Chapter 2 Industrial Ecology and Industrial Symbiosis - Definitions and Development Histories

By Xiaohong Li
Sheffield Hallam University, UK
x.li@shu.ac.uk

Abstract
Various definitions of Industrial Ecology (IE) and Industrial Symbiosis (IS) have been provided in the literature over the past thirty years. These definitions have offered some insights but also confusion due to inconsistency. IE, as an interdisciplinary study field, develops and applies different approaches in its four interrelated areas: industrial ecosystem, IS, industrial metabolism (IM), and environmental legislation and regulations. The ultimate goal of IE is to develop nearly closed-loop industrial ecosystems to enhance environmental sustainability. IS focuses on the development of knowledge webs of novel material, energy and waste exchanges to facilitate the establishment of synergies to support the achievement of this IE goal. The difference between IE and IS lies in the focus, instead of the scale of economy.

Keywords: Industrial Ecology, Industrial Symbiosis, Definitions, Development histories, Relationships between Industrial Ecology and Industrial Symbiosis

2.1 Introduction

A number of researchers have provided definitions and explored applications of IE and IS (e.g. Chertow, 2000; Despeisse et al., 2012; Ehrenfeld, 1997; Heeres et al., 2004; Lombardi and Laybourn, 2012; Lowe and Evans, 1995; Mirata, 2004; Park et al., 2016; Tian et al., 2012; Tibbs, 1992; Valentine, 2016). The proposed definitions have clarified the important roles of IE and IS in achieving environmental sustainability to some extent and have inspired research and applications of IE and IS. However, definitions of IE and IS offered in the literature are not always consistent. Some definitions distinguish IE and IS; whilst others do not. Some definitions set conditions for IS applications, such as geographic proximity and diverse industries (Chertow, 2000; Boix et al., 2015); whilst others considered these conditions unnecessary (Branson, 2016; Lombardi and Laybourn, 2012; Jenson et al, 2011). Differences in understanding IE and IS can stimulate debates. However, unclear concepts can cause confusion and do not support IE and IS development and applications. Therefore, clarifying IE and IS concepts through exploring existing definitions is necessary. Comparing key features of IE and IS defined in the literature helps generate a more consistent understanding of IE and IS which assists their future development and applications.

IS certainly cannot exist alone without the presence of IE, as IS supports the implementation of IE principles and the achievement of the IE goal. However, it is not always the case that reported IS applications have considered IE principles, particularly for a number of eco-industrial parks (EIPs) applications (Gibbs and Deutz, 2005). In addition, there are different understandings of the relationship between IE and IS in the literature. Hence, reviewing the development histories of these two concepts and critically evaluating the relationship between IE and IS presented in the literature can help to clarify some confusion.

Hence, this chapter explores key definitions of IE and IS and their development histories. The common themes of IE and IS and divergences in interpretation of these two concepts in the literature are explored and compared, along with their relationships.

2.2 Definitions of Industrial Ecology and Industrial Symbiosis

Key definitions of IE in the literature are presented in Table 2.1 with identified key features of each definition followed by comments. Identifying and extracting a definition of IE is not always straightforward because explanations of IE and related aspects are fairly often provided within the content of a research paper, rather than being presented in a standard definition format.

(Table 2.1) Industrial Ecology (IE) definitions, associated key features, and comments

Definitions of Industrial Ecology (IE)	Key Features	Comments
‘The industrial ecosystem would function as an analogue of biological ecosystem’ (Frosch and Gallopoulos, 1989, page 144). ‘The traditional model of industrial activity… should be transformed into a more integrated model: an industrial ecosystem. In such a system the consumption of energy and materials is optimised, waste generation is minimised and the effluents of the one process … serve as raw material for another process’ (Frosch and Gallopoulos, 1989, page 144). ‘Equally important is the way in which the inputs and outputs of individual processes are linked within the overall industrial ecosystem. This linkage is crucial for building a closed or nearly closed system’ (Frosch and Gallopoulos, 1989, page 149).	Industrial ecosystems mimic biological ecosystems. An industrial ecosystem is an integrated model of industrial activities. Industrial ecosystems optimise the consumption of energy and materials and minimise waste through linkages between industrial processes. An industrial ecosystem is a closed-loop or nearly closed-loop system.	This entry does not define IE directly, but describes the core of IE, which is to develop industrial ecosystems of closed-loop or nearly closed-loop material and energy exchanges through integrating industrial processes. This entry does not indicate that an industrial ecosystem is part of the natural system. This entry does not imply the need for crossing industrial boundaries for IE. This proposes two questions: what is the overall industrial ecosystem and what is its boundary?

Continued to the next page

(Table 2.1) Continued from the previous page

Definitions of Industrial Ecology (IE)	Key Features	Comments
‘Industrial ecology involves designing industrial infrastructures as if they were a series of interlocking manmade ecosystems interfacing with the natural global ecosystem’ (Tibbs, 1992, page 5). ‘The aim of industrial ecology is to interpret and adapt an understanding of the natural system and apply it to the design of the manmade system, in order to achieve a pattern of industrialisation that is not only more efficient, but that is intrinsically adjusted to the tolerances and characteristics of the natural system’ (Tibbs, 1992, page 6). ‘Industrial ecology permits an integrated managerial and technological interpretation’ (Tibbs, 1992, page 8).	IE is to design interlocked industrial ecosystems which interact with the ecosystem of the Earth. IE is to understand the natural system. IE is to apply an understanding of natural systems to design manmade industrial systems. IE considers both the efficiency of the industrial system and the carrying capacity of the natural global ecosystem within which it is placed. IE contains both managerial and technical aspects.	Adds value by relating IE to an extended system view of industrial ecosystems, their relationships with the natural global ecosystem, improved efficiency of industrial systems, and the concept of the carrying capacity of the natural ecosystem. The last part in this entry indicates that IE is an interdisciplinary study field, including both management disciplines (such as operations management and environment management) and technical (or technology and design) aspects related disciplines (such as environmental science and material engineering).

Continued to the next page

(Table 2.1) Continued from the previous page

Definitions of Industrial Ecology (IE)	Key Features	Comments
'Industrial Ecology is a new approach to the industrial design of products and processes and the implementation of sustainable manufacturing strategies' (Jelinski et al., 1992, page 793). 'Industrial Ecology seeks to optimise the total materials cycle from virgin material to finished materials, to component, to product, and to ultimate disposal' (Jelinski et al.,1992, page 793).	IE is a new approach for sustainable manufacturing. IE is to optimise the total materials cycle.	IE is not just an approach but a study of many approaches. IE actually goes beyond the optimisation of the total materials cycle as described in this entry, from virgin material to ultimate disposal as a linear process. This definition could mislead by neglecting the development of nearly closed-loop industrial ecosystems by IE.

Continued to the next page

(Table 2.1) Continued from the previous page

Definitions of Industrial Ecology (IE)	Key Features	Comments
'Industrial ecology is an emerging framework for environmental management, seeking transformation of the industrial system in order to match its inputs and outputs to planetary and local carrying capacity. A central IE goal is to move from a linear to a closed-loop system in all realms of human production and consumption' (Lowe and Evans, 1995, page 47). 'Industrial ecology offers a theoretical foundation to support the transformation to a sustainable industrial system, operating in this balanced fashion (production and decomposition are well balanced, with nutrients recycling continuously to support the next cycles of production)' (Lowe and Evans, 1995, page 48).	IE is a framework. IE is for environmental management. IE is to transform industrial systems to industrial ecosystems. Industrial ecosystems need to match their inputs and outputs to the carrying capacity of local biological ecosystems and the ecosystem of the Earth. IE aims to move a linear to a closed-loop industrial system. IE offers a theoretical foundation. An industrial ecosystem operates in the balance of production and decomposition.	IE is more than a framework, but a study of a number of frameworks. IE is an interdisciplinary study field, not just for environmental management. Considers both planetary (global) and local carrying capacity for industrial ecosystems to match in design and transformation. Emphasises the transformation from a linear to a (nearly) closed-loop system as the core of IE. Highlights the importance of the balance between production and decomposition in closed-loop industrial ecosystems.

Continued to the next page

(Table 2.1) Continued from the previous page

Definitions of Industrial Ecology (IE)	Key Features	Comments
'Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain sustainability, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimise the total materials cycle from virgin material to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimised include resources, energy and capital' (Graedel and Allenby, 1995/2003, page 18). 'Industrial ecology is the study of technological organisms, their use of resources, their potential environmental impacts, and the ways in which their interactions with the natural world could be restructured to enable global sustainability' (Graedel and Allenby, 1995/2003, page 39).	IE is a means to deliberately and rationally approach and maintain sustainability. IE views industrial systems not in isolation from its surrounding systems, but in concert with them. IE is to optimise the total materials cycle, including resources, energy and capital. IE is related to global sustainability.	IE is not just a means, but a study field. Specifies the element of 'consciousness' in relation to IE for improving environmental sustainability. 'Capital' is associated with 'resources' or 'energy' in monetary value. Hence it should not be individually listed. IE is beyond the optimisation of the total materials cycle as described in this entry, from virgin material to ultimate disposal as a linear process. This definition could mislead by neglecting the development of nearly closed-loop industrial ecosystems by IE.

Continued to the next page

(Table 2.1) Continued from the previous page

Definitions of Industrial Ecology (IE)	Key Features	Comments
'Industrial ecology goes further. The idea is first to understand how the industrial system works, how it is regulated, and its interaction with the biosphere; then on the basis of what we know about ecosystems, to determine how it could be restructured to make it compatible with the way natural ecosystems function' (Erkman, 1997, page 1).	IE is to understand the industrial system and the natural system and their interaction. IE is to restructure the industrial system for it to be compatible with the natural ecosystem.	Emphasises the 'compatibility' of industrial systems with natural systems. How IE can restructure industrial systems to be compatible with natural ecosystems remains unexplored.
'Industrial ecology, in its paradigmatic form, would become part of a new evolving Dominant Social Paradigm (DSP) that would include the maintenance of the natural world as a fundamental normative goal' (Ehrenfeld, 1997, page 88).	IE is part of a new Dominant Social Paradigm (DSP). IE is to maintain the natural world.	Adds value by setting IE within a wider context by considering IE as part of a new DSP. Emphasises the fundamental role of IE in achieving environmental sustainability in a very general way.

Continued to the next page

(Table 2.1) Continued from the previous page

Definitions of Industrial Ecology (IE)	Key Features	Comments
'<u>Industrial ecology</u> symbiotically links industries so that environmental conscious practices can also be profitable. To do this, industrial ecology uses principles of biological ecosystems to optimise the flows and transformations of materials and energy within and across the boundaries of industrial systems' (Dunn and Steinemann, 1998, page 661).	IE is to establish symbiotic relationships across industries. IE can also lead economic gains. IE uses principles of biological ecosystems. IE is to optimise the flows and transformations of materials and energy, within and across the boundaries of industrial systems.	Emphasises the importance of symbiotic relationships among industries in IE, (as now this is specifically considered as IS, which is one area within IE.) Specifies that IE is for both within an industrial system boundary and also across different industrial system boundaries. The nearly closed-loop ecosystem development by IE is not specified.
'In a perfect IE [sic. refers to an industrial ecosystem] both of the systems (the industrial (sub)system and the (mother) ecosystem) operate according to the same principles of system development: roundput, diversity, locality and gradual change' (Korhonen, 2001, page 257).	A perfect industrial ecosystem operates like its mother ecosystem. Industrial ecosystem follows: roundput (closed-loop), diversity, locality and gradual change.	Specifies the four principles of biological ecosystems for industrial ecosystems to mimic/follow. It is debatable for locality (geographic proximity) in the literature.

Continued to the next page

(Table 2.1) Continued from the previous page

Definitions of Industrial Ecology (IE)	Key Features	Comments
'IE should be defined as a field of study (or branch of science) concerned with the interrelationships of human industrial systems and their environments' (Seager and Theis, 2002, page 226).	IE is a field of study. IE is concerned with interrelationships of industrial systems and their environment.	Specifies that IE is a study field. This is a very general definition of IE. Therefore, it is unlikely to be used for IE applications. The closed-loop ecosystem development needs to be specified.
'…, industrial ecology draws on some vision of an ecological network of interconnected actors exchanging matter and energy. Some see the metaphor as ontological-a way of extending the bounds of thinking; others see the metaphor as normative, providing prescriptive guides for designing a more sustainable world' (Ehrenfeld, 2004, page 827).	IE concerns an ecological network of interconnected actors exchanging matter and energy. IE can be a new way of thinking and/or a practical guide for designing a more sustainable world.	Emphasises the ecological requirement of IE in symbiotic relationships (IS).

Continued to the next page

(Table 2.1) Continued from the previous page

Definitions of Industrial Ecology (IE)	Key Features	Comments
'Its (IE's) key feature lies in the integration of various components of a system to reduce its net resource input as well as pollutant and waste outputs' (Despeisse, et al, 2012, page 31)	IE is concerned with the integration of various components of a system. IE reduces net resource inputs and pollutant and waste outputs of a system.	Emphasises the integration of different components in a system in IE. Emphasises that the goal of IE is to reduce inputs and outputs of industrial systems and also implying the concept of closed-loop material exchanges.
'IE considers principles of biological ecosystems when designing and re-designing industrial systems to create more efficient interactions both within industrial systems and between industrial systems and natural systems' (Leigh and Li, 2015)	IE considers principles of biological ecosystems. IE designs and re-designs industrial systems. IE improves the efficiency of interactions within and between industrial systems and the natural system.	Emphasises the consideration of principles of biological ecosystems in IE, but does not specify them. Emphasises interactions between systems, industrial or natural. The closed-loop ecosystem development needs to be specified.

Note: 'Underline' for Industrial Ecology or IE is added by the author of the book.

Some early definitions referred to IE as a method, an approach, or a framework. The definitions have gradually established that IE is an interdisciplinary study field. Like its counterpart biological ecology, IE is a study field which contains different methods, approaches and frameworks to design and transform industrial systems to nearly closed-loop industrial ecosystems. Considering IE only as an approach, a framework, or a method restricts its development and applications.

These definitions also propose other related concepts, such as carrying capacity, sub-industrial ecosystems, and mother ecosystems. Biological sub-ecosystems and industrial sub-ecosystems are subject to their own carrying capacities as well as the carrying capacity of the ecosystem of the Earth, which is a closed-loop system of material exchanges, but an open system for energy flow. Not all the definitions focus on or reveal the core of the IE, which is the design and transformation (development) of industrial systems to nearly closed-loop industrial ecosystems.

IE development has been built upon the understanding of IE related concepts/areas, such as industrial ecosystem, IS, and industrial metabolism (IM) (Tibbs, 1992). The term of IS has existed for a long time and many early publications of IE mentioned IS (Ehrenfeld and Gertler, 1997; Lowe and Evan, 1995; Tibbs, 1992). However, definitions of IS were very rarely provided prior to 2000, except for one study by Ehrenfeld and Gertler (1997) which defined and explained IS using Kalundborg as the case to explore IE in practice. The intensity of studying IS began early this century. Chertow offered the most quoted definition of IS in 2000. Since 2000, there have been an increased number of studies exploring IS and its applications. Chertow (2000) considered eco-industrial parks (EIP) as ‘concrete realisation’ of IS even though the applications of EIPs started early in 1990 in the USA, followed by other countries around the world. On the one hand, many studies of IS explained IE first and made direct relevance of IS in its relationship to IE (Chertow, 2000; Costa and Ferrão, 2010; Lombardi and Laybourn, 2012). On the other hand, some applications of IS have neglected the relevance of IS to IE in terms of its ultimate goal of developing nearly closed-loop industrial ecosystems. Key definitions of IS and associated features followed by comments are presented in Table 2.2.

Table 2.2 Industrial Symbiosis (IS) definitions, associated key features, and comments

Definitions	Key Features	Comments
‘Industrial symbiosis is closely related [with IE] and involves the creation of linkages between firms to raise the efficiency, measured at the scale of the system as a whole, of material and energy flows through the entire cluster of processes’ (Ehrenfeld and Gertler, 1997. Page 68).	IS is closely related to IE. IS involves the creation of linkages between firms. IS raises the efficiency of a system as a whole.	Clearly indicates the close relation between IE and IS and also IS focuses on the creation of linkages between firms. Emphasises the importance of the entire system. The linkages for creating novel material exchanges to increase the level of the closed loop are not indicated. Mentioning that IS is for raising efficiency of material and energy flows can be misleading. The system boundary and how to determine the system boundary remain unaddressed.

Continued to the next page

(Table 2.2) Continued from the previous page

Definitions	Key Features	Comments
'Industrial symbiosis, as part of the emerging field of industrial ecology, demands resolute attention to the flow of materials and energy through local and regional economies' (Chertow, 2000, page 313). 'Industrial symbiosis engages traditionally separated industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and synergistic possibilities offered by geographic proximity' (Chertow, 2000, page 314).	IS is part of IE which deals with the flow of materials and energy through local and regional economies, but not the global economy. IS engages traditionally separated industries. The keys to IS are collaboration and synergistic possibilities. IS is under the condition of geographic proximity.	This is a well-cited definition. However, it raises a critical question regarding whether IS and IE should be distinguished by the scale of economy. IS is part of IE. Emphasises the importance of crossing industrial boundaries using a collective approach for IS. Adds value by considering different physical exchanges, not just waste and by-products for IS. This definition raises another critical question regarding whether geographic proximity is essential for IS. (There have been many symbiotic exchanges between companies across regions reported in the literature.) Another question is whether developing physical exchanges is the only concern in IS?

Continued to the next page

(Table 2.2) Continued from the previous page

Definitions	Key Features	Comments
'As a sub-discipline of industrial ecology, industrial symbiosis is concerned with resource optimisation among co-located companies' (Jacobsen, 2006, page 239). 'Within this framework of inter-firm relationships, industrial symbiosis (IS) can be categorised as a concept of collective resource optimisation based on by-product exchanges and utility sharing among different co-located facilities' (Jacobsen, 2006, page 240).	IS is a sub-discipline of IE. IS is concerned with collective resource optimisation among co-located companies. IS is based on by-product exchanges and utility sharing.	IS is part of IE. This definition considered 'collective resource optimisation' and 'co-located firms' as key features of IS. This can be misleading. IS is to establish symbiotic relationships among different industrial firm. By doing so, IS contributes to collective resource optimisation to co-located facilities, but not just for co-located facilities alone. IS supports the achievement of the IE goal, which is to develop nearly closed-loop industrial ecosystems for improved environmental performance. IS is more than just by-product exchanges and utility sharing among different co-located facilities.

Continued to the next page

(Table 2.2) Continued from the previous page

Definitions	Key Features	Comments
'Thus, at least three different entities must be involved in exchanging at least two different resources to be counted as a basic type of <u>industrial symbiosis</u>' (Chertow, 2007, page 12).	IS requires the involvement of three different entities. IS requires two different resource exchanges.	This 2-3 rule has absolutely no grounding. The number of entities and resources involved to qualify a basic type of IS given in this definition is totally subjective. It is not the involvement of the number of entities or resource, but the type of exchange that qualifies a basic type of IS. The type of exchange should be a novel exchange supporting the development of a higher level of closed-loop material exchanges and efficiency of energy cascading. Interestingly, a symbiotic relationship in the biological ecology involves only two species. (Two plus two becomes four and it will be more as long as we can have more twos in right type of exchanges.)

Continued to the next page

(Table 2.2) Continued from the previous page

Definitions	Key Features	Comments
'Within the field of industrial ecology, Industrial Symbiosis (IS) has emerged as a body of exchange structures to facilitate progress to a more eco-efficient industrial system. By establishing a collaborative web of knowledge, material and energy exchanges among different organisational units, IS networks aim to reduce the intake of virgin materials and lower the production of waste by the industrial sector' (Domenech and Davies, 2011, page 79).	IS is within the field of IE. IS is a body of exchange structures to facilitate progress to a more eco-efficient industrial system. IS establishes a collective web of knowledge, material and energy exchanges. IS networks aim to reduce the intake of virgin materials and lower the production waste.	IS is part of IE. IS focuses on the establishment of a network of collaborations (exchange structures) to achieve the development of a more eco-efficient industrial system. The question is whether eco-efficiency always supports the closed-loop development. Emphasises the eco-efficiency which IS aims for, rather than just efficiency or optimisation of resources. Emphasises the establishment of knowledge webs in IS, leading to physical exchanges. This element is a breakthrough in IS definitions. Specifically mentions that IS networks aim to reduce virgin material intake and waste production outputs. Whether the system boundary is determined by an industrial sector is certainly debatable.

Continued to the next page

(Table 2.2) Continued from the previous page

Definitions	Key Features	Comments
‘Industrial symbiosis examines cooperative management of resource flows through networks of businesses known in the literature as industrial ecosystems’ (Chertow and Ehrenfeld, 2012, page 13).	IS examines cooperative management of resource flows. IS considers networks of businesses as industrial ecosystems.	The definition is too general. It does not provide the focus of IS and distinguish IS from IE in terms of the focus. The purpose of the examination should be mentioned to be meaningful to an IS definition. Again, the boundary of an industrial ecosystem - a network of businesses remains unaddressed.

Continued to the next page

Table 2.2) Continued from the previous page

Definitions	Key Features	Comments
'In our experience, IS is not essentially localised waste and by-product exchanges, nor should it be confused with agglomeration economies or industrial clusters where geographic proximity is a necessary condition' (Lombardi and Laybourn, 2012, page 28). '…geographic proximity is neither necessary nor sufficient for IS, unlike the concepts of agglomeration economies and industrial clusters, which are explicitly geographically based' (Lombardi and Laybourn, 2012, page 31). 'IS engages diverse organisations in a network to foster eco-innovation and long-term culture change. Creating and sharing through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes' (Lombardi and Laybourn, 2012, page 31-32).	IS is not just concerned with localised waste and by-product exchanges. Agglomeration economies or industrial clusters are different from IS required networks of collaboration. Geographic proximity is not a condition for IS applications. IS fosters eco-innovation and long-term culture change by engaging diverse organisations. IS creates a network for sharing. IS searches novel sourcing of required inputs and value-added destinations for non-product outputs. IS improves business and technical processes.	This definition is a breakthrough from the definition by Chertow (2000). IS should not be distinguished from IE by the scale of economy, as Chertow (2000) considered that IS was for local and regional economies but not for the global economy. Adds value by stating geographic proximity is not the condition (restriction) to apply IS. Distinguishes industrial clusters from an IS network of diverse organisations that are traditionally unrelated. Or could IS work on both? Specifies novel exchanges. The definition also emphases mutual economic values for IS engaged companies. However, the role of IS which is to support the achievement of the ultimate goal of IE - developing nearly closed-loop ecosystems, still needs to be explicitly specified.

Continued to the next page

(Table 2.2) Continued from the previous page

Definitions	Key Features	Comments
'IS applies the ecological metaphor of IE to create a collective approach to firms and industries traditionally viewed as separate entities and considers the entire system with regard to the physical exchanges of materials, energy, water and by-products' (Leigh and Li, 2015, page 632).	IS applies the ecological metaphor of IE. IS creates a collective approach. IS considers the entire system.	Emphasises the importance of the IE principle of ecological metaphor required in IS. Emphasises the entire system for IS consideration. The system boundary remains unaddressed.

Note: 'Underline' for Industrial Symbiosis or IS is added by the author of the book.

Early definitions of IS focused on efficiency and optimisation of resources or resource flows without emphasising the eco element or novelty of exchanges based on the establishment of symbiotic relationships. The definition by Domenech and Davies (2011) made a breakthrough, by stressing the need of establishing a web of knowledge to facilitate the establishment of physical exchanges of resources among diverse organisations. This emphasises the importance of knowledge in IS development. The definition by Lombardi and Laybourn (2012) further clarifies that the exchanges must be novel.

These definitions clearly confirm that IS is part of IE. However, most definitions need to make it clearer that IS is to fulfil the goal of IE, which is to develop high levels of nearly closed-loop industrial ecosystems. These definitions also need to address the system boundary aspect.

IS requires the integration of the following features:
1. A web of knowledge
2. A network of diverse organisations
3. Novel sourcing of inputs
4. Value-added destinations of non-product outputs (and further end-life products)
5. Improved business and technical processes
6. A collective approach of a system as a whole.

The question here is how to define the boundary of an industrial ecosystem, which is addressed in chapter 3. The further understanding of IE and IS is explored through exploring their development histories.

2.3 Development histories of Industrial Ecology and Industrial Symbiosis

As we gradually recognised the severity of the long-term negative impact of human industrial activities on the Earth, some of us began to actively compare our industrial systems to biological systems. The learning is for sustaining our human activities on the Earth for our generation and for future generations. The comparison of our industrial systems and biological systems led to the formal initialisation and development of IE and its related areas, including IS, and their applications.

The development history of IE highlights that IE has gradually developed into a study field (Fig. 2.1), which is an interdisciplinary study field. IE, as a study field, includes interrelated study areas, such as industrial metabolism (IM) and industrial symbiosis (IS) (Tibbs, 1992). In each of these areas, different approaches and frameworks have been developed to support the achievement the goal of IE, which is developing nearly closed-loop industrial ecosystems. The development history of IE also suggests that IE is part of the Dominant Social Paradigm (DSP), which represents IE's significance in the social science disciplines.

For this book, the history of IE is reviewed from 1989 when Frosch and Gallopoulos (1989) published their famous article entitled 'Manufacturing Strategy' in the Journal of Scientific American. The original title, 'Manufacturing - The Industrial Ecosystem View' proposed by authors, was not accepted. The famous logo of their paper is 'wastes from one industrial process can serve as the raw materials for another' (Frosch and Gallopoulos, 1989, page 144). The paper focused on 'industrial ecosystems' and how industrial systems could mimic biological ecosystems to be sustainable in the long run (Frosch and Gallopoulos, 1989). They used three material cycles, the iron cycle, the plastic cycle and platinum-group-metals cycle as examples to describe how different industries could work together to create nearly closed-loop material exchanges to develop industrial ecosystems. The article did not directly define IE but clearly mentioned that IE was for developing industrial ecosystems and the key feature of an industrial ecosystem was its nearly closed-loop material exchanges. The paper clearly stated that ‘manufacturing processes in an industrial ecosystem simply transform circulating stocks of materials from one shape to another; the circulating stock decreases when some material is unavoidably lost, and it increases to meet the needs of a growing population’ (Frosch and Gallopoulos, 1989, page 146). The authors emphasised the importance of industries, environmental groups, and individuals contributing to the establishment of industrial ecosystems by working together (Frosch and Gallopoulos, 1989). Developing industrial ecosystems is the core of IE, as IE continuously explores different approaches for designing and developing industrial ecosystems across different disciplines.

The development history of IE confirms that the understanding of IE is still yet to be converged. Which features of biological ecosystems an industrial system can mimic to become an industrial ecosystem still needs further exploration. Some common features of industrial ecosystems identified in IE development history are:

- nearly closed-loop material exchanges,
- balance between production and decomposition,
- diversity of industrial units/processes/organisations, and
- totality, which is an extended system view.

An established industrial ecosystem still needs to change continuously in order to adapt to its business environment and its mother ecosystem. The changes should be gradual, allowing the system to regain and maintain the balance over time and space. A set of nearly closed-loop industrial ecosystems are part of their mother ecosystem - the closed-loop ecosystem of the Earth. Locality in biological ecosystems makes the convenience of exchanges between species without the need for travelling through distance. However, when we look into the three material cycles described by Frosch and Gallopoulos (1989), the three material cycles of iron, plastic and platinum-group-metals or their recycle systems can cover a larger geographic area, even globally. This is the same with many other materials for reuse, remanufacturing and recycling, as human development has created the most extensive transportation system on the planet. Locality should not be a feature for industrial ecosystems to mimic, only if we ignore the globalisation of the industrial world and its advance in transportation technology.

The key question remains the boundary of an industrial ecosystem. The boundary of an industrial ecosystem is up to study purposes, like the boundary of a biological ecosystem. The degree of interaction, which this industrial ecosystem has with other industrial ecosystems and further with the overall ecosystem of the Earth, determines the quantity and rate of material exchanges among them. The quantity and rate of material exchanges within a system influence the level of closed-loop material exchanges of this system and its mother system at an extended system boundary. For example, an industrial ecosystem with a predetermined system boundary might have only 50 per cent of closed loop material exchange within this system boundary. However its mother industrial ecosystem, which contains this industrial ecosystem and a few other ones, has higher, say 70 per cent of closed-loop material exchanges. If increasing the level of closed-loop material exchanges within this industrial ecosystem contributes to the increased level of closed-loop material exchanges of its mother industrial ecosystem, there would not be any problem. However, if that is not the case, should we continue increasing the level of closed-loop material exchanges within this ecosystem or should we allow its material exchanges with other sub-industrial ecosystems in order for its mother industrial ecosystem to achieve a higher level of closed-loop material exchanges overall? As the totality is the key concern for IE, the boundary of an industrial ecosystem becomes an issue for the development of industrial ecosystems. The system boundary issue is further reflected in the development history of IS (Fig. 2.2).

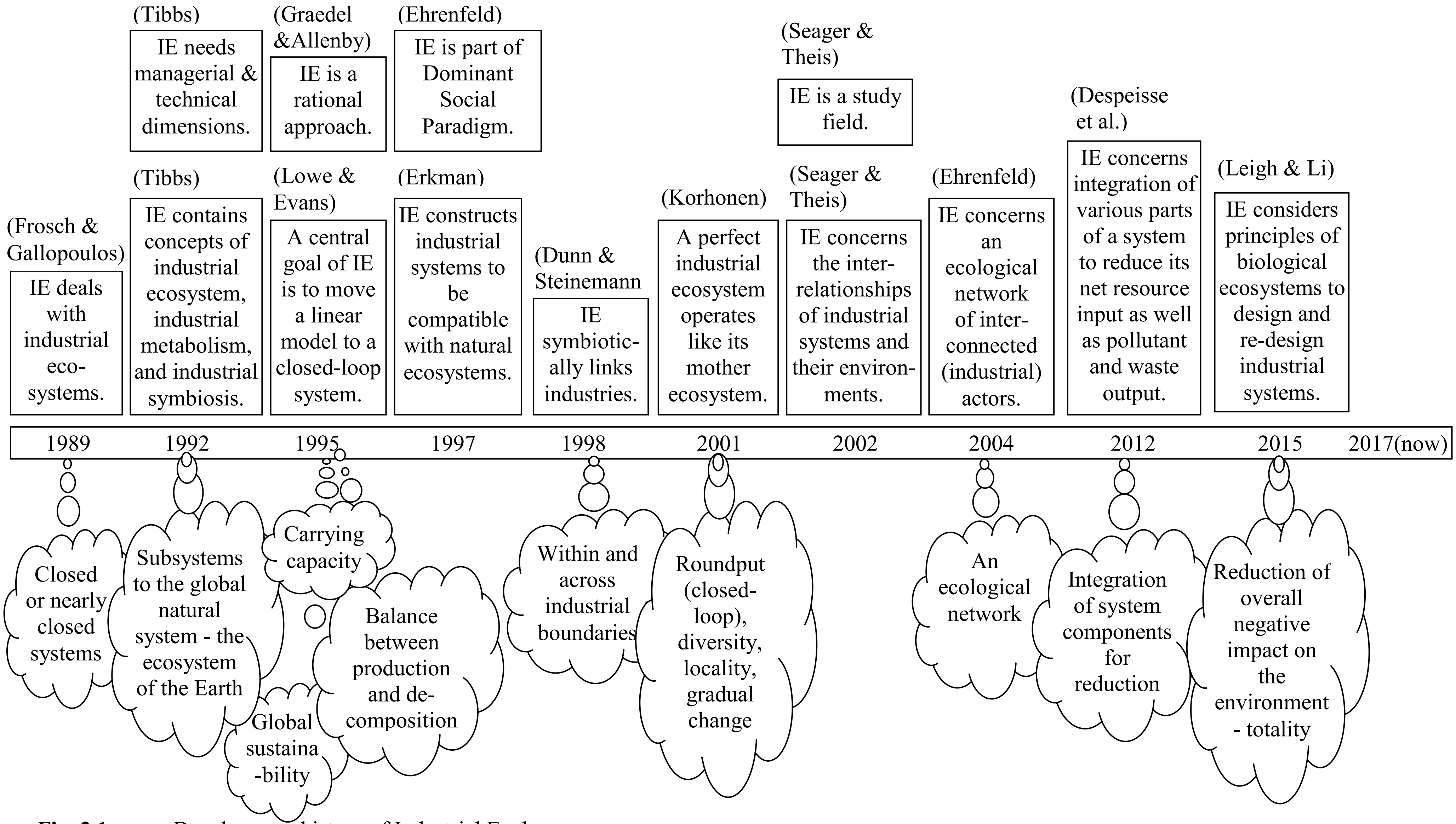

Fig. 2.1 Development history of Industrial Ecology

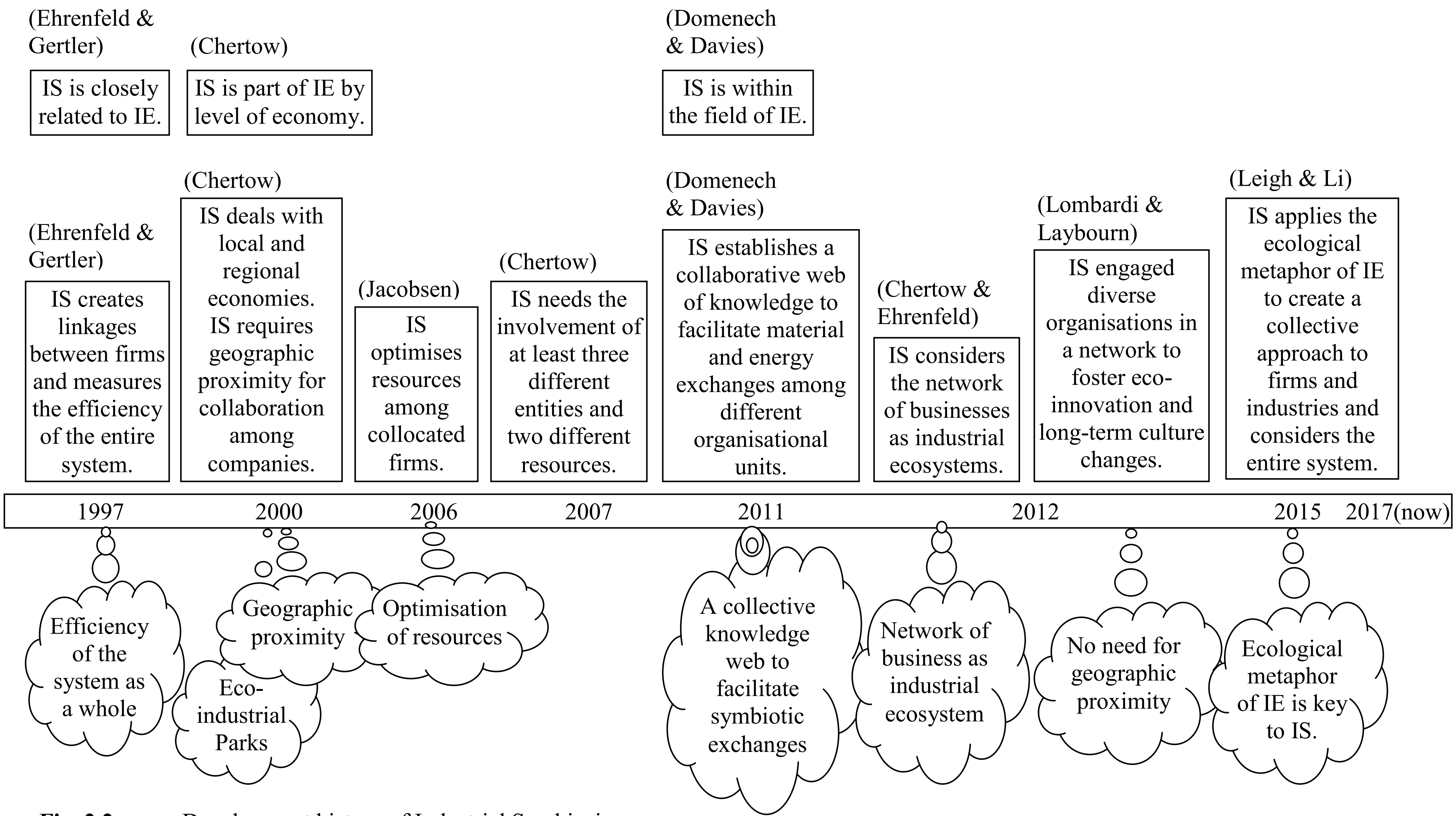

Fig. 2.2 Development history of Industrial Symbiosis

The development history of IS (Fig 2.2) clearly recognises that IS is within the study field of IE (Domenech and Davis, 2011). However, there are a number of debatable concepts presented in the IS development history. This includes geographic proximity, self-organisation, and the required number of entities and different resources involved in an IS exchange. Some of these debatable concepts have been brought to attention when reviewing definitions of IS. Hence, no repetition is given here. The emphasis here is that IS focuses on symbiotic relationship establishment for achieving the ultimate goal of IE, which is the development of nearly closed-loop industrial ecosystems. However, the development history of IS does not always reflect this purpose of IE, and contains some subjective and misleading concepts.

The term, 'industrial symbiosis' (IS) was mentioned many years prior to 2000 (Tibbs, 1992; Lowe and Evans, 1995). For example, Tibbs (1992) considered IS as one of the concepts within IE. The classic example of Kalundborg in Denmark has been used to illustrate applications of both IE and IS in the literature (Domenech and Davis, 2011; Ehrenfeld and Gertler, 1997; Jacobsen, 2006). These studies frequently emphasised the unplanned collaborations established in Kalundborg over the years for cross-industrial materials, waste, by-products and energy exchanges in a local community (Domenech and Davis, 2011; Ehrenfeld and Gertler, 1997; Jacobsen, 2006). However, more recent synergies in Kalundborg have been facilitated by the Kalundborg Symbiosis Centre, established in 1996 (Branson, 2016; Valentine, 2016). In addition, the successful UK national IS programme (NISP) has been a planned and facilitated IS programme, coordinated by NISP centres in different regions and its central NISP team (Mirata, 2004; Jenson, et al., 2011).

A number of researchers emphasised the importance of diverse industries for symbiotic relationship establishment in IS practice (Chertow, 2000; Costa and Ferrão, 2010). However, some researchers implied that IS could also be applied within firms (Despeisse et al., 2012; Lehtoranta, et al., 2011). Some studies focused on IS alone in terms of its role in establishing symbiotic relationships among different industrial companies without consideration of closed-loop industrial ecosystem development (Chertow and Ehrenfeld, 2012; Chertow, 2007). Developing symbiotic relationships is an important step towards the closed-loop principle of IE. However, it is the totality of IE which needs to be reflected in developing these symbiotic relationships in relation to IS. The exploration of the relationships between IE and IS and other areas within the study field of IE aids this understanding.

2.4 The relationship between Industrial Ecology and Industrial Symbiosis and study areas within Industrial Ecology

When a study explores or is entitled IS, it often opens with an explanation of IE (Chertow, 2000; Domenech and Davies, 2011; Lombardi and Laybourn, 2012; Van Berkel et al, 2009; Wang et al, 2013). IS cannot or should not exist without consideration of IE. However, IS has its own distinctive focus within the study field of IE and this needs to be emphasised when exploring IS and its applications. Some explanations of IE and IS share great similarity, which consider both IE and IS focusing on flows of materials and energy and applying ecological metaphor (Chertow, 2000; Ehrenfeld, 1997). This can confuse readers and neglect the important role of IS in achieving the ultimate goal of IE.

Using Chertow (2000)'s paper as an example, the definitions for IE and IS are almost identical, but distinguished by the scale of economy. In the abstract of the paper, IS was explained thus: 'Industrial symbiosis, part of the emerging field of industrial ecology, demands absolute attention to the flow of materials and energy through local and regional economies' (Chertow, 2000, page 313). The first sentence in the introduction of the same paper states "The emerging field of industrial ecology [IE] demands resolute attention to the flow of materials and energy through local, regional, and global economies" (Chertow, 2000, page 314). The difference between these two statements is that IE is concerned with local and regional as well as global economies; whereas IS considers local and regional economies but not the global economy. The question is why not? The reason behind this is the misguided use of geographic proximity as an essential condition of IS, and the assumption that physical material exchanges can only take place in local and regional economies, which is certainly untrue. It might be more advantageous in terms of transportation costs and infrastructure for material exchanges locally. Material exchanges in relation to IE and IS should be distinguished from normal business trading material exchanges by their novelty and impact on the reduction of intakes of virgin materials and disposals of waste to nature. The real difference between IE and IS lies in their focuses, but not the scale of economy concerned.

Chertow (2000) continued that 'Industrial ecology allows focus at the facility level, at the inter-firm level, and at the regional or global level. Industrial symbiosis occurs at the inter-firm level because it includes exchange options among several organisations' (Chertow, 2000, page 314). But how could IE at the global level not involve any exchange options among several organisations? IS does focus on the inter-firm collaborations for novel materials exchanges to develop industrial ecosystems. However, the inter-firm collaboration can be local, regional, national and international. IE and IS are related by the same principles that IS is part of IE. IS has extended the study field of IE by developing a set of methods to promote the establishment of collaborations between companies among different industries for novel exchanges, regardless of geographic location, to achieve the goal of IE.

The same terms, such as 'ecological metaphor' and 'knowledge sharing and collaboration' have been used to explain both IE and IS through their development and applications in the literature (Chertow, 2000; Ehrenfeld, 1997). In some cases, IE practices were explained using the term of IS (Ehrenfeld and Gertler, 1997). Some IS applications, particularly EIPs, need to consider the level of closed-loop material exchanges which is the core of a symbiotic relationship in a biological world where IE originated (Ehrenfeld and Gertler, 1997; Gibbs and Deutz, 2005).

In the study field of IE, there are other areas to consider besides IS. One of the areas is industrial metabolism (IM) (Tibbs, 1992; Ayres, 1989). IM also aims to achieve the ultimate goal of IE, but focuses on the methods that can be deployed to measure and improve eco-efficiency and rates of exchange to allow more profound and effective exchanges. This book does not cover IM in detail (section 3.4 explains some basics of IM). However, we need to highlight the relevance of IM within the study field of IE. In addition, there are studies that have explored legislation and regulations in relation to the development and applications of IE and IS (Malcolm and Clift, 2002) (section 3.5 explores this further). This proposes another important area within the study field of IE. Therefore, the current thinking of IE and its study areas are illustrated in Fig. 2.3.

In each of these areas, theoretical concepts and methods for application have been developed, along with successful factors as well as barriers to overcome. The areas are integrated to support the achievement of the IE ultimate goal. For example, legislation and regulations can serve as either successful factors or barriers depending on how the current legislation and regulations have been set and developed in relation to IE applications, including the development of industrial ecosystems, IS and IM. These all can pose challenges to IE and IS applications. The final chapter of this book explores challenges for IE and IS applications in great detail.

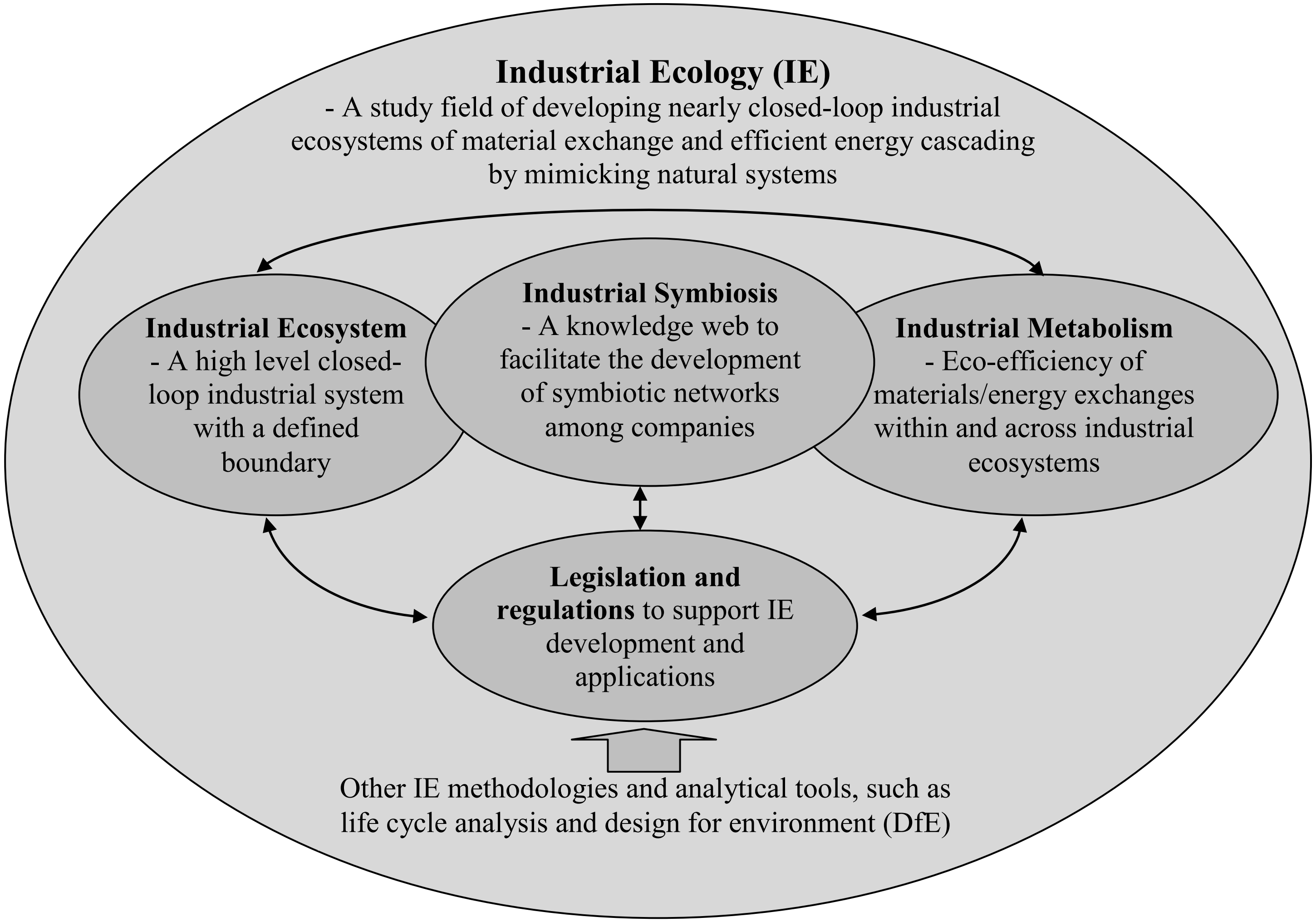

Fig. 2.3 Industrial Ecology and its interrelated four study areas

IE focuses on the theoretical aspects of industrial ecosystems mimicking suitable features of biological ecosystems and explores the principles of biological ecosystems for industrial systems to be developed into nearly closed-loop industrial ecosystems. IE considers that an industrial ecosystem is part of its mother natural ecosystem. Therefore, the development of an industrial ecosystem needs to support the achievement of the balance of interrelated ecosystems whatever biological ecosystems and industrial ecosystems are concerned. The total balance has to be maintained through gradual but constant changes to adjust each player in the total natural ecosystem of the Earth through every single transformation of materials and energy.

IS emphasises the application of IE principles through consciously establishing symbiotic relationships among industrial entities through developing knowledge webs of novel ideas. Explanations and applications of IS (or claimed as IE) need to consider the principles of IE when highlighting the symbiotic relationship establishment to facilitate the movement of industrial systems towards nearly closed-loop industrial ecosystems of material exchanges and energy cascading.

2.5 Summary

By critically reviewing different definitions of IE and IS, this book defines IE and IS as:

> *Industrial Ecology (IE) is an interdisciplinary study field containing interrelated study areas of industrial ecosystem, Industrial Symbiosis (IS), industrial metabolism (IM) and legislation and regulations for IE development and applications. IE embraces and develops different approaches, both technical and managerial, to design industrial ecosystems and to transform industrial systems to industrial ecosystems, through mimicking suitable features of biological ecosystems. IE aims to develop nearly closed-loop industrial ecosystems, which are balanced, diverse, and gradually changing in feature, in terms of material exchanges and energy cascading.*
>
> *Industrial Symbiosis (IS) explores ways to establish knowledge webs of novel material, energy and waste exchanges and business core processes to facilitate the development of networks of synergies within and across different companies to support the development of high levels of nearly closed-loop material exchanges and efficiency of energy cascading within and across industrial ecosystems.*

The four IE areas should not be applied in isolation as each cannot claim to be IE. It is the integrated effect of applications that leads to the achievement of the ultimate IE goal for developing nearly closed-loop industrial ecosystems. IS explores different ways to establish knowledge webs of novel ideas and a network of potential industrial partners to maximise opportunities of novel exchanges within and among different organisations to fulfil the goal of IE.

IE needs to 'draw in theorists and practitioners from many disciplines or fields that have become separated by the inexorable processes of modernist epistemology' (Ehrenfeld, 2014, page 830). IE is an interdisciplinary study field that proposes challenges for integrating different study disciplines. OM should be supported by IE thinking and considers transformation processes and systems in a closed-loop manner instead of a linear representation. The closed-loop thinking for business decisions can impact significantly on the reduction of the intake of virgin materials from, and the disposal of waste to the natural environment.

In the IE and IS development, economic gains as a driven factor for companies to participate in developing symbiotic relationships have been greatly emphasised, such as those described in the classic example of Kalundborg, Denmark. Focusing on economic gains as the primary aim only allows a small scale of randomly occurring IE and IS applications. Environmental gains need to be given much more emphasis in practice. The related areas of IE and their integration in application across disciplines need to be embedded in the development of environmental sustainability. The world needs much greater inputs from IE and IS in order for industrial activities and our living standards to sustain. IE still needs to establish its critical role as part of the Dominant Social Paradigm (DSP) to further influence business decisions and culture change (Ehrenfeld, 1997). The idea of industrial systems, as a form of industrial ecosystem, being part of the mother ecosystem of the Earth needs to be rooted in our thinking for business planning and decision making. In order for businesses and industries to prosper in the long run, our business decisions need to follow or mimic more closely the rules of nature. IE and IS contribute to the transformation of this thinking and business practices.

References:

Ayres, R. U. (1989), Industrial metabolism, in *Technology and Environment* (pp. 23-49), edited by J. H. Ausubel and H. E. Sladovich, National Academies Press, Washington, D.C.

Boix, M., Montastruc, L., Azzaro-Pantel, C., Domenech, S. (2015), Optimization methods applied to the design of eco-industrial parks: a literature review, *Journal of Cleaner Production*, 87, 303-317.

Branson, R. (2016), Re-structuring Kalundborg: the reality of bilateral symbiosis and other insights, *Journal of Cleaner Production*, 112, 4344-4352.

Chertow, M. (2000), Industrial symbiosis: literature and taxonomy, *Annual Review of Energy and the Environment*, 25, 313-317.

Chertow, M. (2007), “Uncovering” industrial symbiosis, *Journal of Industrial Ecology*, 11, 11-30.

Chertow, M. and Ehrenfeld, J. (2012), Organizing self-organising system, towards a theory of Industrial Symbiosis, *Journal of Industrial Ecology*, 16, 13-27.

Costa, I., Ferrão, P. (2010), A case study of industrial symbiosis development using a middle-out approach, *Journal of Cleaner Production*, 18, 984-992.

Despeisse, M., Ball, P.D., Evans, S., Levers, A. (2012), Industrial ecology at factory level - a conceptual model, *Journal of Cleaner Production*, 31, 30-39.

Domenech, T. and Davies, M. (2011), Structure and morphology of industrial symbiosis network: the case of Kalundborg, *Procedia Social and Behavioral Science*s, 10, 79-89

Dunn, B. C., Steinemann, A. (1998), Industrial ecology for sustainable communities, *Journal of Environmental Planning and Management*, 41, 661-672.

Ehrenfeld, J. (1997), Industrial ecology: a framework for product and process design, *Journal of Cleaner Production*, 5, 87-95.

Ehrenfeld, J. (2004), Industrial ecology: a new field or only a metaphor? *Journal of Cleaner Production*, 12, 825–831.

Ehrenfeld, J., Gertler, (1997), Industrial ecology in practice: the evolution of interdependence at Kalundborg, Journal of Industrial Ecology, 1, 67-79.

Erkman, S. (1997), Industrial ecology: an historical view, *Journal of Cleaner Production*, 5, 1-10.

Frosch, R. A., Gallopoulos, N.E, (1989), Strategies for manufacturing, *Scientific American*, 261(September), 144-152.
Gibbs, D., Deutz, P. (2005), Implementing industrial ecology? Planning for eco-industrial parks in the USA, *Geoforum*, 36, 452-464.
Graedel, T. E., Allenby, B. R. (2003), Industrial Ecology, 2nd Edition, AT&T and Prentice Hall (1st Edition, 1995).
Heeres, R. R., Vermulen, W. J. V., de Walle, F. B. (2004), Eco-industrial park initiatives in the USA and the Netherlands: first lessons, *Journal of Cleaner Production,* 12, 985-995.
Jacobsen, N. B. (2006), Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects, *Journal of Industrial Ecology*, 10, 239-255.
Jelinski, L.W, Graedel R.A, Laudise, R.A, McCall, D.W. and Patel, C.K.N. (1992), Industrial ecology: concepts and approaches, *Proceedings of the National Academy of Sciences of the United States of America*, 89, 793-797.
Jensen, P. D., Basson, L., Hellawell, E., Bailey M.R., Leach, M. (2011), Quantifying ‘geographic proximity’: Experiences from United Kingdom’s National Industrial Symbiosis Programme, Resources, *Conservation and Recycling*, 55, 703-712.
Korhonen, J. (2001), Four ecosystem principles for an industrial ecosystem, *Journal of Cleaner Production*, 9, 253-259.
Lehtoranta, S., Nissinen, A., Mattila, T., Melanen, M. (2011), Industrial symbiosis and the policy instruments of sustainable consumption and production, *Journal of Cleaner Production*, 19, 1865-1875.
Leigh, M., Li, X. (2015), Industrial ecology, industrial symbiosis and supply chain environmental sustainability: a case study of a large UK distributor, *Journal of Cleaner Production*, 106, 632-643.
Lombardi, D.R., Laybourn, P. (2012), Redefining industrial symbiosis, *Journal of Industrial Ecology*, 16, 28-37.
Lowe, E., and Evans, L., (1995), Industrial ecology and industrial ecosystems, *Journal of Cleaner Production*, 3, 47-53.
Malcolm, R., Clift, R. (2002), Barriers to Industrial Ecology, The strange case of “The Tombesi Bypass”, *Journal of Industrial Ecology*, 6, 4-7.
Mirata, M. (2004), Experiences from early stages of a national industrial symbiosis programme in the UK: determinants and coordination challenges, *Journal of Cleaner Production*, 12, 967-983.
Park, J. M., Park, J. Y., and Park, H-S. (2016), A review of the eco-industrial park development program in Korea: progress and achievement in the first phase, 2005-2010, *Journal of Cleaner Production*, 114, 33-44.
Seager, T. P., Theis, T. L. (2002), A uniform definition and quantitative basis for industrial ecology, *Journal of Cleaner Production*, 10, 225-235.
Tian, J., Shi, H, Chen, Y., Chen, L. (2012), Assessment of industrial metabolisms of sulfur in a Chinese fine chemical industrial park, *Journal of Cleaner Production*, 32, 262-272.
Tibbs, H. (1992), Industrial ecology, an environmental agenda for industry, *Whole Earth Review*, winter, 4-19
Van Berkel, R., Fujita, T., Hashimoto, S., Fujii, M. (2009), Quantitative assessment of urban and industrial symbiosis in Kawasaki, Japan, *Environmental Science*, 43, 1271-1281.
Valentine, S. V. (2016), Kalundborg Symbiosis: fostering progressive innovation in environmental networks, *Journal of Cleaner Production*, 118, 65-77.
Wang, G., Feng, X., Chu, K. H. (2013), A novel approach for stability analysis of industrial symbiosis systems, *Journal of Cleaner Production,* 39, 9-16.