Front. Earth Sci. 2015, 9(1): 91–104
DOI 10.1007/s11707-014-0445-8

REVIEW

A review of industrial symbiosis research: theory and methodology

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Abstract The theory, methodologies, and case studies in the field of industrial symbiosis have been developing for nearly 30 years. In this paper, we trace the development history of industrial symbiosis, and review its current theoretical and methodological bases, as well as trends in current research. Based on the research gaps that we identify, we provide suggestions to guide the future development of this approach to permit more comprehensive analyses. Our theoretical review includes key definitions, a classification system, and a description of the formation and development mechanisms. We discuss methodological studies from the perspective of individual industrial metabolic processes and network analysis. Analyzing specific metabolic processes can help to characterize the exchanges of materials and energy, and to reveal the ecological performance and economic benefits of the symbiosis. Network analysis methods are increasingly being used to analyze both the structural and functional characteristics of a system. Our suggestions for future research focus on three aspects: how to quantitatively classify industrial symbiosis systems, monitor the dynamics of a developing industrial symbiosis system, and analyze its internal attributes more deeply.

Keywords industrial ecology, industrial symbiosis, industrial metabolism, network analysis

1 Background

In 1947, George Renner used an approach based on ecological science to describe the organic relationships among industries. Based on the production of wastes and byproducts and their flows among industries, he described the possibility that one enterprise may deliver its wastes to another industry that can use those wastes as raw materials. Renner described these relationships as the industrial equivalent of the symbioses that occur in ecosystems (Renner, 1947), but he did not use the term "industrial symbiosis" to describe the relationships. Ayres (1988) later proposed the term "industrial metabolism", and subsequently expanded the concept to describe the whole integrated collection of physical processes that convert raw materials, energy, and labor into finished products and wastes under (more or less) steady-state conditions (Ayres and Simonis, 1994). The modern usage of "industrial symbiosis" can be dated to 1989, when the Danish researcher Valdemar Christensen, a production manager at the Asnaes Power Station, used the Danish equivalent of these words to describe this phenomenon in the Kalundborg eco-industrial park (Dougherty, 1997). Industrial symbiosis studies now use systematic methods that originated in the study of complex ecological or biological systems to build on industrial metabolism research and study details of the exchanges of materials and energy through a network of industries. Because such analyses can provide important insights, the field has developed rapidly for the past 30 years (Harper and Graedel, 2004; Korhonen, 2004).

The development of industrial symbiosis theory involved both the discussion and refinement of the underlying theory, and the development of practical applications. Frosch and Gallopoulos (1989) proposed the concept of an "industrial ecosystem", and noted that the traditional model of industrial activity should be transformed into a more integrated model that is the industrial equivalent of a natural ecosystem. In such a system, the consumption of energy and materials would be optimized, waste generation would be minimized, and the wastes and byproducts from one process would serve as the raw materials for other processes. That is, materials and energy would be cycled in ways similar to the efficient cycling that

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Received July 29, 2013; accepted February 14, 2014

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occurs in a natural ecosystem. Lowe and Evans (1995) described several ways in which an industrial ecosystem is analogous to a closed-loop natural system.

In summary, these contributions provided a theoretical basis for the development of industrial symbiosis research. However, this approach was recognized, though without an underlying theoretical framework, earlier. In the 1970s, a cluster of companies from different industries in the city of Kalundborg (Denmark) began intensively cooperating with each other to reduce their costs, strengthen their waste management, and use fresh water more efficiently. During the late 1980s, some local students recognized many connections among Kalundborg's industries. Basing their description on Valdemar Christensen's Danish terminology, scholars began using the phrase "industrial symbiosis" to describe the Kalundborg system (Ehrenfeld and Gertler, 1997; Jacobsen, 2006; Chertow, 2007). Kalundborg subsequently began to formally develop the relationships among industries in the park, and its success attracted worldwide attention and prompted many subsequent studies (Engberg, 1992; Gertler and Ehrenfeld, 1996; Schwarz and Steininger, 1997; Ehrenfeld and Chertow, 2002).

2 Theoretical discussion of industrial symbiosis

2.1 Definitions of the term "industrial symbiosis"

The term "symbiosis" was introduced into biology from the Greek language ("living together") by Anton de Bary in 1879 (Darlington, 1951). Symbiosis is a biological term referring to "a close, sustained coexistence of two species or kinds of organisms" (Encyclopedia Britannica, 1992). With the development of industrial ecology in the 20th century, the symbiosis in natural systems was adopted as an analogy for how industries interact, and soon became its own field of research (Lowe and Evans, 1995; Harper and Graedel, 2004; Korhonen, 2004).

Scholars have studied industrial symbiosis from three main perspectives: characterization of the conditions under which industrial symbiosis complexes form, the exchange relationships that sustain their development, and the benefits that accrue to industries that participate in them. The precondition for an industrial symbiosis complex is cooperation among the companies, and these companies form a network as a result of that cooperation (Chertow, 2000; Harper and Graedel, 2004; Chertow and Lombardi, 2005). The definitions proposed by Chertow (2000) have been accepted by many subsequent scholars (e.g., Yang and Feng, 2008; Costa and Ferrão, 2010). Chertow (2000) described the keys to industrial symbiosis as cooperation in taking advantage of the synergistic possibilities offered by the geographic proximity of the companies. This is because the relationships among companies involve physical exchanges of materials (including water), energy, and by-products, and these exchanges occur more efficiently over short distances. However, it is important to note that the exchanges can also occur over long distances in some cases, so proximity is not a precondition for the development of symbiosis. Subsequently, Mirata and Emtairah (2005) noted that the relationships could also include exchanges of knowledge and utilization of shared infrastructure. *Industrial Symbiosis*, published by the Kalundborg Company in Denmark (Harper and Graedel, 2004), emphasizes that the development of industrial symbiosis complexes improves the likelihood of survival and the profitability of existing companies, which can potentially optimize the environmental and economic benefits that result from the symbiosis. Chertow and Lombardi (2005) further defined industrial symbiosis according to its environmental benefits. Mirata and Emtairah (2005) combined the insights from a series of studies and proposed a comprehensive framework for industrial symbiosis (Fig. 1).

2.2 Mechanisms of industrial symbiosis

Studies of the mechanisms that underlie an industrial symbiosis have mainly analyzed the factors, including internal industrial metabolic processes that influence the system's formation and future development. The exchanges and flows of resources within the system are the key aspects that define the symbiosis.

There are three factors to consider when analyzing these mechanisms. First, it's necessary to understand the driving force that is responsible for the economic benefits. Symbiotic relationships among different industries or different companies decrease the cost of raw materials and the disposal cost for wastes because the raw materials of one industry or company can be replaced to some extent by the byproducts and wastes of another, and this helps to improve the economics of each participant's operations (Golev and Corder, 2012). Economic benefit was the core driving force in the development of the Kalundborg industrial symbiosis complex. Many companies exchanged resources spontaneously because this reduced their resource consumption, especially for nonrenewable resources, and decreased their production of wastes that would otherwise require expensive treatment (Venta and Nisbet, 1997; Pedersen, 1999; Wolf et al., 2007).

The second factor relates to the legislation and regulations that shape the development of a symbiosis. Many industrial symbioses develop as eco-industrial parks when the managers of the park are asked to comply with environmental regulations, and use this as an opportunity to examine their economic requirements. Therefore, many eco-industrial parks were established intentionally rather than evolving, and were built to meet the need for

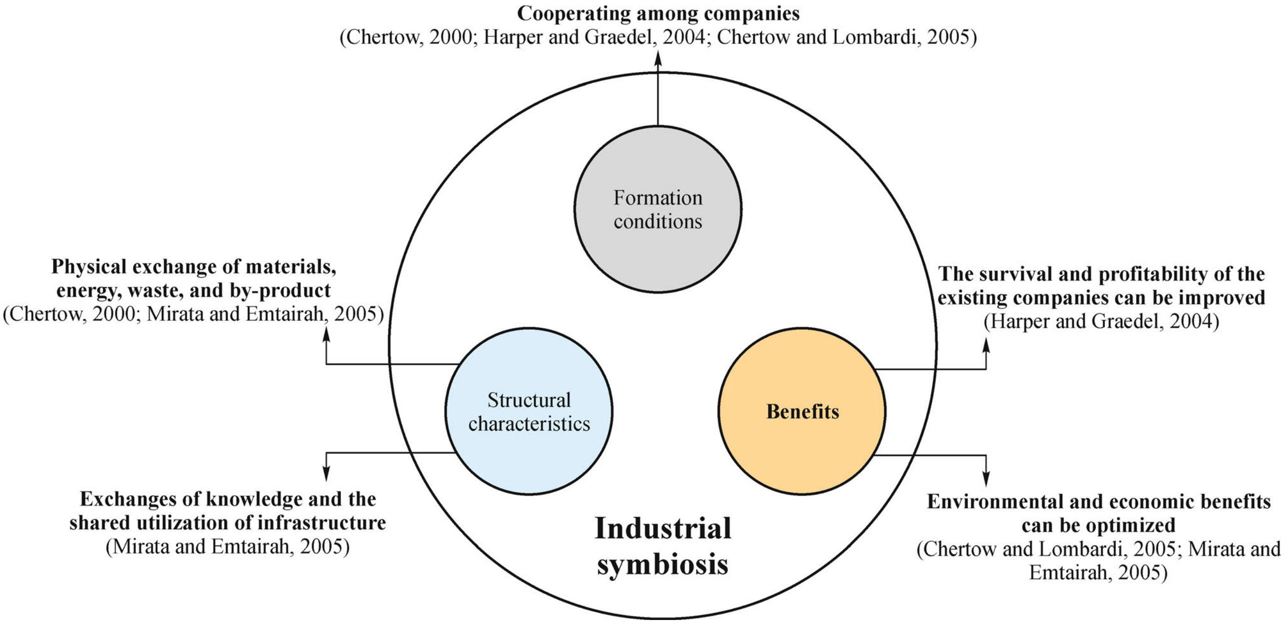

Fig. 1 The connotation of industrial symbiosis.

improved environmental protection and sustainable development (Desrochers, 2004; Gibbs and Deutz, 2007). For example, the Korea National Cleaner Production Center developed in response to national policies to convert existing industrial parks into eco-industrial parks (Park et al., 2008). The United States government also formulated policies to promote the development of eco-industrial parks (Cohen-Rosenthal et al., 1997; Schlarb, 2001).

The third factor relates to technological improvements and innovations, which have stimulated the development of industrial symbiosis complexes. This driving force includes improvements in material utilization and reuse technologies, and the adjustment of industrial production structures (Ehrenfeld and Gertler, 1997; Ohnishi et al., 2012). These innovations improve waste management and the efficiency of resource utilization (Yang and Feng, 2008; van Berkel et al., 2009).

These three factors all influence the formation and development of industrial symbiosis complexes, although in different ways and possibly at different times, and each can lead participants to comprehensively improve the complex’s structure and functions.

Analyzing the interactions among these factors provides a more systematic approach to studying the principles that govern these interactions. Yuan et al. (2004) summarized the factors that influenced the structure and function of industrial symbiosis complexes, and established equations to represent their relationships. In this representation, they divided “structure” into four sub-systems (environment, economy, society, and resources) and divided “functions” into five categories: the flows of materials, information, value, energy, and technology (including know-how). These functions can be quantified in various ways:

a) The flow of materials can be represented by the inputs (raw materials) and outputs (industrial products, byproducts, and wastes) per unit of input.

b) The flow of information can be represented by the transfer of information from a variable x to a variable y within a given process. For example, changes in the market demand for a given product (x) can lead to decreased demand for an input material (y) that is used to manufacture that product.

c) The flow of value can be represented in monetary terms by calculating a value per unit of a given flow or by measuring the number of turnovers (rotations) of stock in an accounting period.

d) The flow of energy can be described based on the quantity of energy consumed or generated as a byproduct, and transferred either directly or indirectly among the components of the system.

e) The flow of technology includes technological innovation, technology transfer, and technology diffusion.

Although some researchers have proposed equations to express the relationships among these factors, these equations have generally been qualitative. Clearly, it would be more meaningful to quantify the relationships among these factors, and analyze their respective degrees of influence. Although the choice among the various quantitative metrics that are available is somewhat subjective, any attempt to quantify the flows and relationships permits a more objective analysis of the system.

2.3 Types of industrial symbiosis

The different types of industrial symbiosis have been defined primarily based on the study of eco-industrial parks, as these are the most obvious example of industrial symbiosis complexes. As the study of industrial symbiosis has developed, it has progressed from studying the exchanges that occur within companies to include the exchanges among companies, and finally to include regional exchanges of resources and information sharing (Chertow, 1999, 2000). Researchers have therefore studied the types of symbioses from different perspectives. First, researchers have examined external factors, such as the location of the eco-industrial park (Lowe, 1997), the factors that are influencing its formation, its development history (Chertow, 2007), and its current status (Yuan et al., 2004). Second, scholars have divided parks into types based on the characteristics of their members and the system's structure. Examples include studies of the industrial structure (Ministry of Environmental Protection of the People's Republic of China, 2006a, b, 2009), of the relationships among its members (Wang and Yin, 2005), and of how these aspects can be understood better by applying the theoretical insights gained from natural systems (Guo and Zhong, 2005).

Based on the location of a park, eco-industrial parks can be divided into co-located eco-industrial parks and virtual eco-industrial parks (Lowe, 1997). The co-located parks are comprised of groups of companies at the same site or in the same small region. Virtual eco-industrial parks can be spread over a much wider area, and may be based on exchanges of by-products and wastes among companies separated by long distances. Their structure is sparse compared with co-located parks (Cohen-Rosenthal et al., 1996; Lowe et al., 1998; Lambert and Boons, 2002). Virtual parks can eliminate the cost of constructing a park from scratch, and greatly improve the efficiency by exchanging resources within or between large regions, particularly when the resources are not available in close proximity to the industry or enterprise that requires them (Martin et al., 1996; Schwarz and Steininger, 1997; Côté and Cohen-Rosenthal, 1998). A typical virtual park is the Brownsville industrial symbiosis complex in the United States (Martin et al., 1996). Although it was only proposed in the literature and did not come to fruition, it still possesses the key characteristics of such a park and undoubtedly influenced the thinking of researchers.

In contrast, co-located eco-industrial parks are comprised of a group of companies located in close proximity. In that context, transportation costs and risks (e.g., chemical spills during transport) are minimized, allowing members to pursue optimization of their environmental and economic benefits (Martin et al., 1996; Heeres et al., 2004; Elabras Veiga and Magrini, 2009). The Kalundborg eco-industrial park is a typical example. Lambert and Boons (2002) further divided co-located eco-industrial parks into industrial symbiosis parks and mixed industrial parks. The former describes geographically concentrated industrial activities with tight couplings among a relatively small number of material- and energy-intensive production processes, whereas the latter describes more diverse industrial activities with a lower level of coupling of the production processes.

Improvement of the system's environmental performance, and of the economic and social benefits, will interact with the regulations imposed by local or national governments to influence the evolution of a complex. Thus, Chertow (2007) analyzed the formation and developmental histories of eco-industrial parks, and proposed two additional categories: planned eco-industrial parks and self-organizing parks. The self-organizing parks emerge from existing private actors who are motivated to exchange their resources in response to these influences. The economic benefits then come in the form of cost reductions, increased revenues, and business expansion. In contrast, planned eco-industrial parks start from conscious efforts (often promoted by a government) to identify companies from different industries that could potentially work together, and to promote sharing of resources among these companies.

Based on the status of a complex, Chinese scholars have divided the parks into newly planned parks and existing industrial groups (Yuan et al., 2004). A newly planned eco-industrial park is built from scratch, based on careful analysis of the design requirements and planning of how to meet these requirements. The primary goal is to unite companies through the adoption of "green manufacturing technologies". This approach asks the members of the park to decrease their impact on the environment through the construction of shared infrastructure such as sewage treatment facilities. The Tianjin Economic Development Area is a typical example (Shi et al., 2010). In parks that have been created by the transformation of existing groups of companies, the goal is to revise or transform the existing technologies by constructing waste- and energy-exchange centers, and to promote greatly increased exchanges of materials and energy among the companies. The Guangxi Guigang eco-industrial park is a typical example (Zhu et al., 2007).

Researchers can also use internal characteristics of the system, such as the relationships between members and the structural distribution of a system, to categorize different types of complexes. According to the Chinese standard for eco-industrial parks that was proposed in 2006, the Ministry of Environmental Protection of the People's Republic of China categorized eco-industrial parks into sector-integrated, sector-specific, and reuse and recycling parks, with the classification based on their different industrial compositions (Ministry of Environmental Protection of the People's Republic of China, 2006a, b, 2009). Sector-integrated eco-industrial parks are composed of enterprises from different industrial sectors, and most have developed from high-tech industrial development zones or economic and technical development zones. Sector-specific eco-industrial parks contain one or more core enterprises from the same industrial sector, as well as some other enterprises from related industries. Most of these parks have developed through increasing the integration of the flows of materials and energy. Reuse and recycling parks are a special type in which the enterprises are mainly engaged in reuse, recycling, and resource recovery. These parks are designed to protect the environment by preventing potentially useful resources from becoming wastes, and by using these resources to replace the consumption of natural raw materials. By using advanced technology, they can transform the wastes generated by industrial production and consumption processes into recycled or reused resources and products (Potts Carr, 1998; Sato et al., 2004).

Based on the nature of the relationships among members in a complex, Wang and Yin (2005) divided eco-industrial parks into dependency-oriented, equality-oriented, and nested categories. Dependency-oriented parks develop around one or more core companies, as in the cases of the Kalundborg, Guangxi Guigang, and Shandong Lubei eco-industrial parks (Chertow, 2007; Zhu et al., 2007; Chen et al., 2010). Based on the "key species" theory from ecology (Paine, 1969), Guo and Zhong (2005) divided the parks into categories based on whether there is a single core company or several dominant companies. Based on this division, Wang (2009) further divided the dependency-oriented parks into single-dependency parks (with a single key member) and multiple-dependency parks (with two or more key members). In equality-oriented parks, the companies have equal status and do not rely exclusively on each other, as in the case of the Burnside Industrial Park (Wright et al., 2009). Parks that combine aspects of both of these categories are referred to as nested eco-industrial parks, and include the Styria industrial symbiosis (Schwarz and Steininger, 1997). By analogy with the relationships among species in natural systems, the companies in these parks can be divided into categories based on whether they are dominated by parasitism, in which one or more of the companies benefit at the expense of one or more of the other companies; by commensalism, in which one or more companies benefit from belonging to the system but without harming other companies; or mutualism, in which most relationships among companies are beneficial to both companies (Kronenberg, 2007). By analogy with the food chains or food webs that exist in natural systems, Song et al. (2008) categorized the companies in eco-industrial parks as "symbiotic" (the members have equal status), parasitic (core companies exploit peripheral companies), or saprophytic (the members engage primarily in reuse and recycling).

Table 1 summarizes the various theories that have been proposed, the types of parks that can be defined based on each theory, and typical examples of each type of industrial symbiosis from around the world.

In summary, the different types of industrial symbiosis have mainly been categorized based on subjective and qualitative judgments. In the future, it will be necessary to divide the parks into categories based on more objective and quantitative criteria, such as quantitative analyses of their internal structural characteristics. This will help to reveal how different structural attributes influence the exchanges of materials, energy, by-products, and wastes, thereby providing managers with a way to identify

Table 1 Examples of industrial symbiosis complexes

Theoretical foundation	**Types of park based on that theory**	**Typical examples from around the world**
Location, history of formation and development (Chertow, 2007)	Planned eco-industrial parks	Tianjin (TEDA) (Shi et al., 2010)
	Self-organizing eco-industrial parks	Kalundborg (Chertow, 2007)
Development process (Yuan et al., 2004)	Newly planned eco-industrial parks	Choctaw (Potts Carr, 1998), Tianjin (TEDA) (Shi et al., 2010)
	Transformed from existing groups of companies	Guangxi Guigang (Zhu et al., 2007), Shandong Lubei (Chen et al., 2010)
	Virtual eco-industrial parks	Brownsville (Martin et al., 1996)
Industrial structure (Ministry of Environmental Protection of the People's Republic of China, 2006a, b, 2009)	Sector-integrated park	Tianjin (TEDA) (Shi et al., 2010)
	Sector-specific park	Shandong Lubei (Chen et al., 2010), Guangxi Guigang (Zhu et al., 2007)
	Reuse and recycling park	Choctaw (Potts Carr, 1998)
Relationships among members (Wang and Yin, 2005; Wang, 2009)	Equality-oriented parks	Burnside (Wright et al., 2009)
	Single-dependency parks	Guangxi Guigang (Zhu et al., 2007)
	Multiple-dependency parks	Kalundborg (Chertow, 2007)
	Nested parks	Styria (Schwarz and Steininger, 1997)
Use of the "key species" theory from research on natural systems	Single dominant company in the park	Guangxi Guigang (Zhu et al., 2007)
	Two or more dominant companies in the park	Kalundborg (Chertow, 2007)

operational problems and increase the system's resource-utilization efficiency.

Based on this review of the literature, we have identified several common themes and useful insights from previous classification systems. To integrate these insights, we propose the classification system shown in Fig. 2. Although this system is not final, we believe that it represents a useful starting point for developing future systems, particularly if the decision at each branching point in the flowchart can be based on quantitative rather than qualitative criteria.

3 Methods of analysis for industrial symbiosis complexes

3.1 Industrial metabolism analysis

Because industrial systems must obtain resources from their external environment and emit wastes or transfer byproducts and products to their environment, these inputs and outputs resemble those of a giant organism (Zhang, 2013). The cycling mechanisms of an organism living within a natural ecosystem can then be used as an analogy to simulate the mechanisms in an industrial symbiosis. Based on this analogy, the insights from research on natural ecosystems can be used to better understand the metabolic processes of socioeconomic systems such as industrial symbiosis complexes.

Industrial metabolism analyzes the total use of materials and energy throughout an entire industrial process. These processes include identifying a source for inputs (raw materials, which are analogous to nutrients), transportation of these inputs to where they will be used, use and reuse of the inputs, and recycling and disposal of all byproducts and wastes generated by use and reuse of these materials (Allenby and Richards, 1994; Marinova et al., 2006). Some researchers have combined these different phases into two sub-processes: product metabolism and waste metabolism (Dolginow, 2011; Giacomo and Maria, 2011). Product metabolism accounts for the sourcing, transportation, and utilization of raw materials, whereas waste metabolism accounts for the disposal and reuse of byproducts and wastes generated by the product metabolism. Waste metabolism is a particularly important process in industrial symbiotic systems. In such systems, the members exchange byproducts and wastes in order to decrease the production of wastes and reduce the cost of obtaining inputs (raw materials) and the cost of treating and disposing of outputs (wastes).

To describe these processes, scholars have mostly used the methods of material-flow analysis or substance-flow analysis to quantify the flows throughout eco-industrial parks or between the external environment and companies in the park. Material-flow analysis represents eco-industrial parks as black boxes (i.e., does not consider the internal flows). By analyzing the inputs of resources into the black box and the resulting outputs of wastes, researchers can evaluate the overall resource consumption efficiencies, production of products, and emission of wastes using various metrics. For example, Goto et al. (2005) analyzed the material flows and waste emissions of

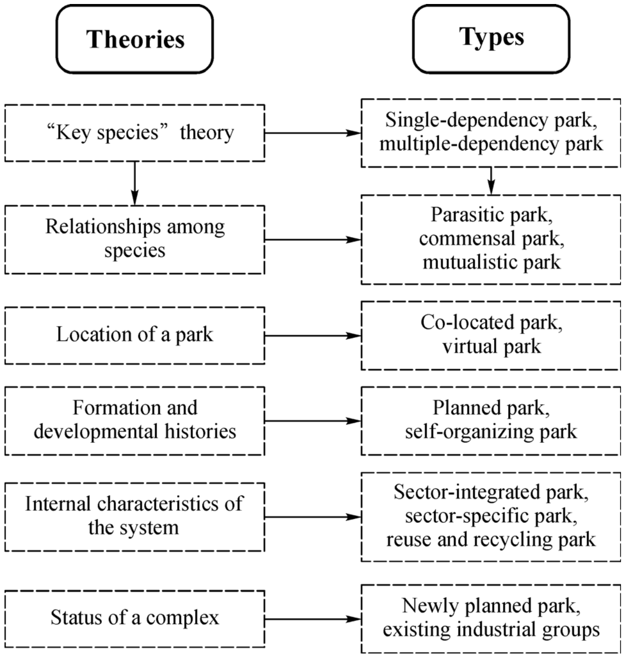

Fig. 2 A classification system including theories and the names of different types.

the Eco-town in Japan's Aichi Prefecture, and showed that this system was still in an early stage of its development, and that its facilities and information systems should be improved to promote sustainable development. Sendra et al. (2007) analyzed the processes that transformed the Catalonia (Spain) industrial park into an eco-industrial park. Although the industrial symbiosis complex is seen as a black box in this approach, the method can be used to describe resource utilization efficiency, and this can reveal whether and how this efficiency should be improved to transform an industrial park into an eco-industrial park.

During the development of industrial metabolism research, the quantitative analysis of industrial metabolism was not limited to the black-box studies. Scholars also studied specific metabolic processes. Fath and Patten (1999) performed such a study using the terminology "environ" analysis. This framework included three parts: the inputs, the industrial system, and the outputs. The industrial system represents the inputs and outputs that result from the flows among the system's member companies. By combining metrics and accounting for the inputs and outputs of materials, the ecological efficiencies of the system and of water utilization can be calculated. As another example, Tian et al. (2013) defined the boundary of such a system and identified its material flow processes, then establish a material-flow analysis framework for industrial parks.

However, due to deficiencies of data and in the method, it is difficult to account for flows of multiple materials using a single method, so some scholars have instead studied industrial metabolic processes by focusing on a single substance. To support this research, substance-flow analysis can be used to analyze the different directions of the flows and geographical distributions of the elements. This approach has been used to study carbon (Tian et al., 2013; Zhang et al., 2013a) and sulfur (Chen, 2003; Tian et al., 2012). It can also be used to study the utilization efficiencies for these and other elements in industrial symbiosis complexes. This method is now widely used in the analysis of flows in chemical industrial parks, such as the Shandong Lubei eco-industrial park (Chen, 2003).

3.2 Network analysis methods

The previous section focused on providing an overview of a symbiosis complex based on its industrial metabolic processes, which provides only an external understanding of the system. To fully understand the system, it is necessary to analyze the internal structural and functional attributes of the system. Because the flows among companies form a network, the techniques of network analysis can be introduced to provide new insights into these flows (Fath and Patten, 1998, 1999).

Using natural systems as an analogy for socioeconomic systems provides an easy way to understand the relationships within such networks. In this approach, the industrial symbiosis system can be abstracted as a network and the methods of network analysis can be used to analyze the internal characteristics of the industrial symbiosis complex (Mirata and Emtairah, 2005; Behera et al., 2012). Social network analysis and ecological network analysis are the two main methods used by this approach. Whereas social network analysis derives from studies of how humans communicate within social networks, ecological network analysis derives from studies of the flows within ecological networks (Doménech and Davies, 2009; Li et al., 2012).

In *Industrial Ecology*, Graedel and Allenby (1995) described two metrics that are used in the analysis of natural ecosystems, and noted that they could be used to analyze industrial systems: species richness (the number or variety of the companies in the system) and species correlation (the relationships among the companies). Subsequently, researchers used these metrics to study the structural attributes of industrial networks. Dai (2010) used species correlation to analyze the ecological relationships among companies and the utilization rates of their byproducts and wastes. They compared the Kalundborg eco-industrial park with eight eco-industrial parks in China for relationships based on the exchanges of byproducts and wastes.

However, these studies were limited because the two metrics were simplistic and primarily reflected the number of companies rather than the structure of their relationships. To provide more useful insights into the relationships among members, researchers adopted the metrics in social network analysis and ecological network analysis, and used them to evaluate the sustainability of industrial parks as ecosystems on a quantitative basis (Wright et al., 2009).

Social network analysis is an effective method used to describe the structural characteristics of a system (Ashton, 2008; Doménech and Davies, 2009, 2011a, b; Paquin and Howard-Grenville, 2009). By examining the exchanges among members of a network, social network analysis provides a framework for understanding the human aspects of the system, and how social relationships drive the exchanges of materials, energy, and information (Doménech and Davies, 2009). Ashton (2008) analyzed the relationships among companies and their managers in the Barceloneta Industrial Park in Puerto Rico, including the relationships among supply chains, interpersonal relationships, trust and organizational relationships, and the associated relationships within the industrial symbiotic network. She found that this approach was an effective tool for analyzing these relationships. Soon afterwards, Doménech and Davies (2009, 2011a, b) used this approach in an empirical study of industrial symbiosis that focused on trust relationships in production or business networks.

Many metrics used in social network analysis can also be used to quantify the resource exchanges among members of the network. For example, core–periphery analysis can be used to determine whether a company plays a core or peripheral role in exchanging resources (Ashton and Bain, 2012; Zhang et al., 2013b). To further clarify the characteristics of companies (which are represented by nodes in the network), researchers can use the nodal degree, betweenness, or closeness, to reflect the status of each node in terms of its ability to control flows and share information within the network (Doménech and Davies, 2011b). The nodal degree represents the number of paths that connect to a node. Betweenness represents the number of times a node lies on the shortest path between two other nodes (Scott, 2000). Closeness represents the shortest linkage between two nodes (Ashton, 2008; Ashton and Bain, 2012). To analyze the overall characteristics of a network, density assessment has also been widely used (Zhang et al., 2013b). This method is similar to correlation analysis, because it can reflect the tightness of the connections among the companies. Doménech and Davies (2011b) used the Kalundborg eco-industrial park as an example and studied its structure to understand the density of exchanges of material and energy and the roles of each member.

Ecological network analysis is based on obtaining data on the storage and flows of resources represented by the ecological relationships among enterprises at the level of the whole eco-industrial park, thereby revealing the structural distribution and functional attributes of the network (Patten, 1982; Szyrmer and Ulanowicz, 1987). This method has been widely applied to the study of natural systems such as bays (Christian and Luczkovich, 1999; Baird et al., 2009), estuaries (Whipple et al., 2007; Christian et al., 2009), and saline ponds (Dame and Christian, 2008). It has also been used to study the sectors of socioeconomic systems, such as industries (Chen, 2003), fisheries (Walters et al., 1997; Pauly et al., 1998), energy (Zhang et al., 2010b), and water (Bodini and Bondavalli, 2002; Zhang et al., 2010a). However, there have been few studies of industrial parks based on ecological network analysis (e.g., Chen, 2003; Lu et al., 2012). Although ecological network analysis can be used to analyze the functional attributes of a system, data for the flows of materials, energy, and information are difficult to obtain. It is also difficult to integrate these flows, because they have different units, and some accounting methods cannot effectively unify flows measured in different units. Chen (2003) used this approach to analyze the average path length and cycling index of sulfur utilization in the Shandong Lubei eco-industrial park. These two metrics revealed the system’s structure and material utilization efficiency. Chen (2003) also developed a new metric, the coupling degree, to characterize the degree to which network nodes were connected to each other via flows of materials. These metrics also represented the degree of integration of the system, and could be used to monitor its evolution over time.

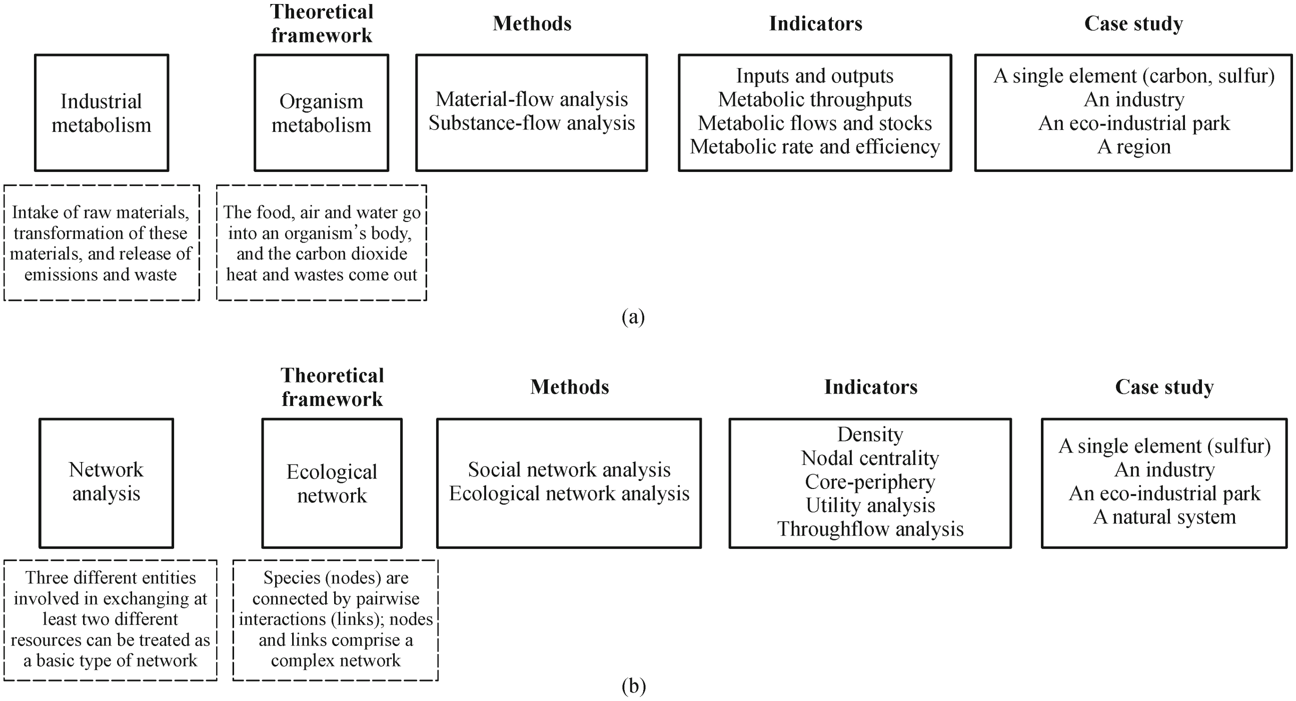

Fig. 3 Diagrams of the theoretical framework, methods, indicators, and examples of typical case studies in (a) industrial metabolism and (b) network analysis methods.

Unfortunately, most studies focused on the use of metrics to analyze only a single case study or used a single metric to compare several case studies. Scholars rarely used multiple quantitative metrics from network analysis or have combined these metrics to compare typical parks throughout the world. Zhang et al. (2013b) performed one of the few studies that used multiple metrics to compare multiple case studies.

Figure 3 illustrates the theoretical framework, methods, indicators, and examples of typical case studies from the industrial metabolism and network analysis methods.

4 Planning and redesign of industrial symbiosis complexes

The development or operation of eco-industrial parks may be affected by changes in the processes or the relationships among the companies. Therefore, it is necessary to plan or redesign industrial symbiosis complexes to mitigate the risks created by these changes.

By analyzing the exchanges of materials and energy, or the inputs from and outputs to the external environment, studies of an industrial symbiosis complex can identify resources that are not being fully recycled, including water and energy. Consequently, industrial metabolism research can be used to provide suitable suggestions to guide a complex's future sustainable development (Lowe, 1997). Suggestions include promoting the reuse of some unutilized or underutilized resources, and recycling wastes and increasing their utilization efficiency (Yuan and Shi, 2009; Dong et al., 2013; Zheng et al., 2013). Suggestions can also focus on improving the technologies used by the park's enterprises, and promoting the development of a more optimal configuration (Meneghetti and Nardin, 2012; Gonela and Zhang, 2014). Researchers have also compared different industrial symbiosis complexes to identify the shortcomings in some parks and propose improvements based on the advantages of other parks (Dong et al., 2013, 2014).

In China, there have been some studies of the future development of symbiotic complexes. Xia et al. (2006) analyzed the existing product metabolism chains in China's Baotou eco-industrial park, and identified unutilized useful resources in the metal processing system and some associated high-technology systems. Based on this discovery, they proposed the development of three industrial metabolism chains that would effectively recycle these resources. Feng and Sun (2009) examined the Xinjiang Shihezi eco-industrial park, which is located in an arid region. They introduced a multi-objective fuzzy optimization model to improve the recycling rate of fresh water within the industrial symbiosis complex. Yuan and Shi (2009) analyzed the unutilized byproducts and wastes in a state-owned smelter and found ways to reuse the wastes, recycle the heavy metals, and extend the industrial chains to improve the value of the smelter's products. They helped to reduce the complex's operating cost and decrease its impact on the environment.

In the development of industrial symbiosis complexes, challenges may arise from instabilities of the complex's structure (Doménech and Davies, 2011a). If there are changes in the core member companies, such as process adjustments, changes in the materials used or scales of production, or changes in the management environment, these can all affect the stability of the relationships between core and peripheral members (Doménech and Davies, 2011a). These adverse impacts can be avoided by introducing new nodes, or changing existing nodes or the linkages among them. Wang et al. (2009) redesigned the Anyang High-tech Industrial Symbiosis Complex using a scenario-analysis method. They proposed the introduction of new companies to strengthen the relationships among the existing companies, and that these alterations would help the complex to utilize its resources more fully. However, simply adding new nodes or linkages cannot ensure the sustainable development of an industrial symbiosis complex. It is necessary to quantitatively analyze where and how to add the new nodes or linkages so that the complex can be developed most efficiently.

If a manager needs to judge the effect of implementing newly planned paths between members of the network or redesigned existing paths, it is reasonable to focus on evaluating the benefits for each enterprise within the complex. The exchanges among the companies in an industrial symbiosis complex can decrease the effects of byproducts, emissions, and wastes on the environment. Downstream companies can utilize these outputs from upstream companies as raw materials, thereby increasing the reuse or recycling of these resources. For example, the sugar production enterprise in the Guigang eco-industrial park produces bagasse, bagasse pith, and waste molasses that can be delivered to downstream companies such as a paper mill, thermal power plant, and alcohol plant that can use these materials as raw materials or fuel (Zhu et al., 2007).

Understanding the benefits of an industrial symbiosis complex is an important reason to analyze its industrial metabolic processes. The evaluation of metabolic processes compares the resources (such as water and energy) that are consumed before and after the exchanges of resources. Chertow and Lombardi (2005) analyzed the environmental and economic benefits from the exchanges of steam and water among a coal-fired power plant, an oil refinery, and a pharmaceutical plant, and found significant reductions in waste gas emissions. Jacobsen (2006) studied the utilization of water resources such as surface water, cooling water, reused water, and boiler water, and of energy resources such as steam and waste heat, and noted that the exchanges of water and energy were all based on cascading utilization and a shared infrastructure. The study also evaluated the decreased use of fresh water and increased use of wastewater that resulted from this structure. In eco-industrial parks dominated by a power plant or refinery, the cascading re-use of water and energy may form the main linkages among the companies. Thus, tracing their metabolic processes can quantify the main symbiotic exchanges.

However, just as biodiversity improves the functioning and stability of a natural ecosystem, incorporating plants engaged in different industries in a symbiosis complex can help to enrich the types and frequencies of symbiotic linkages. By accounting for some key resources, scholars have examined the use of multiple resources in typical industrial symbiosis complexes in Denmark, Japan, and the United States. The Symbiosis Institute (2012)[1)] analyzed several resources used in the Kalundborg eco-industrial park, such as petroleum and gypsum, and evaluated the potential reduction in waste emissions. van Berkel et al. (2009) documented 14 symbiosis linkages that connected steel, cement, chemical, and paper firms and the associated recycling businesses in Kawasaki, Japan. The linkages included exchanges of fuel, mixed plastics, organic matter, and mixed paper wastes. Chertow and Miyata (2011) used a method based on that of Chertow and Lombardi (2005) to analyze six exchanges among eight companies in the Campbell eco-industrial park. These companies were a power plant, an oil refinery, a city water recycling plant, a concrete production company, a quarry, a landfill for construction and demolition wastes, a city water agency, and a recycling company. The environmental benefits included decreased landfilling and increased conservation of primary materials.

Comparing the benefits of different eco-industrial parks is a good way to reveal the advantages and disadvantages that result from the current situations in these parks. For example, Heeres et al. (2004) compared six eco-industrial parks (INES, RiVu, Moerdijk, Fairfield, Brownsville, and Cape Charles) in the Netherlands and the United States in terms of their construction costs and their economic and environmental influences. However, due to the different characteristics of their formation mechanisms and subsequent development, some data could not be obtained with sufficient accuracy, so it was difficult to effectively analyze the advantages and disadvantages of these parks. Scholars have also studied the different operational stages of a single eco-industrial park. For instance, Kurup et al. (2005) evaluated the benefits of an industrial symbiosis throughout its life cycle, including the construction, operation, renovation, and abandonment phases. The work of Kurup et al. (2005) provides a good starting point for dynamic analyses of symbiosis complexes over time.

Evaluating the benefits of industrial symbiosis complexes can help us to understand their operational situations, and this evaluation can lead to the development of suggestions for planning new paths within the complex or redesigning existing paths within the complex.

5 Suggestions for future research

5.1 Improve classification of the systems

Currently, the categorization studies for symbiosis complexes mainly focus on subjective and qualitative judgments. In the future, it will be necessary to classify parks more objectively and quantitatively according to their inner structural characteristics, as this analysis will help researchers to understand how different structural attributes influence the exchanges of by-products and wastes, identify operational problems using tools such as social network analysis, and analyze the advantages and disadvantages of a given network. This kind of analysis will also help to improve planning or redesigning an industrial symbiosis complex's future development, such as by establishing new nodes or linkages, or by identifying the nodes and linkages that should be added at specific locations or positions within a sequence of flows to improve the cycling efficiency. The flowchart we have provided in Fig. 2 provides a good starting point for a classification system, but each decision point in the chart should be supported by one or more quantitative metrics.

5.2 Study changes in the system over time

Currently, studies of the benefits of an industrial symbiosis complex tend to focus on a single point in time that was chosen from among the several stages of a system's development. However, an industrial symbiosis complex can generate benefits throughout its life cycle, and the benefits may change over time. Therefore, it will be necessary to find ways to monitor these changes, such as identifying key points in time, describing the changes that occur between these points, and accounting for the changes in the environmental, economic, and social benefits separately before comparing their effects. This type of analysis can help to reveal whether a complex is developing positively or whether remedial measures should be taken.

5.3 Improve analyses of the relationships among members of the network

A flow analysis for a single element in an industrial symbiosis complex can describe the flow and the utilization efficiency of this element. But because many elements and substances flow through complexes, the analysis cannot fully reflect the relationships among the

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1) Symbiosis Institute (2012). Available at: http://www.symbiosis.dk/en (Accessed in November 2012).

companies or the characteristics of the complex's internal metabolism. Where sufficient data can be obtained, material-flow analysis and input-output analysis can reveal exchanges of multiple key byproducts and wastes, but cannot study the processes involved in the flows of all resources. Therefore, a more flexible method is needed to analyze the relationships and interactions among all companies in a complex for multiple resources, thereby providing a more holistic description of the internal processes, metabolism, and exchanges of all resources involved in the complex. For example, ecological network analysis could be used for this purpose. This method can reflect the system's internal structure and functions from a systematic, holistic perspective. This approach would first determine the flows among the nodes and establish a model of the symbiotic network. Then it would incorporate flow analysis to evaluate the processes involved in the flows of all resources and the strengths of the interactions among all nodes. Next, utility analysis and hierarchical analysis could be used to identify the relationships among the nodes and analyze the network's internal metabolism.

Acknowledgements This work was supported by the National Science Foundation for Innovative Research Group (No. 51121003), by the Program for New Century Excellent Talents in University (No. NCET-12-0059), by the National Natural Science Foundation of China (Grant Nos. 41171068 and 40701004), by the Program for Changjiang Scholars and Innovative Research Team in University (No. IRT0809), by the Special Fund of State Key Joint Laboratory of Environment Simulation and Pollution Control of China (No. 12Y04ESPCN and 10Z02ESPCN), and by the Fundamental Research Funds for the Central Universities.

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