

Chapter 5

Scholarship and Practice in Industrial Symbiosis: 1989–2014

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Abstract Industrial symbiosis, a subfield of industrial ecology, engages traditionally separate industries and entities in a collaborative approach to resource sharing that benefits both the environment and the economy. This chapter examines the period 1989–2014 to “take stock” of industrial symbiosis. First, we look at the earliest days to discuss what inspired industrial symbiosis both in the scholarly literature and in practice. Next, we draw attention to certain dilemmas and sharpen the distinctions between industrial symbiosis and some related concepts such as eco-industrial parks and environmentally balanced industrial complexes. With regard to dissemination of industrial symbiosis ideas, we found that at the country level, China has now received the most attention in industrial symbiosis academic research and this continues to grow rapidly.

The final section looks at both theory (conceptual knowledge largely from academia) and practice (on-the-ground experience of public, not-for-profit, and private organizations working to implement industrial symbiosis) as both are essential to industrial symbiosis. A bibliometric analysis of the scholarly work, capturing 391 articles indexed in Scopus and Web of Science for 20 years between 1995 and 2014, is used to define and track the types of articles, how the mix of articles has changed over time, and what the most popular journals are. Taking a closer look at the research literature, distinct themes are identified and discussed such as the scale of industrial symbiosis, whether industrial symbiosis is based on planning or self-organization, the role of social factors, and what is known about the actual performance of industrial symbiosis. To assess important issues with regard to practice, we compile a list of industrial symbiosis-related events from database searches of reports, media, and key consulting and business organizations and examine trends, mechanisms, and motivations of industrial symbiosis practice by surveying key practitioners and academics.

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Since 1989, there has been significant uptake of industrial symbiosis around the world as shown by the increasing number of journal articles and also events on the ground. Industrial symbiosis has become more geographically and institutionally diverse, as more organizations in more countries learn about the ideas and diffuse regionally specific versions. This presents additional opportunities to understand the phenomenon, but also makes the search to embrace a coherent framework more immediate.

Keywords Eco-industrial park • Industrial ecosystem • By-product reuse • Circular economy • Industrial ecology

1 Introduction

This chapter examines the period 1989–2014 during which many people associated with the industrial ecology community have participated in building the knowledge base of industrial symbiosis. At the heart of industrial symbiosis is cooperative resource sharing of water, energy, and material by-products and wastes across organizations for both environmental and economic benefit. Taking stock of industrial ecology includes looking back at the earliest days and threads of industrial symbiosis, honoring the catalytic role that the industrial symbiosis in Kalundborg, Denmark, has played, and compiling some of the lessons learned about how to describe this phenomenon and its many manifestations as experience and understanding evolve. Industrial symbiosis is designated as a subfield of industrial ecology where both theory (conceptual knowledge largely from academia) and practice (on-the-ground experience of public, not-for-profit, and private organizations working to implement industrial symbiosis) are highly valued. The chapter includes a bibliometric analysis of the scholarly work, a survey of practitioners and projects, and commentary from the authors and many other colleagues who contributed ideas for the chapter.

2 Part I: Why People Sometimes Equate Industrial Symbiosis with Industrial Ecology—Frosch and Gallopoulos, Kalundborg, and Beyond

While there are numerous antecedents to industrial ecology as Erkman (1997) and others have well demonstrated, many agree that modern industrial ecology was greatly inspired by, or even began with, the seminal 1989 article in *Scientific American*, “Strategies for Manufacturing.” Written by two members of the research and development staff at General Motors, this article laid out the conceptual groundwork for industrial ecology with the idea of following material flows through “industrial ecosystems” wherein “the consumption of energy and material is optimized,

waste generation is minimized and the effluents from one process serve as the raw material for another” (Frosch and Gallopoulos 1989). The notion of an industrial ecosystem has played an especially large ideation role in industrial symbiosis. This construct not only denotes a space where industrial symbiosis can occur but also does so through the introduction of a compelling tie back to natural systems. Indeed, we now know that the authors had proposed an alternative title that the editors rejected, but may have offered even more prominence to what would become industrial ecology ideas. This title was “Manufacturing: The Industrial Ecosystem View.”

As industrial ecology developed, industrial symbiosis became known as a sub-field of industrial ecology, distinct from other branches of the new field in that it straddles both theory and practice. Not only were Frosch and Gallopoulos employed by one of the largest automobile companies in the world, but the date of their article, 1989, is the convergent year that the industrial cluster in the City of Kalundborg, Denmark, which had been developing since the 1960s, began to come into much view given the extensive network of cooperating industrial operations there. Industrial ecology lore cites 1989 as the year the label “industrial symbiosis” was applied to Kalundborg by Inge Christensen, a pharmacist, and her husband, Valdemar Christensen, the Kalundborg power plant manager, to describe what was happening in the Kalundborg industrial ecosystem (Hewes and Lyons 2008). The inviting imagery of “the effluents from one process” serving “as the raw material for another” and the recognition of the extensive and interconnected resource sharing network of Kalundborg have proven so powerful for reimagining sustainable industrial development that many people, even today, mistake industrial symbiosis as what defines all of industrial ecology.

In Kalundborg, 1972 is regarded as the year of the first real interfirm symbiosis which, it should be noted, also brought a new enterprise to town. The gypsum board company was established in Kalundborg, in part because of the availability of excess butane from the nearby oil refinery. The butane transaction lasted nearly 30 years, and while it is now inactive, the gypsum board company remains in place under its third set of owners. Having officially celebrated 40 years with a newly published booklet (Kalundborg Symbiosis 2014), there is much to look back upon, and it is hard not to be impressed with the way this icon has continued to evolve and change, even with the generational passage to new management (Ehrenfeld and Chertow 2002; Ehrenfeld and Gertler 1997; Gertler 1995; Jacobsen 2006; Kalundborg Symbiosis 2014). In addition to substantial participation from the long-term partners, several new organizations have joined the symbiosis with 33 identified instances of interfirm resource sharing (Fig. 5.1).

There were foundational changes over the years in Kalundborg that could have shaken the entire system if it were fragile. Instead, this industrial ecosystem has continuously weathered many varieties of disturbance, from changes in the fuel type at the power plant to significant ownership and organizational changes within the companies such as the doubling in size of the oil refinery and the splitting up of the pharmaceutical operation into two separate companies. Even the official City of Kalundborg expanded from 20,000 to 50,000 residents during this period based on reorganization of municipal boundaries. While some have been concerned about

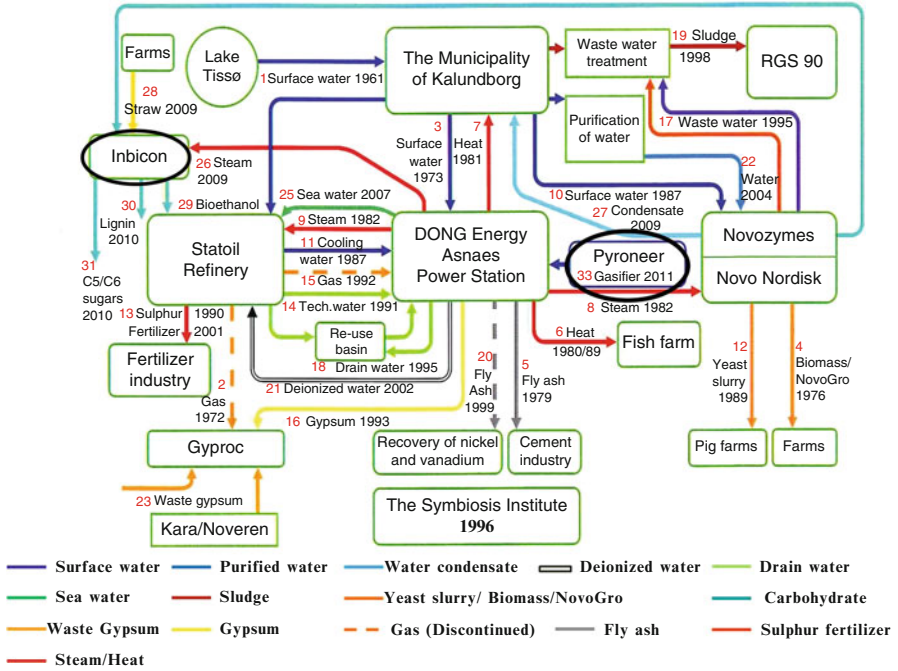


Fig. 5.1 Kalundborg Symbiosis as of 2012 with two new power plants circled. Both use biomass rather than fossil fuel (Source: <http://symbiosecenter.dk>)

technology lock-in and path dependence (Reuter et al. 2005; Sagar and Frosch 1997), two of the newest additions to the industrial ecosystem, both biomass power plants, suggest further breakthroughs in adaptation and regional sustainability (Fig. 5.1). Previously, with only one, albeit large, coal-fired power plant, the Kalundborg system was less resilient to perturbations. Matching the numbers here to Fig. 5.1, the Inbicon Biomass Refinery, begun in 2009, uses local straw (28) for conversion to bioethanol (29) and also generates lignin pellets (30) and molasses (31). DONG Energy’s Pyreoner plant, begun in 2011, is a 6 MW demonstration facility that gasifies local biomass (33). Diversifying energy sources has reduced reliance on fossil fuel toward increased use of bioenergy.

While Kalundborg is a familiar story for most industrial ecologists, the true legacy of Kalundborg comprises all that it spawned geographically and intellectually. While it is not at all the sole narrative for physically connected enterprises, in a surprising number of cases evaluated, Kalundborg is directly cited as an influencing factor, whether the projects envisioned succeeded or failed. Perhaps most interesting, even with some common reference points such as Frosch and Gallopoulos and Kalundborg, is how extensive and varied the evolutionary experiments that embed industrial symbiosis have come to be. The range extends from North American eco-industrial parks (Cohen-Rosenthal and Musnikow 2003; Côté and Hall 1995; Lowe and Evans 1995) to Southeast Asian industrial estates (Panyathanakun et al. 2013;

Van Ha et al. 2009) and even to broader concepts such as Japan’s “resource-circulating society” (Morioka et al. 2011) and China’s “ecological civilization” (Hu 2012).

3 Part II: Bounding Industrial Symbiosis in Time and Space—Distinctions and Differences

As a truly multi-, inter-, and transdisciplinary focus of study, industrial symbiosis easily becomes far-flung and sometimes misunderstood. The diverse communities of industrial symbiosis, from those who pursue scholarship to those creating policy to those facing the reality of business development, do not often overlap in ideas and audiences, as most people see just a part (Fig. 5.2). Some “big data” colleagues complain that examining industrial symbiosis is too much work because the information sources related to material and energy flows reveal only part of a multifaceted story that cannot be told without some human intervention to sort it out (Nikolic 2013, July 1, Personal communication). This section emphasizes a few of the ongoing questions raised and distinctions made as industrial symbiosis has progressed through time and space.

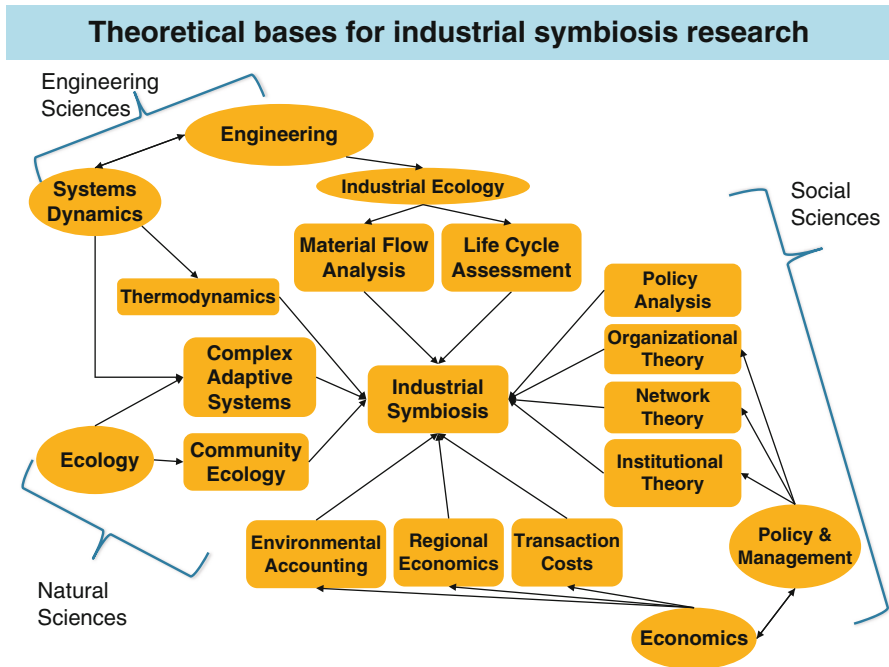


Fig. 5.2 Industrial symbiosis examined through many research fields (Source: Ashton and Chertow, Yale Center for Industrial Ecology, updated 2015)

3.1 *Industrial Symbiosis: Old, New, or Hidden*

One of the distinctive crosscutting themes of industrial ecology is the way it attends to “hidden” flows such as (1) the often uncounted overburden left behind from mining extraction that becomes part of mass flow analysis; (2) the “missing” lead or mercury or other elements that dissipate into air, water, and soil; and, (3) in industrial symbiosis, resource exchanges that may have been implemented long ago, but are not known or recognized other than among the participating economic actors as part of a formal or informal localized supply chain. In each of these classic industrial ecology instances, something formerly hidden or unknown becomes attended to and counted. By identifying these hidden flows and giving them more careful attention, both economic and environmental implications are clarified. Environmental consequences can be negative, as with escaping lead, but can often be positive, as with repurposed sulfur, wastewater, or cogenerated steam characteristic of industrial symbiosis. The nature of economic activities that fly under the radar of visibility and consciousness is a phenomenon within industrial symbiosis first discussed by Schwarz and Steininger (1997) and helps to explain the surprise that often accompanies forays into industrial ecosystems.

In the early 2000s, geographer Pierre Desrochers identified industrial symbiosis transactions as rearrangements of practices that had come before (Desrochers 2000). Indeed, as long as there have been people, products, and wastes—from animal hides to flower pollen to metal scraps—such items have been exchanged if the recipient finds value in the material being received, whether or not there is a special name for it. Desrochers (2001, 2004) cited numerous industrial examples of resource sharing over hundreds of years including the role that cities have played in agglomerating industries in common locations and, in the process, enabling the creation of reuse and recycling among players in those industries. Desrochers has investigated reuse of by-products, for example, in Victorian England, and identified some very interesting historical accounts such as an 1862 volume titled *Waste Products and Undeveloped Substances*, whose authors attributed the ingenuity they saw around them to opportunities to earn additional revenue from what appeared to have no value at all.

Such reflections help to stimulate thinking about industrial symbiosis and claims about it by its observers. When a phenomenon has a strong economic basis—such as the revenue earning aspect of industrial symbiosis—then there is motivation and impetus to pursue it. To a large extent, much of industrial symbiosis has been concealed in the broader realm of economic exchanges. What we recognize and indeed can quantify from today’s version of industrial symbiosis is that alongside the economic benefits, environmental ones are generated as well. These benefits may be hidden, but can be demonstrated to the broader community in the form of reduced emissions and waste and jobs created through reuse and recycling. Once these industrial symbiosis benefits become recognized more broadly and further steps are taken to continue them, then the activities of the business cluster where they occur can be classified as a distinct environmental phenomenon beyond what happens in other economic agglomeration networks (Chertow and Ehrenfeld 2012).

3.2 Single Industry Dominated vs. Multiple Industry Involvement

The 1990s was a time when great effort went into creating bounded systems to include resource sharing across organizations in eco-industrial parks and through related constructs such as zero-waste projects, by-product synergy, or integrated biosystems (IBS). Just as there was a convergence in 1989 with the article by Frosch and Gallopoulos and the revelation of Kalundborg, convergent in 1995 were environmental engineer Nelson Nemerow's book, *Zero Pollution for Industry: Waste Minimization Through Industrial Complexes*, and the first peer-reviewed journal article relating to industrial symbiosis appearing in the scientific literature, "Industrial Ecology and Industrial Ecosystems" by Ernest Lowe and Laurence Evans, in the *Journal of Cleaner Production*. Nemerow imagined the creation of a system of environmentally balanced "industrial complexes" where companies in the complex consume each other's by-products as a means of increasing production efficiency and reducing waste. Since 1992, Lowe and colleagues at Indigo Development along with Professor Ray Côté and colleagues at Dalhousie University in Nova Scotia and Cornell University's former Work and Environment Initiative led by Ed Cohen-Rosenthal formalized the concept of the eco-industrial park. By 1994, the US EPA had hired Lowe and Indigo, along with the Research Triangle Institute staff, to develop the concept further.

Notably, the examples of Nemerow's environmentally balanced industrial complexes were rooted in individual industries such as pulp and paper, sugar refining, and textile complexes. In these bounded systems, Nemerow described the wealth of potential resource sharing opportunities that could be usefully implemented by related industrial operations. In contrast, Lowe and colleagues were envisioning business clusters populated by many unrelated firms thereby creating opportunities for sharing the inputs and outputs from a diverse array of facilities in eco-industrial parks that would foster economic cooperation, environmental improvement, and community benefit. It was understood that if firms had a high diversity of inputs and outputs rather than uniformity, there would be numerous new business opportunities based on reuse of by-products. This distinction of "single-industry dominated clusters" and "multiple industry clusters" is an important one. What Kalundborg, Lowe, and other projects and colleagues demonstrated was the potential involvement of many, diverse industries and outcomes in one geography.

3.3 Industrial Symbiosis and Eco-industrial Parks (EIPs)

While the section above discusses different lineages of more traditional single-industry dominated industrial complexes and the broader diversity within eco-industrial parks, resource sharing occurs in both. Another important element in sorting out concepts of industrial symbiosis is reexamining its relationship to

eco-industrial parks, clusters, and/or estates. When ideas come together from many different places, traditions, and cultures, there are larger and smaller variations in content and emphasis even as many institutions are embracing the notion of inter-firm resource sharing. The international business community has leaned toward other expressions such as by-product synergy, a keystone of the US Business Council for Sustainable Development (US BCSD) with focus not only on interfirm resource reuse but also on intra-firm reuse (Mangan 2015, January 19, Personal communication). The Ellen MacArthur Foundation has greatly popularized the notion of the “circular economy” especially in business circles.

One of the early EIP pioneers, Ray Côté of Dalhousie University, recently expressed his concern with “the number of researchers and practitioners who continue to equate eco-industrial parks with industrial symbiosis or seem to believe that once industrial symbiosis has occurred within an industrial park, the latter can be called an eco-industrial park” (Côté 2015, January 16, Personal Communication). Côté perceives the EIP beginning with the land itself and the necessary understanding of the ecological services of the area where the park is to be situated. In this way, changes to those services can be appropriately addressed—for example, if wetlands will be compromised, planners could incorporate constructed or engineered wetlands. Industrial symbiosis, a less bounded spatial concept than EIP, focuses on resource reuse and how to achieve it technically, economically, and behaviorally, more than the physicality of any particular site, which of course is also very important (Lowitt 2015, January 20, Personal communication with Director of Devens Enterprise Center).

According to Côté, even as the park management looks for symbiotic opportunities involving water, energy, and materials, other key elements of EIPs include, for example, standards or guidelines for green building features, water cycling, reuse, and landscaping. Especially when there are many small- and medium-sized companies in an EIP, then “scavenger and decomposer” operations can be encouraged to fill many reuse niches across firms through “repair, rent, restore, reclaim, remanufacture, and recycle,” which become important components “of local circular economies” (Côté 2015, January 16, Personal Communication; Geng and Côté 2002).

3.4 Diffusion of Industrial Symbiosis

Now in its twelfth year, the annual Industrial Symbiosis Research Symposium, building on smaller regional fora, has linked academics and practitioners in 1–2-day meetings to discuss and exchange ideas in numerous locations around the globe (Table 5.1). In addition, based on the bibliometric analysis presented in Part III, it is possible to track, at least from the perspective of peer-reviewed scientific journals, those articles in which individual countries received some of the focus of industrial symbiosis papers (Fig. 5.3). By this measure, China has now received the most attention in industrial symbiosis academic research and continues to grow rapidly. The strong interest in China appears to be policy driven following establishment of the program creating the Chinese National Demonstration EIPs and circular

Table 5.1 The annual Industrial Symbiosis Research Symposium

Year	Hosting location	Host or contact person
2004	New Haven, Connecticut, USA	Marian Chertow
2005	Stockholm, Sweden	Noel Jacobsen
2006	Birmingham, UK	Peter Laybourn
2007	Toronto, Canada	Ray Côté
2008	Devens, Massachusetts, USA	Peter Lowitt
2009	Kalundborg, Denmark	Jørgen Christensen
2010	Kawasaki, Japan	Tsuyoshi Fujita (with Chinese, Korean, and Japanese sponsorship)
2011	San Francisco, California, USA	Marian Chertow
2012	Tianjin, China	Shi Han, Yuyan Song
2013	Ulsan, South Korea	Hung-Suck Park
2014	Melbourne, Australia	Robin Branson, Biji Kurup
2015	Lausanne, Switzerland	Guillaume Massard, Suren Erkman

economy policy. The second highest number of articles is about the USA, followed by Australia, Denmark, the UK, Finland, Japan, and South Korea, many of which have or had national industrial symbiosis-related programs and initiatives or have representative industrial clusters such as Kalundborg and Kwinana. The increasing focus on developing countries can be seen at the bottom of Fig. 5.3 with each having one peer-reviewed paper, thus entering the broader conversation. Many more papers and conference proceedings appear in the “gray literature” found in search engines and the offices of professors, consultants, and project officials, but this was not fully surveyed here.

3.5 *Understanding Industrial Symbiosis in a Chinese Context*

Given the prominence of industrial symbiosis in China (Fig. 5.3), it is important to describe its development in more depth. Professor Shi Lei of Tsinghua University put together some background information, noting that the emergence of industrial symbiosis and eco-industrial parks in China stems from earlier types of industrial development following the passage of the 1978 policy on Reform and Opening Up. In 1984, the first Economic-Technological Development Areas (ETDAs) began which, according to Pi and Wang (2004), were “designed to break the ice of the planned economy” and subsequently began to focus on attracting foreign direct investment. These were followed by the development of Hi-Tech Parks (HTP) in the early 1990s. By the turn of the new century, China had shaped a large industrial system based on more than 6,000 parks located across China. With the high concentration of industrial activities, resource and environmental problems became increasingly serious, which ignited the rise of EIPs (Shi 2015, January 18, Personal communication).

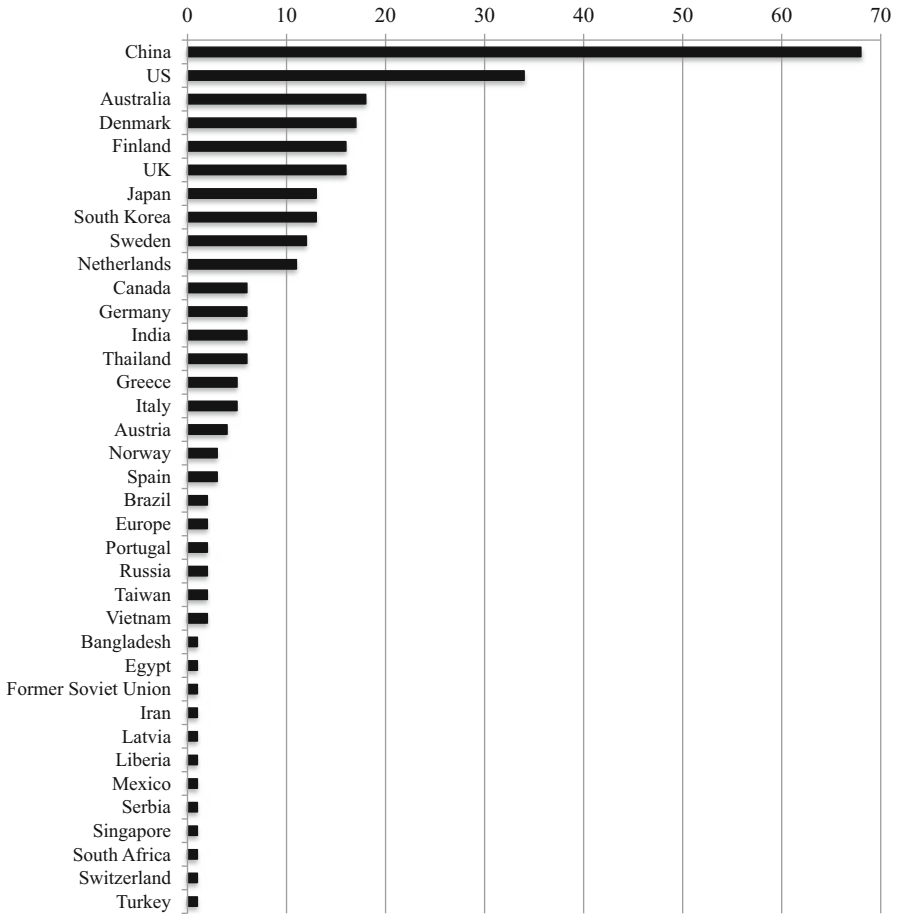


Fig. 5.3 Countries featured in 286 academic papers on industrial symbiosis (out of total reviewed of 391) from 1995 to 2014

The first experimentation happened in single-industry dominated, sector-specific parks, such as chemicals, metals, and sugarcane, then in ETDAs and HTPs, and finally in waste-recycling parks. Along with the spread of EIPs, industrial symbiosis research also has become increasingly diverse in China. The early research mainly focused on EIP conceptual frameworks motivated by industrial ecology metaphors, planning methods/tools based on planning theories and frameworks, and symbiosis system integration from system engineering perspectives. With more and more cases arising, two additional academic communities joined in industrial symbiosis research: environment and ecology and economics and management science. The former mainly focused on win-win solutions, environmental performance evaluation, and formulation of EIP guidelines. The latter mainly focused on cost-benefit analysis, experience identification, and case studies. More recently, research has

begun to uncover the mechanisms and processes of industrial symbiosis from complex theory and network science (Shi and Shi 2014).

Overall, the role of the Chinese government has been crucial in financing and promoting EIPs and opening up space for experimentation and exchange. With the currently perceived need for updating and “eco-transformation,” Yu et al. (2014b) found that the planned EIP model is most useful in the early stage of development, but later it should be combined with a facilitation model to achieve long-term goals with more flexibility. Further, it has become clear that industrial parks cannot succeed without being effectively embedded into the capital, labor, and resources of their local regions. China continues to work toward turning eco-industrial niches into mainstream development, both through practice and through industrial symbiosis research (Gibbs 2009; Shi and Yu 2014).

3.6 Organizational Drivers and Barriers

An ongoing quest in industrial symbiosis is the search for a more definitive understanding of what drives and what hinders it. Since 2011, there have been three review articles with emphasis on the social science side (Boons et al. 2011; Jiao and Boons 2014; Walls and Paquin 2015). Walls and Paquin analyzed 121 industrial symbiosis articles focused on organizational and institutional issues. Using content analysis, they analyzed the factors that authors mention most frequently to explain (1) what facilitates industrial symbiosis in the first place (antecedents), (2) what factors generally help industrial symbiosis to grow over time (lubricants), (3) what inhibits industrial symbiosis over time (limiters), and (4) what are the outcomes of industrial symbiosis (consequences). Table 5.2 lists the top six factors determined by Walls and Paquin in each of the four categories, illuminating where organizational and institutional research in industrial symbiosis has focused. Walls and Paquin’s review highlights the role of the social sciences to contribute to a deeper theory of industrial symbiosis, by taking into account the complex interactions, motivations, and dynamics that occur within and among organizations. A greater understanding of these aspects and dynamics is increasingly important for facilitating and developing robust industrial symbiosis, especially in the policy realm, as industrial symbiosis grows more diverse in typology, geography, and organizational contexts (Jiao and Boons 2014).

4 Part III: Industrial Symbiosis in Both Scholarship and Practice

This section covers scholarship and practice, two integrally related strains of industrial symbiosis. At one level, the rise of bibliometrics has given us a convenient way to analyze the rapidly developing academic area of focus where peer-reviewed

Table 5.2 Drivers and barriers of industrial symbiosis

Antecedents	Lubricants
Co-location, proximity	Intermediaries, coordinators, and champions
Government regulation	Trust, openness
Anchors, scavengers, other roles	Knowledge creation or sharing
Diversity of actor's involvement	Embeddedness
Common strategic vision, beliefs, and alignment	Culture or mind-set
Economic reasons	Social and network ties
Limiters	Consequences
Power, status, asymmetries	Innovation
Too much diversity	Co-benefits: environmental and economic
Exit of player, personnel, or change in flows	Learning
Cost, risk	Resilience
Environmental regulation too restrictive	Lock-in, domino effect
Lack of trust	Social capital

Source: Walls and Paquin (2015)

articles increased sixfold over 10 years and doubled since 2010. Some of the findings of the bibliometric analysis are captured here. At another level, however, it is through practice that we see actual projects and can assess the extent of the contribution of industrial symbiosis to on-the-ground industrial ecosystems, global resource management, and collaborative business behavior. Broadly, practitioners include government actors, private sector actors, and NGO representatives. Of course, there is a great deal of crossover, and ideally, scholarship can eventually be tested in practice, and on-the-ground performance can be measured through academic analysis. Many academics serve as idea brokers and also as evaluators and have been linked to specific projects such as Baas and Boons in Rotterdam, the Netherlands; Park in Ulsan, Korea; Ashton in Puerto Rico; and Salmi on the Kola Peninsula in Russia. Academics also bring projects to light as we have seen in Styria, Austria, TEDA in China, and Östergötland in Sweden. Process engineers, too, have been important bridges between theory and practice.

4.1 Section A: Industrial Symbiosis in Scholarship

Two questions drove the bibliometric analysis of articles from 1995 to 2014:

- What is the intellectual structure of this field based on a review of the academic literature?
- How have frameworks, concepts, and theories advanced in the last 20 years?

This analysis relied on Scopus and ISI Web of Knowledge searches for bibliographic acquisition. Both of these services lean to the “scientific” aspects of a topic under study, in contrast to, for example, Google Scholar, which goes beyond strictly scientific academic journals to include other informative publications. Thus, the

almost 400 articles in this study faced a rigorous test since Scopus and Web of Science are highly selective about which journals they evaluate. We limited our search to articles in English. To begin, we compiled all literature returned by searching for eight keywords as follows:

1. “Industrial symbiosis”
2. “By-product exchange”
3. “By-product synergy”
4. “Industrial ecosystem”
5. “Eco-industrial”
6. “Resource synergy”
7. “Recycling linkage”
8. “Recycling network”

These keywords, derived from the authors’ existing sources on industrial symbiosis, are considered to be broad enough to capture the most significant literature in the field as it has evolved in different regions although surely some material is overlooked. The search covers articles published between 1995 and 2014. After screening for relevance, the 391 papers determined to pertain to industrial symbiosis were classified into one of the seven following categories: Foundations, Performance, Mechanism, Modeling, Structure, Case Study, and Proposal. To avoid multiple allocation of a paper into several categories, the main objective and content of the literature was carefully determined according to criteria described in Table 5.5 in the [Appendix](#). The references for these 391 articles are available upon request.

4.2 Results and Analysis of Bibliometric Study

Figure 5.4 shows that the number of industrial symbiosis papers published in peer-reviewed journals has increased from one paper in 1995 (the first year of publication of a paper meeting our criteria) to 75 in 2014. In particular, 2007 is the year that shows a notable increase in the publication of papers, which is in line with the observation from Yu et al. (2014a), and, notably, the number of papers more than doubled between 2010 and 2014. It is not yet known whether the large increase of articles in 2014 is an outlier, but in general we expect this output to continue to rise at least in the short to medium term (2–5 years) given the trajectory.

Before 2004, the main topic of inquiry concerned conceptual aspects of industrial symbiosis. Case studies began to grow by 2004 with the most for any year being 11 case study articles in 2007. Later, more papers began to focus on analyzing performance and mechanisms of industrial symbiosis and proposing new ideas or strategies for its implementation. Modeling as a topic in industrial symbiosis emerged in 1998, but more than 90 % of modeling papers appeared after 2006. This implies that the focus of industrial symbiosis research has gradually shifted from introducing the concept and presenting specific case studies to delving more into performance and mechanisms of industrial symbiosis and presenting new ideas for industrial symbiosis.

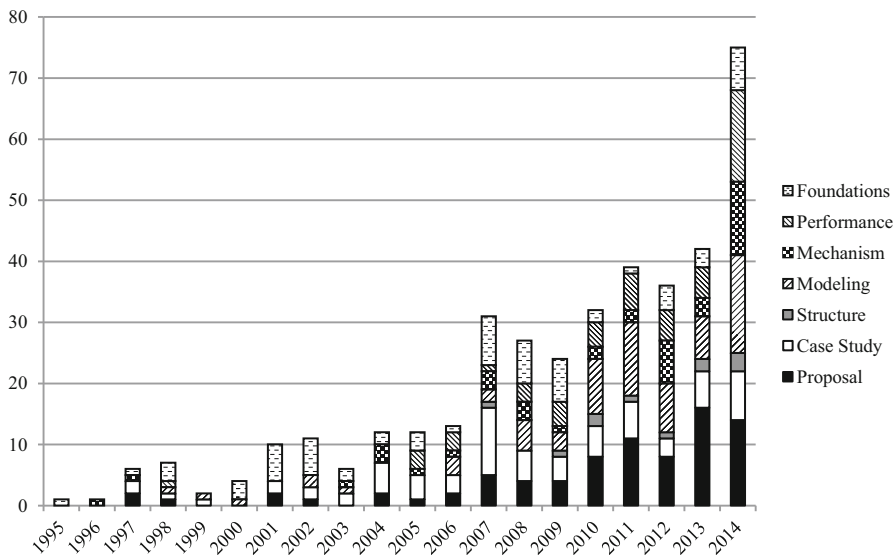


Fig. 5.4 The number of industrial symbiosis papers published between 1995 and 2014 divided into the seven thematic categories

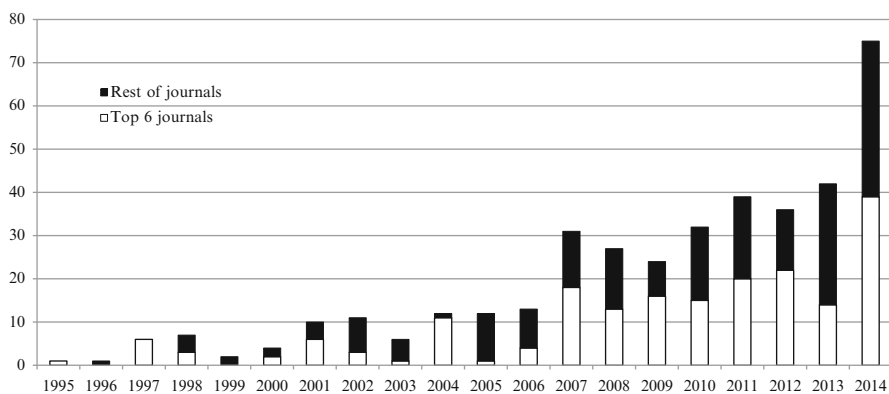
According to Table 5.3, publications of industrial symbiosis papers are concentrated in a few journals, most of which also publish industrial ecology articles. Out of a total of 124 journals publishing industrial symbiosis articles, the top six journals published fifty percent of all the papers captured in the analysis. Figure 5.5 represents the number of industrial symbiosis papers published over time and differentiates whether these articles appeared in the top six journals or the others. Figure 5.5 indicates, in general, that the number of industrial symbiosis papers published in journals other than the top six has increased over time: from one paper in 1996 to 36 papers in 2014. This finding reveals that more industrial symbiosis-related research has emerged in a wider range of journals outside of the core, indicating that industrial symbiosis research is reaching a broader readership.

4.3 Discussion of Industrial Symbiosis Research

The evolution of industrial symbiosis research can be examined qualitatively by looking at common themes and questions addressed in the literature. One key question relates to the scale of industrial symbiosis given that geographic proximity is a well-recognized element that facilitates industrial symbiosis. Sterr and Ott (2004), for example, argued that the regional scale is favorable for industrial symbiosis because it is a scale that is broad enough to offer opportunities for economically viable material reuse among actors and, at the same time, small enough to allow communication and collaboration. Responding to these conceptual discussions

Table 5.3 Journals ranked according to the number of industrial symbiosis papers published

Name of journal	Number of IS papers published
<i>Journal of Cleaner Production</i>	90 (23.0 %)
<i>Journal of Industrial Ecology</i>	50 (12.8 %)
<i>Progress in Industrial Ecology</i>	21 (5.4 %)
<i>Resources, Conservation and Recycling</i>	14 (3.6 %)
<i>Business Strategy and the Environment</i>	11 (2.8 %)
<i>Journal of Environmental Management</i>	9 (2.3 %)
<i>International Journal of Sustainable Development and World Ecology</i>	7 (1.8 %)
<i>Energy</i>	6 (1.5 %)
<i>Clean Technologies and Environmental Policy</i>	5 (1.3 %)
<i>Computers & Chemical Engineering</i>	
<i>Ecological Economics</i>	
<i>Industrial & Engineering Chemistry Research</i>	
<i>Shengtai Xuebao (Acta Ecologica Sinica)</i>	
<i>Environmental Science & Technology</i>	4 (1.0 %)
<i>Fresenius Environmental Bulletin</i>	
<i>Minerals Engineering</i>	
<i>Process Safety and Environmental Protection</i>	
<i>Regional Studies</i>	

**Fig. 5.5** The number of industrial symbiosis papers published over time in the top six journals versus all remaining journals

concerning scale, several studies provided empirical examination of the geographic scale of industrial symbiosis. Lyons (2007) found no preferable scale for recycling and remanufacturing in Texas and argued that recycling boundaries vary for different types of waste and depend on where demand occurs. Jensen et al. (2011) and Chen et al. (2012) presented similar findings about the relationship between reuse distance, the type of materials, and the location of demand. Data from the former

National Industrial Symbiosis Programme (NISP) in the UK showed that half of all resources were reused within 32.6 km (Jensen et al. 2011). According to the data from 88 recycling projects in 23 Japanese eco-towns, the average waste collection and product delivery distance ranged from 15 to 80 km (Chen et al. 2012).

Another key question about industrial symbiosis has evolved around the concept of self-organization and complex adaptive systems. While one stream of IS research has focused on how to replicate Kalundborg through deliberate planning (Potts Carr 1998; Roberts 2004; van Leeuwen et al. 2003), another stream of studies focused more on the organic nature of industrial symbiosis development. Based on historical appraisals, Desrochers (2004) argued that industrial symbiosis has existed and can exist primarily through market mechanisms instead of top-down planning. Chertow (2007) proposed an “uncovering” approach to industrial symbiosis, which stimulates the identification of existing precursors of symbiosis and nurtures them. Considering industrial symbiosis as a self-organizing phenomenon was then developed further by adopting the framework of complex systems science to understand industrial ecosystems as complex adaptive systems (Chertow and Ehrenfeld 2012). Along this line of understanding, tools from complex systems began to be applied to examine evolution and resilience of industrial ecosystems (Cao et al. 2009; Chopra and Khanna 2014; Romero and Ruiz 2014; Zheng et al. 2013; Zhu and Ruth 2013, 2014).

Early studies view industrial symbiosis mainly as a favorable outcome and focused on exploring ways to implement the most optimal form of industrial symbiosis from technological and economical perspectives. With increasing experiences with successes and failures, however, more studies have examined the role of social factors (Ashton 2008; Gibbs 2003; Hewes and Lyons 2008; Howard-Grenville and Paquin 2008; Jacobsen 2007). Some studies describe industrial symbiosis as a learning process and link it to innovation for sustainability at local and regional levels (Mirata and Emtairah 2005; Posch 2010; Ristola and Mirata 2007; Walter and Scholz 2006). Recently, industrial symbiosis was conceptualized as a dynamic process, which can offer new insights about the emergence, evolution, and dissolution of symbiotic relationships and broader institutional dynamics (Boons et al. 2011, 2014; Spekkink 2014).

Finally, measuring performance of industrial symbiosis has attracted much attention, particularly because economic and environmental benefits are what comprise the core industrial symbiosis approach. Some papers estimated net cost savings for different industrial symbiosis scenarios (Karlsson and Wolf 2008; Martin et al. 1998) or for existing industrial symbiosis networks in Kalundborg (Jacobsen 2006); Guayama, Puerto Rico (Chertow and Lombardi 2005); Oahu, Hawai'i (Chertow and Miyata 2011); and Kawasaki, Japan (Van Berkel et al. 2009a). Going beyond quantifying cost savings, Wen and Meng (2014) quantified changes in resource productivity through industrial symbiosis, and Park and Behera (2014) measured how symbiosis increases eco-efficiency. Park and Park (2014) showed how cost savings achieved through industrial symbiosis contributed to obtaining competitive advantage in the market.

Understanding the environmental performance of industrial symbiosis began with quantifying avoided landfilling or material/energy use reductions. While these

are based on direct measurement of material/energy changes, more theoretical understanding of environmental performance came from applying thermodynamic indicators such as emergy or exergy (Geng et al. 2010, 2014; Valero et al. 2013; Wang et al. 2005; Yang et al. 2006). Responding to the issue of climate change, several studies focus on quantifying greenhouse gas or carbon reductions through industrial symbiosis (Dong et al. 2014; Hashimoto et al. 2010; Jung et al. 2012; Liu et al. 2012; Salmi and Wierink 2011). Application of life cycle assessment (LCA) tools to the area of industrial symbiosis was seen mainly after 2010 (Eckelman and Chertow 2013; Mattila et al. 2012; Sokka et al. 2011b; Yu et al. 2014c). Quantification efforts have developed along with the discussion of methodological aspects (Martin et al. 2013; Mattila et al. 2012; Sokka et al. 2008; Wolf and Karlsson 2008) and led to the further development of comprehensive indicator systems, particularly in China (Geng et al. 2009, 2012; Tian et al. 2014).

4.4 Section B: Industrial Symbiosis in Practice

Examining industrial symbiosis in practice for this section involved three primary activities: (1) a review of the project literature with database searches primarily in Google and LexisNexis and materials recommended by colleagues including the 2012 International Survey on Eco-innovation Parks published by the Swiss Federal Office for the Environment, the expanding activities of International Synergies, and the newsletters of the Eco-Industrial Development/Industrial Symbiosis (EID/IS) section of the International Society for Industrial Ecology, (2) the compilation of a list of industrial symbiosis-related events (Table 5.4), and (3) email correspondence with key practitioners and academics studying specific projects to reflect on questions posed:

1. What motivates industrial symbiosis in practice, including what is successful and what is less so?
2. What trends are you seeing and what mechanisms are being adopted for evolution and change?
3. What linkages/evidence do you see that might show the influence of academia on industrial symbiosis practice and industrial symbiosis practice on academia?

Our findings are outlined below.

Industrial symbiosis practitioners emphasize that to increase the success rate of industrial symbiosis, the needs and concerns of private businesses must be better understood and accounted for. Uncovering and identifying viable symbiosis opportunities are often not enough for success, as private firms may not take up the opportunity for many reasons such as uncertain risk, inflexibility owing to the ownership structure, and lack of trust. As an example, several textile dyeing companies in a Chinese industrial park refused low-cost steam from a government-owned coal plant, as they were reluctant to be tied to a giant. There are also issues with private businesses being hesitant to disclose internal information (Mangan 2015, January 19, Personal communication; Tian 2015, January 21, Personal communication).

Table 5.4 Key events related to industrial symbiosis, 1989–2014

Year	IS-related events
2014	US BCSD launches the Austin Materials Marketplace
	European Commission adopts the Communication “Towards a Circular Economy: A Zero Waste Programme for Europe”
	European Union’s Horizon 2020 innovation and research funding plan calls on industrial symbiosis to deliver circular economy
	Finnish Industrial Symbiosis System launched
	Southern African Development Community (SADC) Knowledge Sharing Week on industrial symbiosis in Cape Town
	Green Industrial Symbiosis national program launched in Denmark
	NISP Canada launched
2013	European Industrial Symbiosis Association (EUR-ISA) launched
	European Resource Efficiency Platform recommends pan-European network of industrial symbiosis initiatives
	Chinese Association of Circular Economy established
	Western Cape Industrial Symbiosis Programme (WISP) pilot project, South Africa
2012	Indo-German Environment Partnership Programme fosters work on EIPs in India
2011	Industrial symbiosis embedded in European Resource Efficiency Flagship Initiative, part of the Europe 2020 Strategy
	European Commission adopts the Roadmap to a Resource Efficient Europe
	EU, Turkey, Romania, Bulgaria, and Moldova begin the Industrial Symbiosis Network for Environmental Protection and Sustainable Development in the Black Sea Basin (SymNet)
2010	Portugal’s National Waste Management Plan introduces the concept of IS
	ECOMARK Initiative fosters development of EIPs in France, Greece, Italy, Slovenia, and Spain
2009	EU funds the project ZeroWIN (Towards Zero Waste in Industrial Networks) that terminated in 2014
2008	China passes the Law for the Promotion of the Circular Economy, set to begin in 2009
	Sweden launches SymbioCity project to promote symbiosis in urban systems
	France launches COMETHE project to design methodology and tools for the implementation of industrial ecology approaches on a business park scale (ended in 2011)
2006	China SEPA establishes national guidelines for EIPs
2005	The UK National Industrial Symbiosis Programme (NISP) launched with funding from Defra’s Business Resource Efficiency and Waste Programme
	Korean National Eco-industrial Park Program begins
	China NDRC launches circular economy pilot demonstration projects
2004	<i>Progress in Industrial Ecology</i> begins publication
	Resource Optimization Initiative founded in India
	The annual Industrial Symbiosis Research Symposium initiated at Yale
2001	China SEPA (now MEP) approves the first national pilot EIP (Guangxi Guitang Group)
2000	The Business Council for Sustainable Development – United Kingdom (BCSD-UK) leads its first IS program in the Humber region, UK
	Waste & Resources Action Programme (WRAP) launched in the UK

(continued)

Table 5.4 (continued)

Year	IS-related events
1997	<i>Journal of Industrial Ecology</i> begins publication Eco-town program in Japan begins (ended in 2006)
1995	The Business Council for Sustainable Development – Gulf of Mexico (BCSD-GM) receives an EPA grant for by-product synergy South Korea passes the Act to Promote Environmental Friendly Industrial Structure (APEFIS)
1994	The US President’s Council on Sustainable Development (US-PCSD) assigns demonstration EIPs
1993	<i>Journal of Cleaner Production</i> begins publication
1992	The predecessor to the US Business Council for Sustainable Development, which was the Business Council for Sustainable Development – Gulf of Mexico (BCSD-GM) is launched
1991	US National Academy of Sciences meeting on industrial ecology marks the first official academic meeting on IE
1990	The <i>Financial Times</i> reports on Kalundborg (November 14)
1989	The term “industrial symbiosis” is coined in Kalundborg

Practitioners consider it very important to find ways to move past known hurdles and to get buy-in from businesses, which is essential for success. Many practitioners noted the significance of company champions (Lowitt 2015, January 20, Personal communication with Director of Devens Enterprise Center; Mangan 2015, January 19, Personal communication) as well as the importance of using the language of business (costs, revenues, risk) to generate this buy-in (Laybourn 2015, January 26, Personal communication). Especially in many business situations, as one Nicaraguan business person was quoted as saying, “no company is looking for eco-technologies or eco-innovation. What they are looking for is a solution to a business problem” (Laybourn 2015, January 26, Personal communication).

Another effective and growing avenue for addressing these concerns is through platforms and tools offered by industry organizations or facilitator companies. Industry organizations such as the US BCSD, or facilitators such as NISP, allow businesses a safe and common platform for discussing synergies through symbiosis (Mangan 2015, January 19, Personal communication). A growing trend is the use of Internet-based technological tools (often offered by the aforementioned platforms) such as the Materials Marketplace by US BCSD, SYNERGie by International Synergies, or the Resource-eXchange-Platform as part of the ZeroWIN EU project to further promote coordination and exchanges.

Also emphasized by practitioners is the importance of supportive laws and policies, as well as enabling regulations to incentivize and promote industrial symbiosis. The slow uptake of industrial symbiosis in North America is perceived to be related to the lack of supportive national policies, in contrast to regions with strong supportive policies such as Europe and East Asia, which have seen growing numbers and scale of industrial symbiosis (Lowitt 2015, January 20, Personal communication with Director of Devens Enterprise Center; Massard 2015, January 28,

Personal communication; Shi 2015, January 18, Personal communication; Tian 2015, January 21, Personal communication).

A potential double-edged sword for industrial symbiosis noted by practitioners is that governments, organizations, and businesses have diverse motivations for pursuing and promoting zero-waste/by-product synergy/eco-development and are not necessarily strictly focused on industrial symbiosis (Massard 2015, January 28, Personal communication). A large motivation seems to be the growing cost of landfills. Few actors are overly concerned if their activities neatly fit an academic mold, as long as the cost of waste is reduced. While this is beneficial for the environment, it may not acknowledge or increase awareness of industrial symbiosis (Massard 2015, January 28, Personal communication). At the same time, the growing recognition of industrial symbiosis in various national and regional programs and policies, as illustrated in Table 5.4, is a countervailing positive trend for industrial symbiosis.

Generally, the relationship between practitioners and academics seems productive. There continue to be several business-interested groups, and academics and practitioners are both represented in the EID/IS section of the ISIE, which produces a newsletter and fosters other personal exchanges (Lowitt 2015, January 20, Personal communication with Director of Devens Enterprise Center). Practitioners appreciate academics for providing graduates who help identify symbiosis opportunities and seek to “determine what is working, what isn’t, and why.” Academics can also usefully address big questions such as “what is the function of global market competition for the industrial symbiosis system in a given area?” Still, there is much room for improvement. While the literature describes a wide diversity of industrial symbiosis cases, this diversity appears to be easily overlooked, meaning some scholarship is built on a limited empirical basis where even the most available anecdotes of resource sharing remain out of view (Howard-Grenville 2015, January 28, Personal communication; Spekkink 2015, January 21, Personal communication). Practitioners want more novel ideas beyond the existing canon of symbiosis such as combined heat and power (CHP) or gypsum reuse identified in the academic literature. Others feel that academics sometimes misunderstand what they see on the ground or may not sufficiently engage the work of practitioners in their research (Laybourn 2015, January 26, Personal communication; Mangan 2015, January 19, Personal communication; Tian 2015, January 21, Personal communication).

Going forward, it seems that industrial symbiosis will have to be more attuned to the wants and needs of private businesses to abate the trust and risk barriers identified earlier. Also, more attention needs to be paid to the individual and intra-firm level motivations and dynamics in choosing whether to engage industrial symbiosis practices (Walls and Paquin 2015). The role of facilitator companies such as International Synergies, Sofies, and many more regionally focused firms will continue to grow, as will the role of specialized waste companies (Massard 2015, January 28, Personal communication). While these facilitators can help identify more opportunities for industrial symbiosis and thus accomplish greater environmental gains, a side effect may be that the direct relationship between firms becomes weaker as the role of the facilitator grows. This will be an interesting issue for continued observation.

5 Conclusion: Industrial Symbiosis in a World of Difference

Industrial symbiosis construed as networks of organizations cooperatively sharing “wastes” has created irresistible imagery and high hopes for a time when virtually all water, energy, and materials will be used more than once, and not to do will have become societally unacceptable. On the one hand, industrial symbiosis research and practice have blossomed in the last 25 years and have established a significant and meaningful subfield of industrial ecology and a record of achievement both in policy and in the built environment. On the other hand, there is much more work ahead to prove the appropriateness and effectiveness of industrial symbiosis. The quest is to understand the level at which material, energy, and water reuse, spurred by the cooperative behavior inherent in industrial symbiosis, causes real reductions in total primary resource consumption, actual revenue-generating opportunities for businesses, net positive environmental externalities for communities, and enhanced people-to-people collaboration.

We see that industrial symbiosis has become and is becoming more and more diverse as it expands to additional regions of the world. There is, for example, a growing foothold in Turkey and Colombia and exploration in southern Africa, with facilitated or planned projects springing up, not necessarily in the traditional Kalundborg mold. This diversity is also reflected in the wide range of terminology (as illustrated by the use of eight keywords for the bibliometric search). Indeed, one of the most vexing puzzles of the last several years has been the difficulty of comparing across projects: how can we compare a huge, 5,000-company “Economic and Technology Development Zone” in China with Kalundborg or small-scale agriculturally based systems (Alfaro and Miller 2014; Klee 1999) or a biomass, biofuel, or biogas region developed in Norrköping and Linköping, Sweden (Martin and Eklund 2011)?

A new proposal by an international team the authors are working with has been trying to identify convergence based on the acknowledgement that there are many paths to industrial symbiosis. These researchers have sorted projects into a typology of seven industrial symbiosis dynamics that establish the differences but emphasize, also, that there are common building blocks even in seemingly disparate origins (Boons et al. 2015). Some colleagues are calling for a stronger linkage between industrial symbiosis and national and international efforts aimed at climate change, resource efficiency, and circular economy (Côté 2015, January 16, Personal Communication; Mangan 2015, January 19, Personal communication).

The industrial symbiosis community has a unique property with roots in practice aided by intellectual development, which is all the richer for the ability to bring this knowledge back to practice. In 1997, Volume 1 Number 1 of the *Journal of Industrial Ecology* had one of the early articles about industrial symbiosis coauthored by MIT’s John Ehrenfeld and the graduate student he sent to explore Kalundborg, Nicholas Gertler. They recognized the opportunity that industrial symbiosis represents once the spirit of collaboration could be opened and embedded. They stated the goal we are still seeking that together with new institutional approaches, “more

deep-seated cultural changes can provide a foundation from which symbioses and other forms of material exchange begin to actually move economies toward sustainability” (Ehrenfeld and Gertler 1997).

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Appendix

Table 5.5 Seven categories used for bibliometric analysis and criteria for classification

Category	Industrial symbiosis classification criteria followed by example paper(s)	
Foundations	<i>Address concepts or issues regarding industrial symbiosis at an abstract level</i>	
	Introduce ideas, concepts, potentials of IS	Lowe and Evans (1995)
	Emphasis on the “biological analogy”	Hardy and Graedel (2002)
	Establish a definition, framework, or theory	Chertow (2000) and Korhonen (2005)
	Conduct a comprehensive review of industrial symbiosis as a field of study	Yu et al. (2014a) and Zhang et al. (2014)
	Relate IS to a different field or concept	Parto (2000) and Gregson et al. (2012)
	Define and describe characteristics	Ashton (2009) and Schiller et al. (2014)
Performance	<i>Evaluate the performance outcomes of industrial symbiosis</i>	
	Economic performance	Jacobsen (2006) and Van Berkel et al. (2009a)
	Environmental performance	Mattila et al. (2010), Sokka et al. (2011a), Dong et al. (2013), and Eckelman and Chertow (2013)
	Thermodynamic performance	Wang et al. (2005), Yang et al. (2006), and Geng et al. (2014)
	Efficiency	Salmi (2007) and Park and Behera (2014)
	Implications of industrial symbiosis on regional cooperation and innovation	Mirata and Emtairah (2005) and Posch (2010)
	Develop evaluation methodologies	Sokka et al. (2008) and Mattila et al. (2012)
Develop evaluation indicators	Geng et al. (2009) and Liu et al. (2014)	

(continued)

Table 5.5 (continued)

Category	Industrial symbiosis classification criteria followed by example paper(s)	
Mechanism	Analyze underlying <i>processes</i> through which IS develops and related influencing factors such as institutional capacity, government policy, and social relations that play a significant role	Gibbs (2003), Mirata (2004), Baas and Huisingsh (2008), Grant et al. (2010), and Domenech and Davies (2011)
Modeling	<i>Adopt and discuss various modeling schemes, for example, to optimize material flows or to understand evolution or changes in resilience for an industrial ecosystem</i>	
	Optimize water, energy, waste flows	Nobel and Allen (2000), Hipólito-Valencia et al. (2014), and Cimren et al. (2011)
	Adopt system dynamics	Bailey et al. (1999)
	Adopt agent-based modeling	Cao et al. (2009) and Kim et al. (2012)
	Model evolution of industrial symbiosis	Qin (2006), Huo and Chai (2008), and Zhu and Ruth (2014)
	Model resilience of industrial symbiosis	Chopra and Khanna (2014)
	Model stability of industrial symbiosis	Ng et al. (2014)
Structure	<i>Analyze structural elements of the industrial symbiosis network such as connectance, diversity, or scale</i>	Lyons (2007), Zhang et al. (2013), and Penn et al. (2014)
Case study	<i>Present a broad overview of specific industrial symbiosis initiatives/projects from various perspectives or examine multiple cases to conduct a review or make comparisons</i>	
	Case study at the level of firm	Zhu et al. (2007)
	Case study at the level of industry	Wolf and Petersson (2007) and Dong et al. (2013)
	Case study at the level of cluster	Park et al. (2008) and Taddeo et al. (2012)
	Case study at the level of city	Elabras Veiga and Magrini (2009)
	Case study at the level of region	Baas (2008) and Shi et al. (2010)
	Case study at the level of nation	Van Berkel et al. (2009b), Sakr et al. (2011), and Su et al. (2013)
Proposal	Propose a new idea or more specific plan or strategy for industrial symbiosis using a particular waste material, industry, or site	
	Proposal pertains to a specific plan or site	Alfaro and Miller (2014)
	Proposal pertains to a specific industry	Anh et al. (2011) and Martin and Eklund (2011)
	Proposal pertains to specific waste materials	Mirabella et al. (2014)
	Propose plans based on the evaluation of potential benefits or modeling results	Taskhiri et al. (2014)
	Propose a strategy to design, develop, and implement industrial symbiosis	Tsvetkova and Gustafsson (2012)

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