lct.jrc.ec.europa.eu/assessment/projects#d*