Industrial Symbiosis Dynamics and the Problem of Equivalence

Proposal for a Comparative Framework

Frank Boons, Marian Chertow, Jooyoung Park, Wouter Spekkink, and Han Shi

Keywords:

business strategy
comparative analysis
industrial ecology
industrial park
industrial symbiosis (IS)
social science

Supporting information is linked to this article on the *JIE* website

Summary

Industrial symbiosis (IS), one of the founding notions within the field of industrial ecology, has diffused throughout significant parts of the world as a practice that can reduce the ecological impact of the industrial processes of groups of firms. In this article, we propose a fresh look at this research topic, building on the considerable advances that have been made in the last 15 years in understanding how IS comes about. We propose a conceptual and theoretical framework for taking on the challenge of comparative analysis at a global level. This requires developing an approach to address a solution to the problem of equivalence: the difficulty of comparing instances of IS across different institutional contexts. The proposed framework emphasizes IS as a process and attempts to address the obstacles to comparative study by (1) identifying terminology to examine IS variants, (2) providing a typology of IS dynamics, and (3) formulating key research questions to illuminate a way forward. In developing our argument, we build on the collective experiences of collaborative research efforts in North America, Europe, and Asia as evidenced in recent overviews of the literature.

Introduction

Industrial symbiosis (IS), one of the founding notions within the field of industrial ecology, has diffused throughout significant parts of the world as a practice that can reduce the ecological impact of industrial processes (figure 1). As such, it has left its mark in the realms of policy makers, businesses, nongovernmental organizations (NGOs), and knowledge institutes as well as in physical reality through its actual implementation in regional industrial systems. It also has resulted in a wealth of individual case studies, conceptual and methodological advances, and normative frameworks, as evidenced in several recent review articles of the IS literature: Boons and colleagues (2011) presented a theoretical framework of dynamics; Yu and colleagues (2014b) quantitatively assessed the evolution of recent research; Zhang and colleagues (2015) documented the development of IS from both theoretical and methodological perspectives; Walls and Paquin (2015) examined 121 IS articles specifically about organizational and institutional issues; and Chertow and Park (2016) provided a review of both scholarship and practice over the last 25 years including a bibliometric analysis of 391 peer-reviewed IS articles published between 1995 and 2014 (list available upon request). Such interest holds a large promise of advance through comparative analysis.

Importantly, however, any attempt to advance comparative analysis must address what has been called the *problem of equivalence* in national comparative studies (Teune 1990; Hantrais 1999): that is, the difficulty of finding concepts that identify equivalent empirical phenomena in different countries. This problem has emerged at events where IS researchers have sought to develop a common understanding. One example is the 8th Annual Industrial Symbiosis Research Symposium (held in San Francisco in 2011) that required entry by team and brought together close to 50 participants, including three teams from Asia,

Address correspondence to: Frank Boons, Professor of Innovation and Sustainability, University of Manchester, Sustainable Consumption Institute, University of Manchester, 188 Waterloo Place, Oxford Road, Manchester M13 9PL, United Kingdom. Email: frank.boons@mbs.ac.uk

DOI: 10.1111/jiec.12468

Editor managing review: Donald Lyons

Volume 21, Number 4

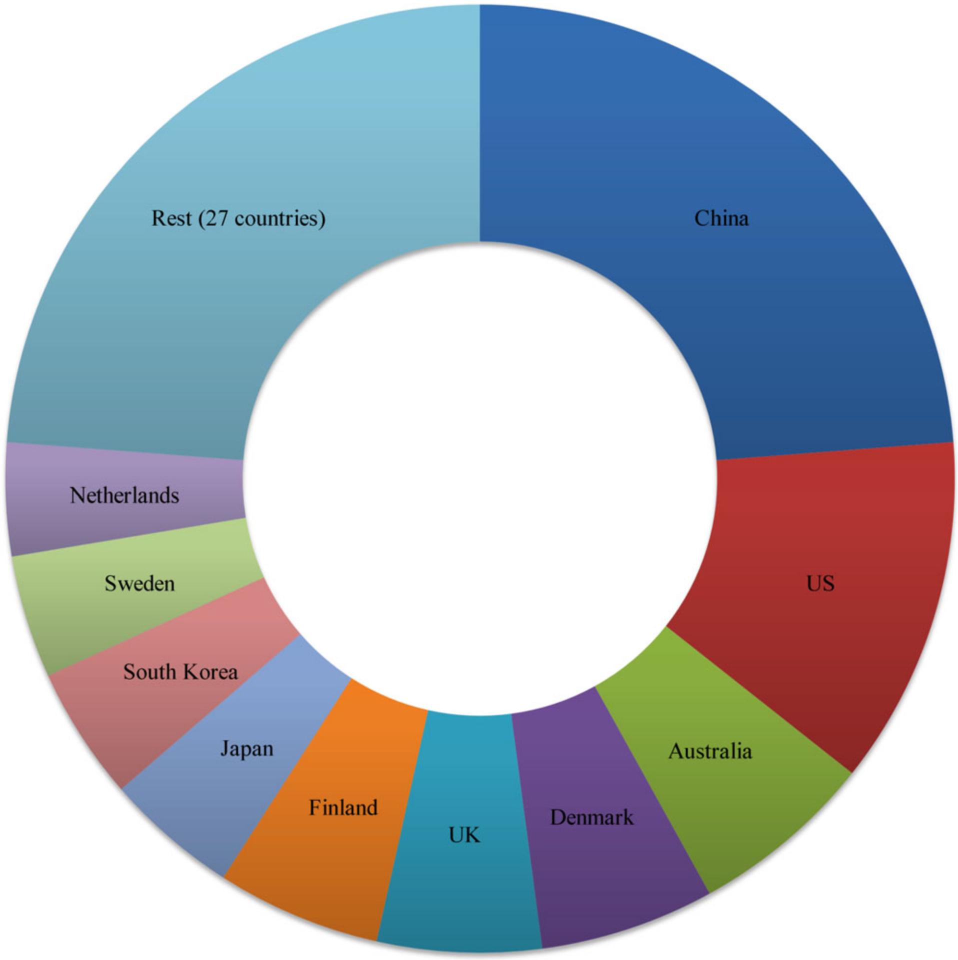

Figure 1 Top ten countries studied for industrial symbiosis in 286 academic papers published between 1995 and 2014 (adjusted from Chertow and Park 2016).

two from Europe, one from North America, and one mixed international team (table 1). The meeting sought a means of generalizing IS findings from projects across the world by discussing core definitional questions and the processes through which IS emerges (see the Supporting Information available on the Journal's website). Along with considerable agreement about the concept and practice of IS, a specific gap was identified during the meeting: the need for a framework to capture the complexity and differences across the various examples of IS.

This result matched the experience of a European network of researchers who have been working on a comparative project since 2010 (Boons et al. 2015). It seems that as the amount of empirical data on IS increases, it becomes more and more difficult for the research community to distill the findings in such a way that this material can be included in a comparative assessment. We specifically address this issue here. Our aim is to provide an integrative conceptual foundation, framework, and research agenda to facilitate the comparative study of IS, adequately dealing with the problem of equivalence.

We begin by disentangling two dimensions of conceptual development in the field of IS: (1) the evolution of concepts as our knowledge base evolves and (2) the differentiation of concepts that results from studying similar phenomena in different institutional contexts. This leads us to propose a conceptual foundation for the comparative analysis of instances of IS based on our developing insight that IS is best conceived as a process, that is, as a sequence of events rather than a certain state of affairs (Boons et al. 2011, 2014; Chertow and Ehrenfeld 2012; Schwarz and Steininger 1997; Baas and Boons 2004; Chertow 2009; Yu et al. 2014a; Spekkink 2013). We offer some screening terminology to aid in the selection of explicit choices that any researcher must make in addressing the problem of equivalence; but we do not prescribe any one specific way of dealing with these issues, leaving them open for continual reflection and development from the scholarly community. We illustrate our comparative framework with cases from the literature.

We conclude the article with three overarching research questions that, in our view, are among the key questions that should be addressed in future studies. This serves the ultimate aim of comparative analysis, which, after all, implies recognizing differences as well as similarities.

Table 1 Attendees at the 8th Annual Industrial Symbiosis Research Symposium

Team	*Team members*
Tsinghua China+	**Lei Shi**, Jinping Tian, Lvjun Chen, Zhen Wang, Weiqiang Chen
KSIE Korea +	**Hung-Suck Park**, Shishir Kumar Behera, Kyeong Ho Kim, Man Jae Han, Yong Un Ban, Junghoon Kim, Junmo Kim
NIES Japan +	**Tsuyoshi Fujita**, Xudong Chen, Minoru Fujii, Son Le
EU Consortium	**Frank Boons and Leo Baas**, Wouter Spekkink, Ralf Isenmann, Graham Aid, Ankit Agarwal, Guillaume Massard
Kalundborg IS+	**Jorgen Christensen**, Martin Anderson, Inez Costa, Robin Branson, Anthony Chiu
International Practitioners	**Peter Lowitt**, Rachel Lombardi, Tim Nolan, Katelyn Harris, Andreas Koenig
Yale USA +	**Marian Chertow**, Weslynne Ashton, Jooyoung Park, Zhouwei Diao, Megha Shenoy, Suzanna Russel, Han Shi, Andrew Zingale

Note: The PLUS sign indicates the name of the core organization and that others from the same region or category also participated on the named team, as appropriate. Names of team leaders appear in bold.

Scientific Concepts Evolving

IS is not an immutable concept. The specific interpretation of the concept that individual (teams of collaborating) researchers adopt in their research depends on the fit of the concept with the research question(s) that the researchers seek to answer, and on the fit of the concept with the empirical data of the researchers. Concepts are building blocks of theory (Stinchcombe 1968; Bacharach 1989), which means that as our knowledge of a phenomenon increases, it may involve modifications in our conceptual language.

In the field of IS, after a period of exploratory research, a definition emerged that has been influential in terms of it being cited (Chertow 2000). However, as our understanding grows, discussion about the definition continues. This has led Deutz (2014) to examine a plethora of definitions and propose a new one, which, in her view, presents the "essence" of IS.

In this article, we take a different route: In pursuing a comparative framework, we have chosen to offer neither an old nor a new definition of IS. We concluded that rather than a single definition made to fit every occasion, our goal would be better informed by the willingness to freely examine a variety of cultural and institutional contexts to see how different concepts and insights became embedded in discussions of IS over time.

There are two phenomena that come into play in our research. First, there is the evolutionary process of scientific knowledge production (Toulmin 1972; Hull 1988).[1] In the confrontation between theory and empirical evidence that occurs in every research project, concepts may be modified. Some variations of concepts are selected, others discarded, and new concepts are put forward. As a whole, the conceptual toolkit used by researchers in any new area thus evolves over time. This view differs fundamentally from the Kuhnian storyline, which depicts conceptual change in terms of revolution, with little possibility of interparadigmatic comparison (Kuhn 1962). Instead, this view examines conceptual evolution with explicit acknowledgment that these concepts are created, contested, shared, and discarded in the interaction among the researchers that constitute an academic field.

A second process is dealing with the problem of equivalence. This issue arises whenever a phenomenon of interest is found to be fundamentally shaped by the cultural and institutional context in which it occurs. This context may be nationally delimited, but institutional context may also differ across regions and within a nation state. In comparative studies in the social sciences, this has led to a range of approaches that can be ordered on a continuum bounded by the following extremes. *Universalism* assumes that in developing knowledge we are looking for universal truth, which implies concepts that are easily applicable in any social context. *Culturalism*, on the other hand, assumes that any phenomenon is shaped by its particular context to such an extent that comparison across social contexts becomes deeply problematic. For IS, where the phenomenon under study is influenced by its social context, this issue needs to be addressed, given that it complicates the evolutionary process of knowledge production: Researchers are, in part, proposing different concepts because they build on an instance of the phenomenon that is specific for a particular social context.

Such a complication of conceptual development definitively occurs in the realm of IS. We seek to advance beyond the point where researchers interested in IS, coming together, find that there is conceptual divergence. The way forward is to explicitly deal with the problem of equivalence. We propose to do so in the following two ways:

(1) By developing a conceptual framing with accompanying terminology that allows an informed discussion of various instances of IS in different social contexts. Researchers can use this terminology to make clear on what grounds they are looking for comparison in their research.
(2) By calling for the need to explicitly study the way in which the concept of IS acquires a different meaning in various social contexts.

Terminology Supporting Conceptual Framing

Any systematic approach to the study of a phenomenon requires a careful framing of the focus of research. Based on the research thus far, we find that there is considerable diversity in defining and understanding the concept of IS: from how to interpret "proximity" to what is meant by "exchanges" or "network," and what types of resources (e.g., industrial and/or municipal solid waste, by-product, or nonmaterial resources) need to be considered. We assume that this is, to a great extent, a result of differences in empirical manifestations in different regions of the world that result from many underlying factors: from how the economy is financed to legal systems to cultural norms and many others. Indeed, the problem of equivalence appears to be quite serious for IS. Rather than get "stuck" with so much divergence, we seek a means of moving forward.

One idea we put forward to underlie the discussion of dynamics is to adopt terminology to facilitate comparison across empirical phenomena in different regions. We add this terminology to our conceptual framework to signify a set of inclusive statements about the phenomenon we study. The set of such statements presented below has a far different mission than a definition of IS, given that it is intended to help us identify commonalities and differences, up to the point where we can discuss on what grounds an empirical case should be considered under the label of IS. We use the terminology in the paragraph below as a filtering tool to establish a more concrete proposal concerning the dynamic nature of IS, to set the stage for the introduction of specific dynamic types and to foster ongoing discussion as new cases are added by researchers.

For these purposes, we recognize IS as a process of connecting flows among industrial actors through (1) use of secondary material, water, and energy resources and/or (2) utility and service sharing, such as collective use of infrastructure or environmentally related services across a network. The associated process of change entails, to varying degrees, the development and mobilization of intangible resources, such as intellectual capital and social capital by public and/or private actors. A key to IS that differentiates it from other forms of multiactor economic development is the recognition of net environmental benefits associated with the connecting of flows.

This statement uses *a process of connecting flows* as its central characteristic to make clear that IS can be, and often is, built upon a set of industrial actors that are already related with or without being connected by material flows. It is not a static phenomenon, but a series of events through which connections are built up, maintained, and eventually dissolve. We seek to identify typical ways in which this process unfolds, and we term these *industrial symbiosis dynamics* (see the section on *The Dynamics of Industrial Symbiosis*).

Broadly, *secondary resources* points us to materials that are put to circular use instead of being discarded or discharged, after being generated from a process of production or previous use. Materials in this case can differ from resources such as steam and other types of energy and also water where previous use cannot always be determined.

One change that we propose for IS is to instill the idea that IS involves a *network* of at least three actors. This presents a difference from symbiosis in biology, where exchange between two organisms can be classified as symbiotic. Not surprisingly, early industrial ecologists, borrowing from environmental science, picked up on the notion of at least two organisms (Côté and Cohen-Rosenthal 1998). Describing IS as a network that involves at least three actors implies a certain level of complexity that transcends a flow that is only between two actors, with the latter considered a precursor to IS at the time that a network is still emerging (Chertow 2007), or as a component of IS once the network has materialized. When a bilateral flow is embedded in a network, any changes that occur in that flow may ripple through the network (Choi and Wu 2009). Therefore, our terminology urges researchers to look beyond the level of bilateral exchanges to also consider wider network effects that will be overlooked if the focus is restricted to that level. The network of IS actors need not be established all at once, but may instead spring from a series of bilateral flows, which reconciles the pairing of twos with the evolving network of three or more and the network benefits that result from it (Jacobsen and Anderberg 2004; Laybourn and Morrissey 2009).

Industrial actors are the economically and organizationally discernible units (with some discretionary decision-making power) that undertake activities that transform inputs into outputs intended for further transformation or consumption.

Connecting flows involves coordinated activities by industrial actors. A wide variety of coordinated activities has been observed in empirical work on IS, including (but not limited to) contract negotiation, joint visioning, facilitation, and the formulation, implementation, monitoring, and evaluation of policy programs. Engaging in coordinated activities requires the industrial actors to mobilize intangible resources, such as social capital (i.e., resources that industrial actors derive from their position in social networks) and intellectual capital (i.e., tacit and explicit knowledge to which industrial actors have access) (Healey et al. 2003; Boons and Spekkink 2012; Spekkink 2013, 2015).

Connecting flows by using secondary resources generated from one industrial actor can begin for any reason, but ultimately, whether intentionally or unintentionally, carries with it different consequences for *environmental impact*. Even *environmental benefits* can be unobserved for short or long periods of time, but it is only after these benefits are recognized, and/or enter the public consciousness, and result in further steps to ensure their continuation that a process of connecting flows is seen as IS (Chertow and Ehrenfeld 2012).

Each of the underlined terms constitutes terminology of the new comparative framework. Each is potentially subject to the problem of equivalence. We have described the italicized items carefully with some precision as a first attempt to validate them as a workable basis of comparison.

The Dynamics of Industrial Symbiosis

In our proposal, we refer to IS dynamics as the typical pathways through which the process of IS unfolds. In our view, the existing empirical evidence provides us with enough insight to specify a number of such dynamics and we expect that this number will expand over time. This is a step in theory building: Pathways specify sequences of events that we find regularly in empirical material.[2] These can be viewed as social mechanisms, which Elster (2007, 36) defines as "frequently occurring and easily

Table 2 Seven types of industrial symbiosis dynamics, characterized by initial actors, their motivation, overall storyline, and typical outcomes (as indicated in literature)

Dynamics / *Typology*	*Initial actor(s)*	*Motivation of the initial actor(s)*	*Following actions/overall storyline*	*Typical outcomes*
Self-organization	Industrial actor	See economic and/or environmental benefits from IS	Industrial actors expect benefits in developing symbiotic linkages → industrial actors search for suitable partners (existing partners in vicinity or new partners attracted from further away) → after finding a suitable partner, contracts are negotiated → linkage becomes operative → [repeat].	Agglomeration Hub-and-spoke network Decentralized network
Organizational boundary change	Industrial actor	Eco-efficiency and business strategy	An industrial actor expands its activities through vertical integration and develops internal exchanges → the industrial actor changes its strategy from vertical integration into outsourcing → the linkages remain and the system evolves into an interorganizational network.	
Facilitation-brokerage	A public or private third-party organization	Establish/increase transparency of market for firms to develop IS	A third-party organization sets up a brokerage system → the broker establishes a market for industrial symbiosis development → industrial actors engage and develop symbiotic exchanges through the market system.	One-off network of symbiotic exchanges
Facilitation—collective learning	A public or private third-party organization	Enable firms to develop tacit knowledge and exchange experiences	A facilitator picks up the concept of industrial symbiosis from existing examples → the concept is translated into specific regional context → industrial actor and facilitator engage in collaborative learning to develop symbiotic network.	
Pilot facilitation and dissemination	A public or private third-party organization	Learn from nonlocal existing IS cases and experiment in a local context	A facilitator picks up the concept of industrial symbiosis from existing examples → the concept is translated into specific national/regional context → groups of colocated industrial actors are selected to serve as exemplary cases → further refinement of the concept occurs through learning in pilot projects → the experiences from pilot projects are transmitted by the facilitator to other groups of colocated industrial actors.	Diffusion of IS concept among clusters
Government planning	Governmental actor(s)	Learn from existing IS cases and implement	A governmental actor picks up the concept of industrial symbiosis from existing examples → the concept is included in policies and translated to the specific national/regional context → the governmental actor develops a plan for the development of linkages through stimulating and/or enforcing policy instruments → the progress of implementation is monitored → the results of evaluations are fed back into the policy to realize continuation/renewal/closure.	
Eco-cluster development	Governmental and/or industrial actors	Innovation, economic development	Local governments and/or industrial actors develop a strategy for the development of an eco-cluster → symbiotic linkages are developed through participatory process among multiple stakeholders as part of the broader eco-innovative strategies.	Redevelopment Brownfield development Greenfield development Innovation cluster

Note: IS = industrial symbiosis.

recognizable causal patterns that are triggered under generally unknown conditions or with indeterminate consequences." The task for a researcher, then, is to specify the conditions and consequences for the occurrence of a specific dynamic. Table 2 provides an overview of the proposed dynamics. Each dynamic is identified by initial actor(s), actor motivations, and the actions that follow, which provides an overall storyline revealing how each dynamic is composed and sequenced. Together, these descriptors allow for a variety of analytical approaches, ranging from regression analysis to narrative analysis.

In order to emphasize the process focus of our conceptualization, we have used a mode of representation in figure 2 indicating that the evolution of IS can be seen as a sequence of events. Identifying patterns in these sequences consists of two

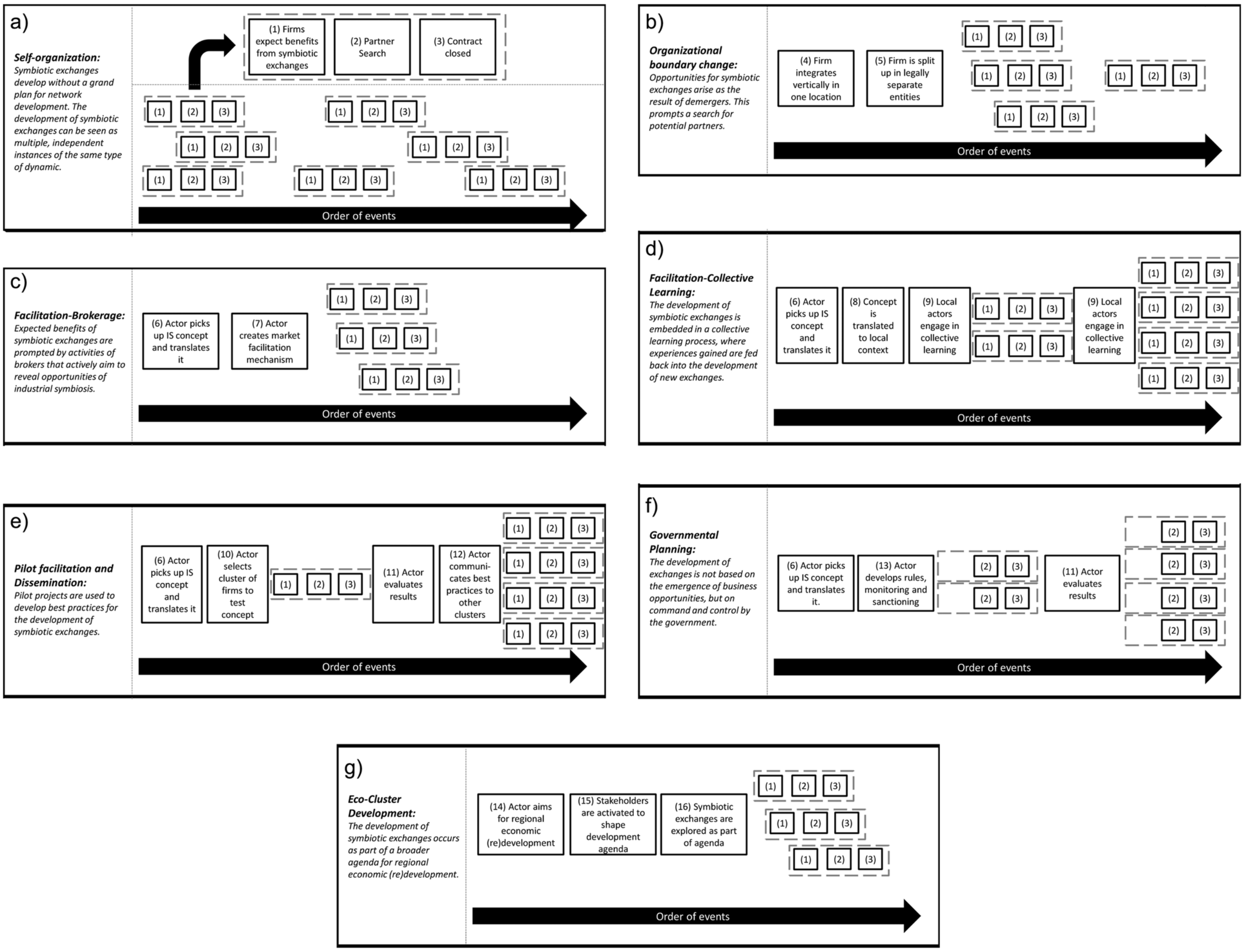

Figure 2 Diagram visualizing sequences of events for dynamics as listed in table 2.

steps: (1) finding building blocks, that is, events that make up the sequences and (2) constructing common sequences out of these building blocks. The visualization makes clear that the seven different dynamics that we identify contain the same building blocks. Events are numbered to make it easy to detect where the same events occur in different sequences.

These seven dynamics are, at this moment, a result of our knowledge of the literature and collective experience. They are thus propositions in the sense that we put them forward for empirical testing. In its strongest form, the sequences can be taken as combinations of conditions that have to be fulfilled to produce a symbiotic network. Each dynamic (i.e., the sequence of events as a whole) is a sufficient condition for producing a symbiotic network; how the individual events relate to one another (e.g., whether each event is a necessary condition for the event that follows it) is a matter for empirical testing. Another way of looking at these is as "ideal types" in the sense that this term is used in the social sciences: They specify recurring patterns of action that serve a heuristic function in comparative analysis; actual empirical patterns can be compared to them (and through the ideal type, with others) to see how the case under scrutiny is similar or dissimilar (Kalberg 2012).[3]

After having developed our typology of IS dynamics, we studied existing case descriptions of IS for the occurrence of the events that we include as building blocks of our dynamics. This enabled us to determine which dynamics are manifested in which cases, and we used this information to pick our examples of the dynamics. From the outset, we want to stress that these dynamics are not intended to cover complete empirical cases of IS throughout their evolution. As we will make clear throughout our examples, the same case (i.e., an industrial park in a specific geographical location) may display a certain dynamic for some period of time and then shift into another dynamic.

Self-Organization

The dynamic of self-organization describes the development of symbiotic activities as a result of the self-motivated strategies of industrial actors. Self-organized IS does not start with the ambition to develop a network of symbiotic exchanges. Most often, the linkages that constitute the network have developed more or less autonomously and are driven by various motivations and incentives from the individual industrial actors. These autonomous actions of individual industrial actors occur within a certain underlying context that is, in turn, shaped and influenced by institutional factors such as the level of trust, social norms, regulatory programs, and policy. This context provides the boundary conditions,[4] which are necessary for the process of self-organization to occur (Boons 2008). Kalundborg is an iconic example of this dynamic, given that its symbiotic network has developed over four decades through the close interactions among industrial actors (which, in this case, includes firms as well as a facility owned by the municipality) without any grand plan for network development (Ehrenfeld and Gertler 1997). Similar cases of self-organization include Styria in Austria (Schwarz and Steininger 1997), Guayama in Puerto Rico (Chertow and Lombardi 2005), Kwinana in Australia (Van Beers et al. 2007), and Nanjangud in India (Bain et al. 2010).

Because of the nature of autonomous development, actors in one part of a symbiotic network may have no or only partial knowledge about actors participating in another part of the network. This was the case in Hawaii, according to interviews conducted with facility managers (Chertow 2011). When the spontaneously developed symbiotic linkages have been uncovered, the development of IS becomes a conscious strategy (Chertow 2007), and thus it is likely that the dynamic would gradually shift into another one.

A special case of the self-organization dynamic occurs when a core industrial actor (anchor) attracts other actors (tenants) to develop a symbiotic network (Korhonen 2001; Chertow 1999), primarily for the benefit of the core actor. One example of this dynamic is the Campbell Industrial Park in Hawaii, where the core firm AES (developer of a modern coal-fired power plant) attracted satellite firms that can provide input substitutes for coal to AES from their outputs and also use by-products from AES for production (Chertow and Miyata 2011). This anchor tenant strategy has been widely adopted in the development of eco-industrial parks (EIPs) in China. A representative example is a fine-chemical industrial park called Zhejiang Hangzhou Bay Shangyu Industrial Area (Tian et al. 2012a, 2012b). Two world-leading dyestuff manufacturers have served as the anchors of an increasingly expanded industrial symbiotic network. The growing IS network built along the value chain of the two dye groups has played a significant role in improving the sulfur utilization efficiency and reducing the greenhouse gas emissions (Tian et al. 2012a).

Organizational Boundary Change

The dynamic of organizational boundary change describes cases where symbiotic networks form and evolve when firms make changes in their organizational boundaries, such as through outsourcing or insourcing, vertical (des)integration, or divesting a subsidiary. When the boundary becomes less inclusive, internal exchanges within a vertically integrated firm turn into interfirm exchanges, creating the core of a symbiotic network that may continue to grow. Examples of this dynamic can be found in the Scandinavian forest industry, where some symbiotic linkages evolved from exchanges that used to take place within the organizational boundaries of one company (Wolf and Petersson 2007; Pakarinen et al. 2010). Another example is the case of the Guitang Group (Zhu et al. 2007), first established as a state-owned enterprise in China. The Guitang Group was designed to focus primarily on sugar refining and molasses production, but early on it expanded its business to include paper production from its own fibrous sugar cane by-product, bagasse. Outside companies subsequently joined the system to contribute input material, making it a case of IS. A similar dynamic is seen in the case of British Sugar, which evolved through boundary expansion to create trade for numerous by-products including excess energy and carbon dioxide, which helped the company become not only the largest sugar manufacturer in the country, but also the largest tomato grower as well (Short et al. 2014).

Several cases of IS are characterized by the activities of an actor seeking to enable the development of symbiotic linkages among industrial actors. We distinguish two forms, depending on the nature of the activities, knowing there is no bright line between them: facilitation-brokerage and facilitation–collective learning.

Facilitation (a): Brokerage

Brokerage is a dynamic where a third-party organization steps in to make the potential market for secondary resources more transparent, to help it emerge or increase in terms of the quantity of exchange. The exemplary model of this dynamic was the National Industrial Symbiosis Programme (NISP) in the United Kingdom in its initial phase (Mirata 2004; Paquin and Howard-Grenville 2012). Regional coordinators of NISP organized forums to facilitate communication and networking among industrial actors and thus facilitated identification of symbiotic opportunities. They also stayed involved by providing assistance for implementation and follow-up monitoring activities.

The United States Business Council for Sustainable Development (USBCSD), a nonprofit business association, plays a similar role in facilitating IS, what they call by-product synergy (Mangan and Olivetti 2010). The USBCSD provided many case examples preceding the creation of NISP through its earlier incarnation as the Business Council for Sustainable Development-Gulf of Mexico (BCSD-GM) (BCSD-GM 1997). The USBCSD particularly acts as an information broker by compiling information related to IS and using it to explore synergistic opportunities. Most recently, the organization has developed software, to establish an online market for secondary resource transactions (USBCSD 2016).

Facilitation (b): Collective Learning

Third parties may adopt a more intensive stance beyond seeking to make the market for secondary resources transparent. They may seek to initiate and maintain a process of collaborative learning, which they deem necessary to arrive at more structural and more advanced symbiotic linkages. The learning process may lead to the development of advanced levels of trust, which enables firms to engage in transactions of higher asset specificity. Facilitators focus on the development and exchange of experiential knowledge, which distinguishes it from the role of an information broker. An example of this dynamic concerns the first phases of the Indicators of Education Systems (INES) Mainport programme (1994–2002), where the business association, Deltalinqs, facilitated a wide range of projects in several phases to learn about the implementation of IS in the Rotterdam Harbor and Industry Complex (Baas and Boons 2007). According to Paquin and Howard-Grenville (2012), over time the NISP program also evolved into this type of dynamic. NISP initially focused on creating interaction space for industrial actors. But as learning occurs, the actors began to engage in more strategic and goal-directed processes, for example, by introducing available symbiosis projects to relevant firms and selectively developing high-value linkages. As illustrated here, these two types of facilitation, brokerage and collective learning, can also shift back and forth.

Pilot Facilitation and Dissemination

The dynamic of pilot facilitation describes instances of IS in which a facilitator picks up the concept of IS from existing examples, and develops a conceptual model that is adapted to a specific national or regional context. This model is then the source of experiments in existing or planned industrial parks. The facilitator may play a wide range of roles from collecting technical data to organizing workshops or meetings, conducting feasibility studies, being involved in negotiation, decision making, and follow-up activities for operation of symbiosis. Facilitators can come from a variety of organizations, including government bodies, business associations, or research institutes; in each case, their aim is to foster the uptake of IS in the selected industrial park by demonstrating its viability in the local context in which it operates.

The EIP Development Program in South Korea explicitly took the approach of pilot experimentation and facilitation (Park et al. 2008; Behera et al. 2012; Park et al. 2016). In the first phase (2005–2010) of the 15-year, three-phase program, pilot projects were carried out in five selected industrial complexes, facilitated by organizations such as the Korea National Cleaner Production Center, a research institute, and later the Korea Industrial Complex Corporation, a quasi-governmental body. The program has completed its second phase, where knowledge and experiences gained in the pilot projects are disseminated to other sites and is now in its third phase that aims to establish an IS network at a national level and Korea's own model to IS development.

Another example of this dynamic is a national policy program in the Netherlands that seeks to stimulate the diffusion of sustainable industrial parks (Boons and Janssen 2004; Boons and Spekkink 2012; Pellenbarg 2002). The program was carried out by an agency of the Ministry of Economic Affairs, which acted as a facilitator of a large number of local projects on industrial parks. The program led to the development of descriptions of best practices, dissemination of useful contract and planning forms, and manuals for planning agencies, park managers, and firms. The subsidy program, however, did not get continuing support as a result of changing priorities of the national government.

Government Planning

In this dynamic, governmental actors consciously plan place-based eco-industrial development. To implement it in the specific regional or national context, governmental actors formulate strategies and develop and implement plans of action using incentives and enforcement. Usually, the implementation of the action plans is monitored for its results. Based on an evaluation of the results the governmental actor may decide to continue, renew, or end its policies on IS or EIPs. EIPs that are granted approval from the Chinese Ministry of Environmental Protection or the National Development and Reform Commission are examples of this dynamic (Zhang et al. 2010). The development of symbiotic linkages was initiated and driven by the national policy for EIPs and circular economy, which has gone through several evolutions in the past 10 to 15 years (Shi et al. 2012a, 2012b; Geng et al. 2012). Examples of well-developed EIPs in China include Tianjin Economic-Technological Development Area and Suzhou Industrial Park (Shi et al. 2010; Yu et al. 2014a). The EIP Development Program in South Korea also has the aspect of this dynamic in that the national government established a law specifically targeting the development of EIPs and the mechanisms for financial support. Within this larger institutional support, regional EIP centers are actively involved in the process of exploration, feasibility testing, and implementation of IS as illustrated by the first phase of the Korean national program described above under the dynamic of "Pilot Facilitation."

Eco-Cluster Development

The dynamic of eco-cluster development describes cases where different local actors (e.g., local governments, firms, and interest organizations) come together around the goal of achieving economic development and/or technological innovation, and IS is implemented as part of that developmental strategy. One example of this dynamic can be seen in the adaptive reuse of the decommissioned Fort Devens Army Base in Massachusetts (Veleva et al. 2015). The planned objective of the redevelopment was to attract jobs and investment into the region with IS as one of the component strategies (Deutz and Gibbs 2004; Lowitt 2008). ReVenture Park, a former textile dye manufacturing facility in Charlotte, North Carolina, is another example of this dynamic, albeit in an earlier stage of development. Several innovative projects regarding renewable energy, alternative fuel, and recycling are being planned or implemented by taking advantage of dormant industrial facilities on site, including wastewater and energy infrastructure (ReVenture Park 2016)

In Östergötland, Sweden, local firms, governments, and knowledge institutes work together to integrate the local transport system and energy system through IS based on a complex network of exchanges within the biofuel industries (Martin and Eklund 2011). To integrate these two systems that used to be separate, a participatory process was essential to resolve any barriers among actors from the two different systems (Vernay and Boons 2015). A similar example is the Biopark Terneuzen initiative in Zeeland, the Netherlands (Spekkink 2013). Here, firms, governmental organizations, knowledge institutes, and interest groups engaged in a participatory process to develop a cluster of companies active in the bio-based economy. It emerged out of separate projects that developed individual symbiotic linkages and moved toward a process that was driven by an explicit vision about a bio-based cluster. The Japanese Eco-Town program may also be understood as an example of this dynamic because of the attempt to integrate urban systems with industrial systems (Van Berkel et al. 2009b).

Generative Research Questions

In order to advance the comparative analysis of IS, we propose a structured research agenda in this section. The agenda is based on the material presented above and, in that sense, represents a distinctive approach to the study of IS, in which the concept of IS dynamics is key, and identifying the conditions and consequences of these dynamics provides a starting point. At the same time, the agenda is open, considering that answering these questions requires further theoretical and methodological choices, which are up to each individual research team. In doing so, a researcher may want to develop propositions. Given that there is already a wealth of empirical material built up in the last 15 years, it is possible to formulate generalized expectations about how key variables relate to one another. But, given that these propositions build on specific theoretical positions, we abstain from formulating a complete set; we will only give some indicative examples.

Figure 3 summarizes the structure of our research agenda. Propositions under research question 1 (R1) address causal relationships between IS dynamics and underlying conditions that trigger a certain dynamic to occur, whereas propositions under research question 2 (R2) link IS dynamics to its outcomes. Propositions under research question 3 (R3) explore any linkages among dynamics typologies that build to multistage phase models. Each typology is represented as an arrow with different shades of gray. Each phase model is represented by a single arrow (i.e., typology A) or a group of connected arrows (i.e., typology B and C, typology D, E, and F). Below, we present what we believe to be three key research questions and related propositions. We stress the importance of making clear what theories are used as a basis for developing ideas about relationships among variables, and in our examples will mention these explicitly. This does not mean that these are the only possible theories to be used; as stated above, this is left to the discretion of each researcher that works with these questions. Further, we reiterate the points made earlier in relation to the problem of equivalence, calling for: (1) an explicit formulation of IS terminology to address both (the commonalities across all cases and the dimensions researchers are examining for variation) and (2) an explicit analysis of the way in which the specific instance of IS in the contexts studied came about.

R1. Are different dynamics triggered under specific conditions?

Although many of the conditions that trigger the different types of dynamics are not yet fully known (Elster 2007), we argue that based on previous research, it is possible to identify conditions that are generally more or less favorable to certain dynamics. In order to do so, we can distinguish technical, economic, geospatial, as well as social and institutional conditions (Gibbs 2003; Mirata 2004; BCSD-GM 1997).

Technical conditions relate to physical resources and the set of production processes available in a region of colocated industrial actors. These conditions include the availability of secondary resources for appropriate input-output matching (Trokanas et al. 2014) and technologies that enable transformations and processing of resources (Geng and Côté 2002; Liwarska-Bizukojc et al. 2009).

Economic conditions are important in that industrial actors are sensitive to net benefits of IS. High price of input resources or high disposal costs, for example, incentivize industrial actors to search for alternatives, which may sometimes be found in the form of secondary resources of colocated industrial actors. Several previous studies estimated net cost savings through IS, either for potential networks (Karlsson and Wolf 2008; Martin et al. 1998) or for existing networks (Jacobsen 2006; Van Berkel et al. 2009a).

Geospatial conditions, such as the distance among industrial actors, influence the feasibility of implementing certain symbiotic relationships. Proximity has been known as a key facilitator of IS (Chertow 2000), which influences not only the transportation cost, but also social dynamics among industrial actors (Sterr and Ott 2004). The scale of IS and its underlying factors began to be the focus of empirical testing (Lyons 2007; Jensen et al. 2011; Chen et al. 2012). Recently, the spatial concentration and agglomeration of symbiosis activities became the subject of analysis (Gregson et al. 2012; Cerceau et al. 2014).

IS operates on interactions and collaborations of various types of actors and therefore hinges on *social and institutional conditions*. Social and institutional conditions have been studied from various aspects, such as trust among actors (Gibbs 2003; Ashton 2008; Jacobsen 2007), role of champions (Hewes and Lyons 2008) or facilitators (von Malmborg 2004; Paquin and Howard-Grenville 2013), organizational capacities (Boons and Spekkink 2012; Liu et al. 2012; Spekkink 2015), and policy interventions (Yu et al. 2015; Jiao and Boons 2014). To integrate these factors conceptually, the framework of "social embeddedness" was developed (Boons and Howard-Grenville 2009) and applied to analyze IS cases (Baas and Huisingh 2008; Domenech and Davies 2011).

Building onto previous research, as presented above, the framework of a dynamics typology can help to advance our understanding of the link between conditions and dynamics

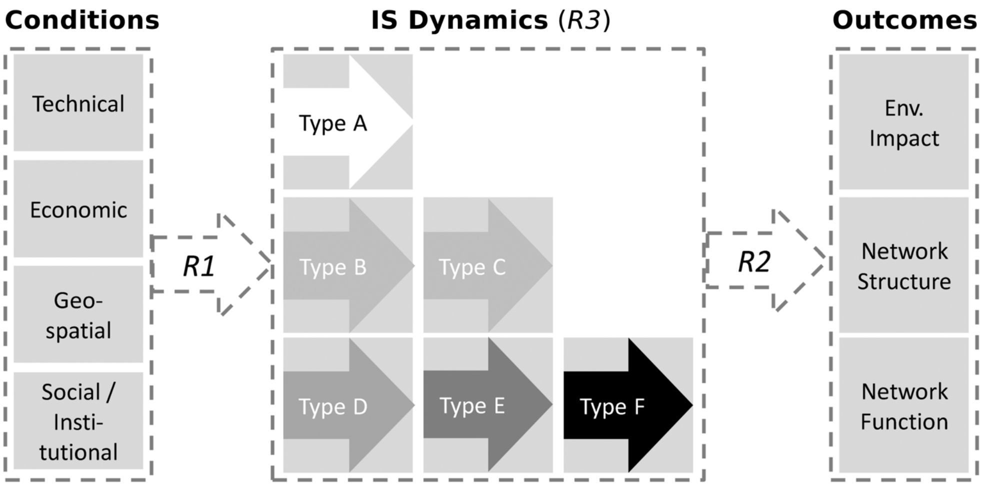

Figure 3 Diagram that shows relationship among theoretical concepts to construct propositions. Research question 1 (R1) addresses the causal relationship between IS dynamics and underlying conditions, R2 links IS dynamics to its outcome, and R3 explores any linkages among dynamic typologies. Each typology is represented as an arrow and each phase model is either represented by a single arrow or by a group of connected arrows. IS = industrial symbiosis.

of IS. For example, according to one of the central theses of the *Varieties of Capitalism* approach in political economy (Hall and Soskice 2001), which says that economic actors base their strategies for interaction on opportunities generated by the institutional structure in which they are embedded, we can establish a similar proposition for IS to examine the relationship between institutional structure (in terms of levels of trust, relationships with communities, and levels/types of state involvement) and dynamics of industrial symbiosis. An example hypothesis would be: *The self-organizing dynamic tends to correlate more often with communities that have greater social capital.* Testing of this hypothesis can be built on previous studies, such as Ashton (2008).

Propositions may address the relative importance of different types of conditions. Given that much of the literature has focused on institutional conditions, the implicit idea has been that these conditions are the main factor that accounts for the successful establishment of symbiotic linkages. Using the insights of the ecological analogy developed by Geng and Côté (2002) and Liwarska-Bizukojc and colleagues (2009), we can develop an argument that certain constellations of industrial processes are unlikely to develop symbiotic linkages, no matter what institutional conditions are present. In this line of thinking, another hypothesis we can develop and test is: *Without sufficient variety of industrial actors in terms of producers, consumers and decomposers, institutional conditions will not affect the establishment of symbiotic linkages.*

R2. What outcomes are linked to different types of dynamics?

The generic underpinning of the second research question may come from process theories that claim that the explanation of certain phenomena requires the analysis of the sequence of events that precedes them, for instance, when we speak of path dependency (Mahoney 2000). Each of the IS dynamics specifies a sequence of events that leads to certain outcomes. Such outcomes may be defined in terms of the reduction of environmental impact (compared with the baseline impact of the set of firms before additional connections were made) (Geng et al. 2014; Dong et al. 2014; Mattila et al. 2010; Sokka et al. 2011), or in terms of the characteristics of the network (e.g., connectance, structure, resilience, and stability) that emerges among firms (Chopra and Khanna 2014; Wang et al. 2013a; Wright et al. 2009; Zhu and Ruth 2013; Hardy and Graedel 2002). Whereas previous research focuses more on developing a methodology and measuring actual outcomes of IS, a whole line of research can be developed to see whether a dynamic constitutes a pathway to a specific outcome, and whether it is a necessary and/or sufficient condition for bringing about a certain outcome. Note that this builds on the assumption that the dynamics are an intermediating variable between conditions and outcomes.

In certain cases, outcomes may be directly related to starting conditions, or alternatively, a dynamic may have certain characteristics that are seen as explaining an outcome. For example, we can postulate that the involvement of state agencies will lead to a certain type of company commitment that produces different results than when firms are self-motivated. Here, neo-institutional theory may provide a possible basis by specifying the mechanisms under which a concept like IS spreads through an organizational field, based on the core assumption that industrial actors may adopt such concepts for reasons of legitimacy (DiMaggio and Powell 1983; Boons et al. 2011). When state agencies are involved, firms may adopt the language and rituals (Meyer and Rowan 1977) of IS without actually producing new linkages and environmental benefits.

A question that is of great interest to the field is whether different dynamics of IS development lead to different magnitudes of environmental benefits. Who initiated and developed the IS network with what motivations, as well as the subsequent events that unfold, may influence the quantity and the type of physical resources exchanged, which, in turn, determines the magnitude of environmental benefits. For example, direct public intervention may involve strategies to promote the most public good and so would foster the types of resource exchanges that lead to the highest environmental benefits.

We also posit that structural characteristics of the IS networks depend on the dynamics that brought them about. For example, in certain cases, the dynamic of shifting organizational boundaries and the dynamic of self-organization can both be expected to lead to a relatively centralized IS network where a core firm is surrounded by several satellite firms. One empirical study already examined the relationship between different IS development dynamics and the resulting network structures. Based on 15 IS networks, Zhu and Ruth (2014) showed that self-organization and planning lead to different network growth patterns.

Another expectation is that a particular dynamic will have consequences for the type of exchanges that will result. When a third-party actor takes on the role of broker, exchanges may resemble arms-length transactions, such as with online transfers, whereas the facilitation of learning can be expected to lead to longer lasting exchanges based on a higher level of trust.

R3. How do dynamics add up into phase models?

If we apply the dynamics to known IS cases, then, in several instances, we see that a case is characterized by several dynamics that follow one another in time. This leads into the question of typical sequences of dynamics. The phase models that have been proposed to analyze the evolution of IS postulate that there is a specific order in which symbiotic networks build on one another. For example, one phase model may start with self-organization and shift toward facilitated collective learning. Such learning may have a better chance of success if it builds on existing symbiotic exchanges that have already achieved a certain level of maturation.

We propose that a basic distinction can be made between (1) self-reinforcing dynamics that tend to "extend their own duration" through positive feedback mechanisms (Sterman 2000) and (2) unstable dynamics that tend to shift relatively easily into another type of dynamic. For example, the dynamic of facilitation–collective learning may include a positive feedback mechanism suggesting that the establishment of one symbiotic exchange leads to the establishment of additional symbiotic exchanges. This could be the reason why this dynamic is persistent in several cases. A dynamic that shifts relatively easily into another dynamic is that of self-organization, because once the potential of industrial symbiosis is "uncovered" (Chertow 2007), the involved actors are likely to gravitate toward intentional strategies favoring the further development of the network. In the Chinese context, several leading EIPs, including the Tianjin Economic-Technological Development Area (Shi et al. 2010; Yu et al. 2014a) and Sino-Singapore Suzhou Industrial Park (Wang et al. 2013b) have manifested a similar transition from the government planning dynamic to the facilitation–collective learning dynamic. The common features of the transition include a higher level of interfirm exchange, which are often sustained self-initiated symbiotic exchanges.

Conclusion

In this article, we have sought to bring more unity and clarity to understanding the diverse instances of IS clusters and the pathways through which they emerge and evolve. Identifying the need for a means of comparing across disparate IS developments in consultation with research teams across the world (table 1) has enabled our research community not only to acknowledge the complexity of IS, but also to search more deeply for a way to look for common driving forces and evolutionary pathways/trajectories and find a way to address the problem of equivalence

Our first decision for this article was to explicitly conceptualize IS as a process. Our second was *not* to offer a standardized definition of IS, but rather to establish sensitizing terminology that enables researchers to make explicit, for their specific research project, the dimensions for which they look for commonalities and differences in the cases they are comparing. Building on these insights, we identified seven pathways through which the process unfolds, identifying these as dynamics of IS and illustrating them in narrative and visual form (table 2 and figure 2) based on detailed discussion of dozens of case studies. Eliciting these dynamics then allowed us to set a foundation for our own generalized expectations, in the form of research questions about the relationships among starting conditions, IS dynamics, and outcomes.

We consider this article to be a fruitful starting point for comparative studies that seek to deepen our understanding of IS in its vastly differing manifestations as observed by researchers over at least the last two decades. Of great need now is empirical testing of the dynamics, reaching out to examine research questions we have suggested, and requesting and dissecting many more. In this way, our article is a call for increased discussion and engagement with one another, through contributions to theory, through finding limitations and improvements to the method proposed here, and, most of all, through informing practice so that disparate instances of IS can be commonly understood and their trajectories assessed and assisted according to the findings of our research community. In this sense, our article is an invitation to all interested researchers to join the process and constructively engage development of the framework initiated here.

Having been deeply engaged in questions of environment and development for most of our careers, we have a further hope, which is that others beyond the IS community also find something useful in this work. We have observed debates about sustainability, how to define it, when sustainable development is differentiated from sustainability, and so forth. We offer the framework of terminology, dynamics, and propositions to others who find great variation in their own areas of study across empirical instances, involving, for example, different geographies, economic development projects, or comparisons across industries. Colleagues studying economic business clusters might see promise here (Porter 1998; Martin and Sunley 2003), as well as those seeking to understand other types of innovation projects that emerge spontaneously across many regions. Those thinking deeply about business model innovation and sustainable business models where great variation has already been seen (Stubbs and Cocklin 2008) might also benefit in adopting the type of framework we have proposed for IS. For, after all, we have a common quest to improve the linkage of economic and environmental performance in a broad array of circumstances and gain from recognizing that diversity can provide a means of common understanding.

Notes

1. Our position thus reflects an evolutionary perspective on science. Especially in small fields of research, such evolution is more complex than the blind operation of mechanisms of variation, selection, and transmission. For a developed perspective on evolution in social systems, see the work of Boyd and Richerson (1985).
2. Note that this is an inductive approach to theory building from empirically derived typologies. See Doty and Glick (1994) for background. Seeing theory as a set of social mechanisms is the core idea of analytical sociology (Hedström and Bearman 2009); it can be easily extended to include socioecological mechanisms (Boons 2013).
3. The reason we provide alternative ways of looking at dynamics (as ideal types and sets of conditions) is that we seek to accommodate both positivistic and interpretive approaches to comparative analysis.
4. It is important to distinguish the role of government in providing boundary conditions and that of the government controlling the activities of industrial actors. In the latter case, specific rules are set, monitored, and, when necessary, sanctioned, and the only choice open to an industrial actor is to comply or not. If the government sets boundary conditions, it alters the opportunity set of industrial actors, for instance, through taxes or subsidies. In these cases, an industrial actor still has autonomy of choice.

References

Ashton, W. 2008. Understanding the organization of industrial ecosystems: A social network approach. *Journal of Industrial Ecology* 12(1): 34–51.

Baas, L. W. and F. A. Boons. 2004. An industrial ecology project in practice: Exploring the boundaries of decision-making levels in regional industrial systems. *Journal of Cleaner Production* 12(8–10): 1073–1085.

Baas, L. W. and F. Boons. 2007. The introduction and dissemination of the industrial symbiosis projects in the Rotterdam Harbour and Industry Complex. *International Journal of Environmental Technology and Management* 7(5–6): 551–577.

Baas, L. W. and D. Huisingh. 2008. The synergistic role of embeddedness and capabilities in industrial symbiosis: Illustration based upon 12 years of experiences in the Rotterdam Harbour and Industry Complex. *Progress in Industrial Ecology* 5(5–6): 399–421.

Bacharach, S. B. 1989. Organizational theories: Some criteria for evaluation. *Academy of Management Review* 14(4): 496–515.

Bain, A., M. Shenoy, W. Ashton, and M. Chertow. 2010. Industrial symbiosis and waste recovery in an Indian industrial area. *Resources, Conservation and Recycling* 54(12): 1278–1287.

BCSD-GM (Business Council for Sustainable Development–Gulf of Mexico). 1997. *By-product synergy: A strategy for sustainable Development—A primer*. Austin, TX: The Business Council for Sustainable Development–Gulf of Mexico.

Behera, S. K., J.-H. Kim, S.-Y. Lee, S. Suh, and H.-S. Park. 2012. Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'Research and development into business' as the enabling framework. *Journal of Cleaner Production* 29–30: 103–112.

Boons, F. 2008. Self-organisation and sustainability: The emergence of a regional industrial ecology. *Emergence: Complexity and Organization* 10(2): 41–48.

Boons, F. 2013. Organizing within dynamic ecosystems: Conceptualizing socio-ecological mechanisms. *Organization and Environment* 26(3): 281–297.

Boons, F. and J. Howard-Grenville. 2009. *The social-embeddedness of industrial ecology*, 1st ed. Northampton, MA, USA: Edward Elgar.

Boons, F. and W. Spekkink. 2012. Levels of institutional capacity and actor expectations about industrial symbiosis. *Journal of Industrial Ecology* 16(1): 61–69.

Boons, F. and M. A. Janssen. 2004. The myth of Kalundborg: Social dilemmas in stimulating eco-industrial parks. In *Economics of industrial ecology: Materials, structural change, and spatial scales*, edited by C. J. M. Jeroen et al. Cambridge, MA, USA: The MIT Press.

Boons, F., W. Spekkink, and Y. Mouzakitis. 2011. The dynamics of industrial symbiosis: A proposal for a conceptual framework based upon a comprehensive literature review. *Journal of Cleaner Production* 19(9–10): 905–911.

Boons, F., W. Spekkink, and W. Jiao. 2014. A process perspective on industrial symbiosis: Theory, methodology, and application. *Journal of Industrial Ecology* 18(3): 341–355.

Boons, F., W. Spekkink, R. Isenmann, L. Baas, M. Eklund, S. Brullot, P. Deutz, et al. 2015. Comparing industrial symbiosis in Europe: Towards a conceptual framework and research methodology. In *International perspectives on industrial ecology*, edited by P. Deutz, et al. Cheltenham, UK: Edward Elgar.

Boyd, R. and P. Richerson. 1985. *Culture and the evolutionary process*. Chicago, IL, USA: University of Chicago Press.

Cerceau, J., N. Mat, G. Junqua, L. Lin, V. Laforest, and C. Gonzalez. 2014. Implementing industrial ecology in port cities: International overview of case studies and cross-case analysis. *Journal of Cleaner Production* 74: 1–16.

Chen, X., T. Fujita, S. Ohnishi, M. Fujii, and Y. Geng. 2012. The impact of scale, recycling boundary, and type of waste on symbiosis and recycling: An empirical study of Japanese eco-towns. *Journal of Industrial Ecology* 16(1): 129-141.

Chertow, M. 1999. The eco-industrial park model reconsidered. *Journal of Industrial Ecology* 2(3): 8–10.

Chertow, M. 2011. Industrial Symbiosis (FES 884b: Industrial Ecology): Lecture conducted from Yale School of Forestry and Environmental Studies, January 30, 2011.

Chertow, M. 2009. Dynamics of geographically based industrial ecosystems. In *The dynamics of regions and networks in industrial ecosystems*, edited by M. Ruth and B. Davidsdottir. Cheltenham, UK: Edward Elgar.

Chertow, M. and Y. Miyata. 2011. Assessing collective firm behavior: Comparing industrial symbiosis with possible alternatives for individual companies in Oahu, HI. *Business Strategy and the Environment* 20(4): 266–280.

Chertow, M. and J. Ehrenfeld. 2012. Organizing self-organizing systems: Toward a theory of industrial symbiosis. *Journal of Industrial Ecology* 16(1): 13–27.

Chertow, M. and J. Y. Park. 2016. Scholarship and practice in industrial symbiosis: 1989–2014. In *Taking stock of industrial ecology*, edited by R. Clift and A. Druckman. Cham, Switzerland: Springer International AG.

Chertow, M. R. 2000. Industrial symbiosis: Literature and taxonomy. *Annual Review of Energy and the Environment* 25: 313–337.

Chertow, M. R. 2007. "Uncovering" industrial symbiosis. *Journal of Industrial Ecology* 11(1): 11–30.

Chertow, M. R. and D. R. Lombardi. 2005. Quantifying economic and environmental benefits of co-located firms. *Environmental Science & Technology* 39(17): 6535–6541.

Choi, T. Y. and Z. Wu. 2009. Taking the leap from dyads to triads: Buyer-supplier relationships in supply networks. *Journal of Purchasing and Supply Management* 15(4): 263–266.

Chopra, S. S. and V. Khanna. 2014. Understanding resilience in industrial symbiosis networks: Insights from network analysis. *Journal of Environmental Management* 141: 86–94.

Côté, R. P. and E. Cohen-Rosenthal. 1998. Designing eco-industrial parks: A synthesis of some experiences. *Journal of Cleaner Production* 6(3–4): 181–188.

Deutz, P. 2014. Food for thought: Seeking the essence of industrial symbiosis. In *Pathways to environmental sustainability: Methodologies and experiences*, edited by R. Salomone and G. Saija. Cham, Switzerland: Springer International AG.

Deutz, P. and D. Gibbs. 2004. Eco-industrial development and economic development: industrial ecology or place promotion? *Business Strategy and the Environment* 13(5): 347–362.

DiMaggio, P. J. and W. W. Powell. 1983. The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. *American Sociological Review* 48(2): 147–160.

Domenech, T. and M. Davies. 2011. The role of embeddedness in industrial symbiosis networks: Phases in the evolution of industrial symbiosis networks. *Business Strategy and the Environment* 20(5): 281–296.

Dong, H. J., S. Ohnishi, T. Fujita, Y. Geng, M. Fujii, and L. Dong. 2014. Achieving carbon emission reduction through industrial & urban symbiosis: A case of Kawasaki. *Energy* 64: 277–286.

Doty, D. H. and W. H. Glick. 1994. Typologies as a unique form of theory building: Toward improved understanding and modeling. *Academy of Management Review* 19(2): 230–251.

Ehrenfeld, J. R. and N. Gertler. 1997. Industrial ecology in practice: The evolution of interdependence at Kalundborg. *Journal of Industrial Ecology* 1(1): 67–79.

Elster, J. 2007. *Explaining social behavior*. Cambridge, UK: Cambridge University Press.

Geng, Y. and R. P. Côté. 2002. Scavengers and decomposers in an eco-industrial park. *International Journal of Sustainable Development & World Ecology* 9(4): 333–340.

Geng, Y., J. Fu, J. Sarkis, and B. Xue. 2012. Towards a national circular economy indicator system in China: An evaluation and critical analysis. *Journal of Cleaner Production* 23(1): 216–224.

Geng, Y., Z. X. Liu, B. Xue, H. J. Dong, T. Fujita, and A. Chiu. 2014. Emergy-based assessment on industrial symbiosis: A case of Shenyang Economic and Technological Development Zone. *Environmental Science and Pollution Research* 21(23): 13572–13587.

Gibbs, D. 2003. Trust and networking in inter-firm relations: The case of eco-industrial development. *Local Economy* 18(3): 222–236.

Gregson, N., M. Crang, F. U. Ahamed, N. Akter, R. Ferdous, S. Foisal, and R. Hudson. 2012. Territorial agglomeration and industrial symbiosis: Sitakunda-Bhatiary, Bangladesh, as a secondary processing complex. *Economic Geography* 88(1): 37–58.

Hall, P. A. and D. Soskice. 2001. *Varieties of capitalism: The institutional foundations of comparative advantage*. Oxford, UK: Oxford University Press.

Hantrais, L. 1999. Contextualization in cross-national comparative research. *International Journal of Social Research Methodology* 2(2): 93–108.

Hardy, C. and T. E. Graedel. 2002. Industrial ecosystems as food webs. *Journal of Industrial Ecology* 6(1): 29–38.

Healey, P., C. de Magalhaes, A. Madanipour, and J. Pendlebury. 2003. Place, identity and local politics: Analyzing initiatives in deliberative governance, edited by M. A. Hajer and H. Wagenaar. Cambridge, UK: Cambridge University Press.

Hedström, P. and P. Bearman. 2009. *The Oxford handbook of analytical sociology*. Oxford, UK: Oxford University Press.

Hewes, A. and D. I. Lyons. 2008. The humanistic side of eco-industrial parks: Champions and the role of trust. *Regional Studies* 42(10): 1329–1342.

Hull, D. 1988. *Science as a process*. Chicago, IL, USA: University of Chicago Press.

Jacobsen, N. B. 2006. Industrial symbiosis in Kalundborg, Denmark: A quantitative assessment of economic and environmental aspects. *Journal of Industrial Ecology* 10(1–2): 239–255.

Jacobsen, N. B. 2007. Do social factors really matter when companies engage in industrial symbiosis? *Progress in Industrial Ecology* 4(6): 440–462.

Jacobsen, N. B. and S. Anderberg. 2004. Understanding the evolution of industrial symbiotic networks: The case of Kalundborg. In *Economics of industrial ecology: Materials, structural change, and spatial scales*, edited by C. J. M. Jeroen et al. Cambridge, MA, USA: The MIT Press.

Jensen, P. D., L. Basson, E. E. Hellawell, M. R. Bailey, and M. Leach. 2011. Quantifying 'geographic proximity': Experiences from the United Kingdom's National Industrial Symbiosis Programme. *Resources, Conservation and Recycling* 55(7): 703–712.

Jiao, W. T. and F. Boons. 2014. Toward a research agenda for policy intervention and facilitation to enhance industrial symbiosis based on a comprehensive literature review. *Journal of Cleaner Production* 67: 14–25.

Kalberg, S. 2012. *Max Weber's comparative historical sociology today*. Farnham, UK: Ashgate.

Karlsson, M. and A. Wolf. 2008. Using an optimization model to evaluate the economic benefits of industrial symbiosis in the forest industry. *Journal of Cleaner Production* 16(14): 1536–1544.

Korhonen, J. 2001. Co-production of heat and power: An anchor tenant of a regional industrial ecosystem. *Journal of Cleaner Production* 9(6): 509–517.

Kuhn, T. S. 1962. *The structure of scientific revolutions*, 1st ed. Chicago, IL, USA: University of Chicago Press.

Laybourn, P. and M. Morrissey. 2009. *The pathway to a low carbon sustainable economy*. Birmingham, UK: National Industrial Symbiosis Programme.

Liu, C., C. Ma, and K. Zhang. 2012. Going beyond the sectoral boundary: A key stage in the development of a regional industrial ecosystem. *Journal of Cleaner Production* 22(1): 42–49.

Liwarska-Bizukojc, E., M. Bizukojc, A. Marcinkowski, and A. Doniec. 2009. The conceptual model of an eco-industrial park based upon ecological relationships. *Journal of Cleaner Production* 17(8): 732–741.

Lowitt, P. C. 2008. Devens redevelopment. *Journal of Industrial Ecology* 12(4): 497–500.

Lyons, D. I. 2007. A spatial analysis of loop closing among recycling, remanufacturing, and waste treatment firms in Texas. *Journal of Industrial Ecology* 11(1): 43-54.

Mahoney, J. 2000. Path dependence in historical sociology. *Theory and Society* 29(4): 507–548.

Mangan, A. and E. Olivetti. 2010. By-product synergy networks: Driving innovation through waste reduction and carbon mitigation. In *Sustainable development in the process industries: Cases and impact*. New York: John Wiley & Sons.

Martin, M. and M. Eklund. 2011. Improving the environmental performance of biofuels with industrial symbiosis. *Biomass and Bioenergy* 35(5): 1747–1755.

Martin, R. and P. Sunley. 2003. Deconstructing clusters: Chaotic concept or policy panacea? *Journal of Economic Geography* 3(1): 5–35.

Martin, S. A., R. A. Cushman, K. A. Weitz, A. Sharma, and R. C. Lindrooth. 1998. Applying industrial ecology to industrial parks: An economic and environmental analysis. *Economic Development Quarterly* 12(3): 218–237.

Mattila, T. J., S. Pakarinen, and L. Sokka. 2010. Quantifying the total environmental impacts of an industrial symbiosis—A comparison of process-, hybrid and input-output life cycle assessment. *Environmental Science & Technology* 44(11): 4309–4314.

Meyer, J. W. and B. Rowan. 1977. Institutionalized organizations: Formal structure as myth and ceremony. *American Journal of Sociology* 83(2): 340–363.

Mirata, M. 2004. Experiences from early stages of a national industrial symbiosis programme in the UK: Determinants and coordination challenges. *Journal of Cleaner Production* 12(8–10): 967–983.

Pakarinen, S., T. Mattila, M. Melanen, A. Nissinen, and L. Sokka. 2010. Sustainability and industrial symbiosis—The evolution of a Finnish forest industry complex. *Resources, Conservation and Recycling* 54(12): 1393–1404.

Paquin, R. L. and J. Howard-Grenville. 2012. The evolution of facilitated industrial symbiosis. *Journal of Industrial Ecology* 16(1): 83–93.

Paquin, R. L. and J. Howard-Grenville. 2013. Blind dates and arranged marriages: Longitudinal processes of network orchestration. *Organization Studies* 34(11): 1623–1653.

Park, H. S., E. R. Rene, S. M. Choi, and A. S. F. Chiu. 2008. Strategies for sustainable development of industrial park in Ulsan, South Korea—From spontaneous evolution to systematic expansion of industrial symbiosis. *Journal of Environmental Management* 87(1): 1–13.

Park, J. M., J. Y. Park, and H.-S. Park. 2016. A review of the National Eco-Industrial Park Development Program in Korea: Progress and achievements in the first phase, 2005–2010. *Journal of Cleaner Production* 114: 33–44.

Pellenbarg, P. H. 2002. Sustainable business sites in the Netherlands: A survey of policies and experiences. *Journal of Environmental Planning and Management* 45(1): 59–84.

Porter, M. E. 1998. Clusters and the new economics of competition. *Harvard Business Review*, December, 77–90.

ReVenture Park. 2016. About Reventure Park. www.reventurepark.com/about-reventure-park. Accessed 14 June 2016.

Schwarz, E. J. and K. W. Steininger. 1997. Implementing nature's lesson: The industrial recycling network enhancing regional development. *Journal of Cleaner Production* 5(1–2): 47–56.

Shi, H., M. Chertow, and Y. Song. 2010. Developing country experience with eco-industrial parks: A case study of the Tianjin Economic-Technological Development Area in China. *Journal of Cleaner Production* 18(3): 191–199.

Shi, H., J. Tian, and L. Chen. 2012a. China's quest for eco-industrial parks, part I. *Journal of Industrial Ecology* 16(1): 8–10.

Shi, H., J. Tian, and L. Chen. 2012b. China's quest for eco-industrial parks, part II. *Journal of Industrial Ecology* 16(3): 290–292.

Short, S. W., N. M. P. Bocken, C. Y. Barlow, and M. R. Chertow. 2014. From refining sugar to growing tomatoes: Industrial ecology and business model evolution. *Journal of Industrial Ecology* 18(5): 603–618.

Sokka, L., S. Lehtoranta, A. Nissinen, and M. Melanen. 2011. Analyzing the environmental benefits of industrial symbiosis: Life cycle assessment applied to a Finnish forest industry complex. *Journal of Industrial Ecology* 15(1): 137–155.

Spekkink, W. 2013. Institutional capacity building for industrial symbiosis in the Canal Zone of Zeeland in the Netherlands: A process analysis. *Journal of Cleaner Production* 52: 342–355.

Spekkink, W. 2015. Building capacity for sustainable regional industrial systems: An event sequence analysis of developments in the Sloe Area and Canal Zone. *Journal of Cleaner Production* 98: 133–144.

Sterman, J. D. 2000. *Business dynamics: Systems thinking and modeling for a complex world*. New York: Irwin Professional/McGraw-Hill.

Sterr, T. and T. Ott. 2004. The industrial region as a promising unit for eco-industrial development—Reflections, practical experience and establishment of innovative instruments to support industrial ecology. *Journal of Cleaner Production* 12(8–10): 947–965.

Stinchcombe, A. 1968. *Constructing social theories*. Chicago, IL, USA: University of Chicago Press.

Stubbs, W. and C. Cocklin. 2008. Conceptualizing a "sustainability business model". *Organization & Environment* 21(2): 103–127.

Teune, H. 1990. Comparing countries: Lessons learned. In *Comparative methodology: Theory and practice in international social research*, edited by E. Oyen. London: Sage.

Tian, J., H. Shi, X. Li, and L. Chen. 2012a. Measures and potentials of energy-saving in a Chinese fine chemical industrial park. *Energy* 46(1): 459–470.

Tian, J., H. Shi, Y. Chen, and L. Chen. 2012b. Assessment of industrial metabolisms of sulfur in a Chinese fine chemical industrial park. *Journal of Cleaner Production* 32: 262–272.

Toulmin, S. 1972. *Human understanding: The collective use and evolution of concepts*. Princeton, NJ, USA: Princeton University Press.

Trokanas, N., F. Cecelja, and T. Raafat. 2014. Semantic input/output matching for waste processing in industrial symbiosis. *Computers and Chemical Engineering* 66(1): 259–268.

USBCSD (US Business Council for Sustainable Development). 2016. United States Materials Marketplace. http://materials-marketplace.org/#about. Accessed 8 February 2016.

Van Beers, D., G. Corder, A. Bossilkov, and R. van Berkel. 2007. Industrial symbiosis in the Australian minerals industry—The cases of Kwinana and Gladstone. *Journal of Industrial Ecology* 11(1): 55–72.

Van Berkel, R., T. Fujita, S. Hashimoto, and M. Fujii. 2009a. Quantitative assessment of urban and industrial symbiosis in Kawasaki, Japan. *Environmental Science & Technology* 43(5): 1271–1281.

Van Berkel, R., T. Fujita, S. Hashimoto, and Y. Geng. 2009b. Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006. *Journal of Environmental Management* 90(3): 1544–1556.

Veleva, V., S. Todorova, P. Lowitt, N. Angus, and D. Neely. 2015. Understanding and addressing business needs and sustainability challenges: Lessons from Devens eco-industrial park. *Journal of Cleaner Production* 87(1): 375–384.

Vernay, A.-L. and F. Boons. 2015. Assessing systems integration: A conceptual framework and a method. *Systems Research and Behavioral Science* 32(1): 106–123.

von Malmborg, F. 2004. Networking for knowledge transfer: Towards an understanding of local authority roles in regional industrial ecosystem management. *Business Strategy and the Environment* 13(5): 334–346.

Walls, J. L. and R. Paquin. 2015. Organizational perspectives of industrial symbiosis: A review and synthesis. *Organization & Environment* 28(1): 32–53.

Wang, G., X. Feng, and K. H. Chu. 2013a. A novel approach for stability analysis of industrial symbiosis systems. *Journal of Cleaner Production* 39: 9–16.

Wang, H., Y. Lei, H. Wang, M. Liu, J. Yang, and J. Bi. 2013b. Carbon reduction potentials of China's industrial parks: A case study of Suzhou Industry Park. *Energy* 55: 668–675.

Wolf, A. and K. Petersson. 2007. Industrial symbiosis in the Swedish forest industry. *Progress in Industrial Ecology, an International Journal* 4(5): 348–362.

Wright, R. A., R. P. Côté, J. Duffy, and J. Brazner. 2009. Diversity and connectance in an industrial context: The case of Burnside Industrial Park. *Journal of Industrial Ecology* 13(4): 551–564.

Yu, C., M. De Jong, and G. P. J. Dijkema. 2014a. Process analysis of eco-industrial park development—The case of Tianjin, China. *Journal of Cleaner Production* 64: 464–477.

Yu, C., C. Davis, and G. P. J. Dijkema. 2014b. Understanding the evolution of industrial symbiosis research: A bibliometric and network analysis (1997–2012). *Journal of Industrial Ecology* 18(2): 280–293.

Yu, C., G. P. Dijkema, and M. de Jong. 2015. What makes eco-transformation of industrial parks take off in China? *Journal of Industrial Ecology* 19(3): 441–456.

Zhang, L., Z. Yuan, J. Bi, B. Zhang, and B. Liu. 2010. Eco-industrial parks: National pilot practices in China. *Journal of Cleaner Production* 18(5): 504–509.

Zhang, Y., H. Zheng, B. Chen, M. Su, and G. Liu. 2015. A review of industrial symbiosis research: Theory and methodology. *Frontiers of Earth Science* 9(1): 91–104.

Zhu, J. and M. Ruth. 2013. Exploring the resilience of industrial ecosystems. *Journal of Environmental Management* 122: 65–75.

Zhu, J. and M. Ruth. 2014. The development of regional collaboration for resource efficiency: A network perspective on industrial symbiosis. *Computers, Environment and Urban Systems* 44: 37–46.

Zhu, Q. H., E. A. Lowe, Y. A. Wei, and D. Barnes. 2007. Industrial symbiosis in China—A case study of the Guitang Group. *Journal of Industrial Ecology* 11(1): 31–42.

About the Authors

Frank Boons is a professor of innovation and sustainability at the Sustainable Consumption Institute, University of Manchester, Manchester, United Kingdom. **Marian Chertow** is an associate professor of industrial environmental management at the School of Forestry and Environmental Studies, Yale University, New Haven, CT, USA. **Wouter Spekkink** is a research associate at the Sustainable Consumption Institute, University of Manchester. **Jooyoung Park** is an assistant professor at the School of Management, Universidad de los Andes, Bogotá, Colombia. **Han Shi** is an assistant professor at City University, Hong Kong.

Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information contains information distributed in preparation to the 8th Annual Industrial Symbiosis Research Symposium-Reassessing the Basics of Industrial Symbiosis, San Francisco, CA, USA – June 5-6, 2011.