CHAPTER 3: Industrial Symbiosis

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3.1. Introduction

Industrial ecology aims to develop and transform industrial systems into industrial ecosystems that achieve high levels of closed-loop material exchanges and energy cascade efficiency. Industrial symbiosis, a subfield of industrial ecology, explores ways to build knowledge networks that facilitate the establishment of new material and energy cascade exchanges within and across companies and industries.

The effective application of industrial ecology and symbiosis significantly enhances environmental sustainability. Operations management focuses on continuously improving the efficiency and effectiveness of processes for producing goods and delivering services. However, it often relies on a linear transformation process.

To successfully transition industrial systems into sustainable industrial ecosystems, the linear transformation mindset must be replaced with closed-loop thinking in operations management.

3.2. Part 1: Closed-Loop Concept in Industrial Ecology

This section discusses the fundamental issue of using linear transformation representations in operations management when striving for environmental sustainability. Linear transformation thinking must evolve into systemic closed-loop thinking, which industrial ecology can help achieve.

This section introduces key concepts in industrial ecology, including biological ecosystems, industrial ecosystems, sub-ecosystems, and their interactions with Earth's ecosystem. Industrial ecology seeks to develop advanced closed-loop industrial ecosystems by mimicking the core principles of biological ecosystems. An industrial ecosystem should aim for high levels of closed-loop material exchanges and efficient energy cascades. System boundaries are defined for study purposes, with broader systems thinking applied as needed.

3.2.1. Linear Transformation Processes

Environmental sustainability is critical for achieving long-term economic and social sustainability. This chapter focuses on industrial ecology, particularly industrial symbiosis, and how they can promote environmental sustainability through closed-loop process representations in operations management.

Humans have significantly impacted the planet, producing goods at a faster rate than ever before, which leads to overuse of natural resources and high waste levels. Despite efforts to mitigate these issues, more substantial interdisciplinary action is required.

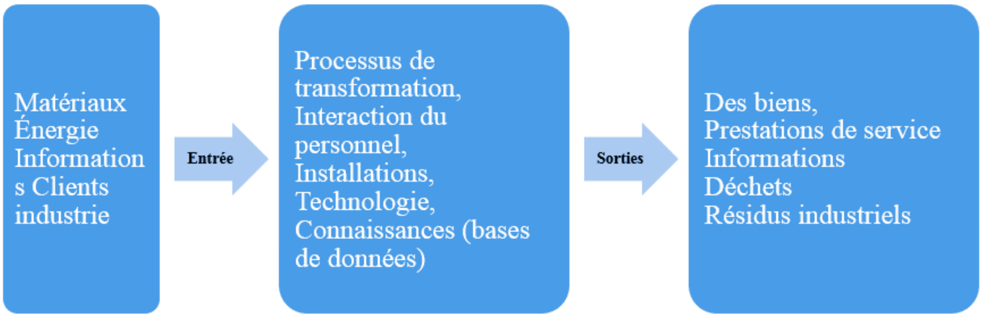

Figure 3.1: Linear transformation process

Operations management traditionally focused on production and delivery processes, must address environmental sustainability. Currently, it mainly considers processes as linear transformations, aiming to improve their efficiency without factoring in resource origins or waste destinations. This linear perspective fails to fully integrate environmental sustainability, despite some progress in recognizing its importance.

Linear transformation processes involve using personnel and facilities to convert raw materials and energy into finished products, with waste or by-products as outputs (Figure 3.1). However, waste and by-products are often overlooked in such analyses, limiting the scope of environmental performance improvement.

3.2.2. Closed-Loop Operations Management Processes

Industrial systems cannot remain viable indefinitely when natural resources become scarce and waste levels surpass the Earth's capacity to process them. To ensure long-term sustainability, industrial activities must contribute to the natural world's sustainability. Closed-loop systems thinking is necessary. Nearly 30 years ago, Frosch and Gallopoulos introduced the concept of an industrial ecosystem, advocating for closed-loop systems where waste from one process becomes raw material for another.

To scale this idea, industries must collaborate to reduce waste production and increase the reuse, refurbishment, and recycling of waste and post-use products. Designing for environmental compatibility is essential to maximize recycling and reuse potential.

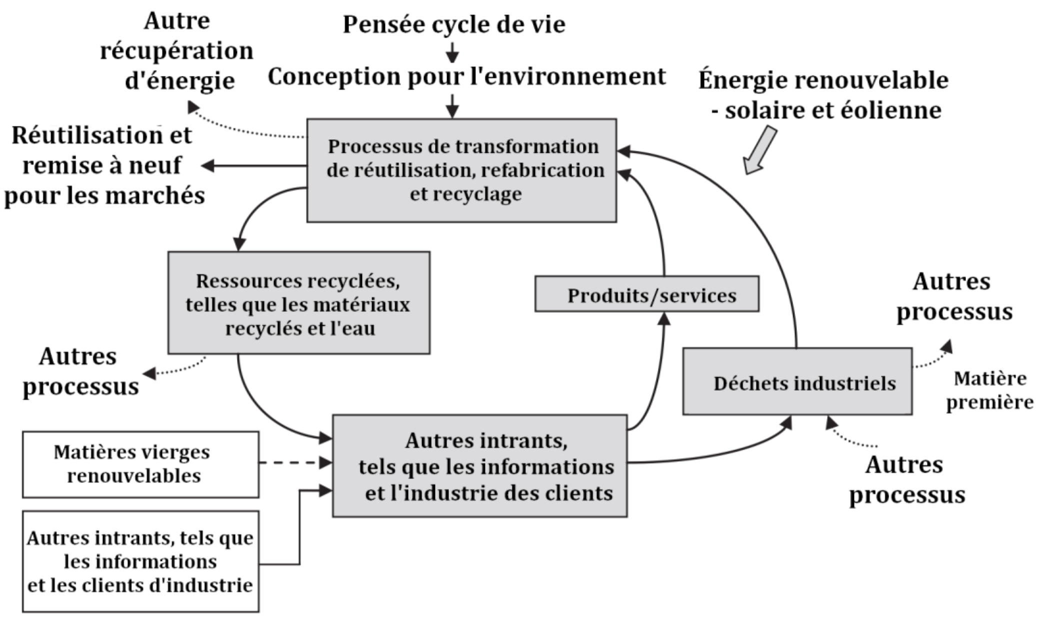

Figure 3.2: Thinking about the closed-loop operations management process

Despite some advancements, the use of recycled materials remains limited, and the adoption of waste-to-resource practices across industries has much room for growth. Closed-loop thinking in operations management can drive decision-making that supports both economic and environmental sustainability (Figure 3.2).

3.2.3. Biological Ecosystems

Biological ecosystems consist of abiotic components (e.g., sunlight, water, soil chemistry) and biotic components (e.g., plants, animals, bacteria). These components interact and transform through material exchanges and energy cascades over time and space (Figure 3.3).

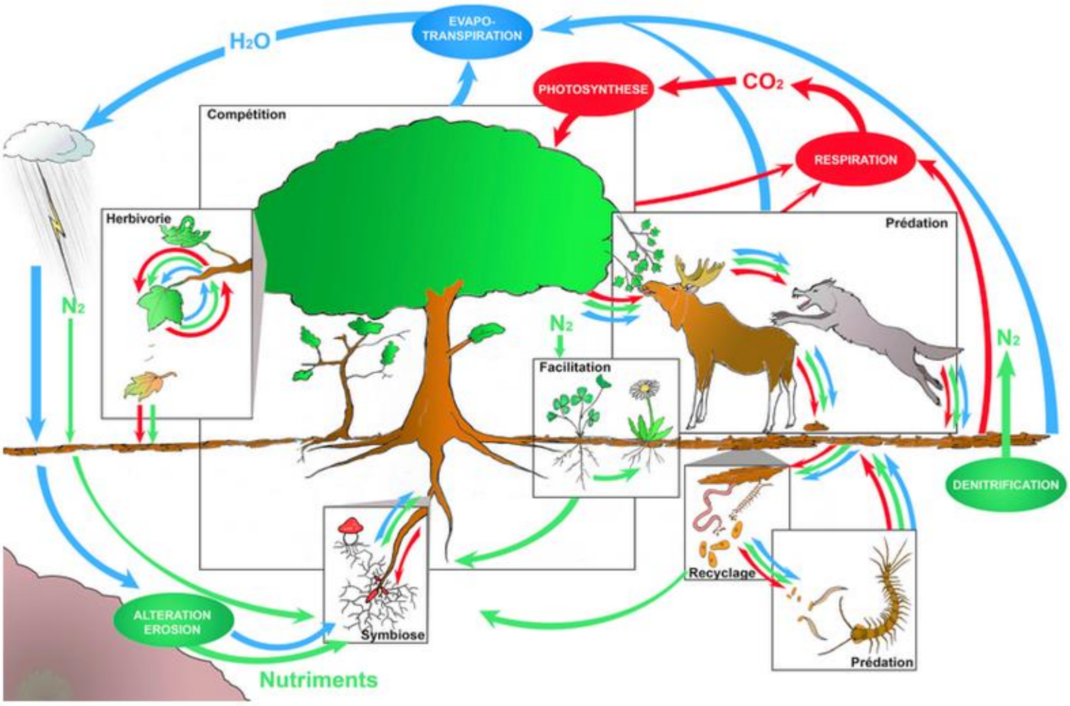

Figure 3.3: Functioning and interactions of ecosystems and symbiosis

Key characteristics of biological ecosystems include:

1. **Closed-loop material cycling**: Earth's subsystems recycle materials within a nearly closed-loop system.
2. **Open-system energy flow**: Energy flows through subsystems, driven by solar input from the sun.

The boundaries of biological ecosystems are flexible and defined for study purposes. These ecosystems maintain equilibrium when the waste they generate does not exceed their capacity to process it. Similarly, Earth's global ecosystem sustains itself when its waste levels remain within its overall carrying capacity.

3.2.4. Conclusion

Not all industrial systems qualify as industrial ecosystems, and many are far from achieving this status. An industrial ecosystem should strive for a high degree of closed-loop material exchanges, akin to biological ecosystems.

Although 100% closed-loop material exchange is unattainable even in biological sub-ecosystems, industrial systems should continuously improve toward higher levels of closed-loop exchanges. The shift from traditional linear transformation processes to closed-loop systems is essential for enhancing environmental sustainability.

The industrial revolution accelerated production rates, amplifying the limitations of linear transformation processes. The industrial ecosystem concept challenges this traditional view, emphasizing systemic closed-loop material exchanges.

Subsequent sections in this chapter delve into the definitions, development history, and interrelationships of industrial ecology and symbiosis.

3.3. Part 2: The Closed-Loop Concept in Industrial Ecology

Various definitions of ecology and industrial symbiosis have been provided in the literature over the past thirty years. These definitions have offered some ideas but also caused confusion due to inconsistencies. Industrial ecology, as an interdisciplinary field of study, develops and applies various approaches across its four interdependent areas:

1. Industrial ecosystem,
2. Industrial symbiosis,
3. Industrial metabolism, and

4. Environmental legislation and regulation.

- The ultimate goal of industrial ecology is to develop nearly closed-loop industrial ecosystems to improve environmental sustainability.
- Industrial symbiosis focuses on developing knowledge networks for new exchanges of materials, energy, and waste to facilitate synergies supporting the achievement of this industrial ecology objective.
- The difference between ecology and industrial symbiosis lies in the orientation rather than the scale of the economy.

3.3.1. State of the Art in Industrial Symbiosis

Several researchers have provided definitions and explored the applications of industrial ecology (IE) and industrial symbiosis (IS). The definitions offered have clarified the significant roles of IE and IS in achieving environmental sustainability to some extent and have inspired research and applications of IE and IS.

However, the definitions of IE and IS presented in the literature are not always consistent. Some definitions distinguish IE and IS, while others do not. Some definitions set conditions for IS applications, such as geographical proximity and industry diversity, while others consider these conditions unnecessary. The differences in the understanding of IE and IS can spark debates.

However, unclear concepts can lead to confusion and hinder the development and applications of IE and IS. Therefore, it is necessary to clarify the concepts of IE and IS by exploring existing definitions. Comparing the key characteristics of IE and IS as defined in the literature can lead to a more consistent understanding of both, which will facilitate their future development and applications.

IS certainly cannot exist on its own without the presence of IE, as IS supports the implementation of IE principles and the achievement of its goals. However, it is not always true that declared IS applications have taken IE principles into account, particularly in a number of eco-industrial park (EIP) applications. Furthermore, there are various understandings of the relationship between IE and IS in the literature. Therefore, this section of the chapter explores the key definitions of IE and IS and their developmental histories. The common themes of IE and IS, as well as the divergences in the interpretation of these two concepts in the literature, are explored and compared, along with their relationships.

3.3.2. The Relationship between Industrial Ecology (IE) and Industrial Symbiosis (IS)

The main definitions of IE in the literature are presented in Table 3.1, along with the key features identified for each definition, followed by comments. Identifying and extracting a definition of IE is not always straightforward, as explanations of IE and related aspects are often provided within the content of a research paper rather than in a standard definition format.

Some early definitions referred to IE as a method, approach, or framework. Over time, definitions gradually established that IE is an interdisciplinary field of study. Like its counterpart in biological ecology, IE is a field that contains various methods, approaches, and frameworks for designing and transforming industrial systems into nearly closed-loop industrial ecosystems. Considering IE solely as an approach, framework, or method limits its development and applications.

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

Table 3.1: Definitions of Industrial Ecology (IE), Key Features, and Comments

Definitions of Industrial Ecology (IE)	Key Features	Comments
The industrial ecosystem would operate as an analogue to the biological ecosystem	- Industrial ecosystems mimic biological ecosystems.	- This entry does not directly define IE but describes its core, which is the development of nearly closed-loop industrial ecosystems through material and energy exchanges.
	- An industrial ecosystem is an integrated model of industrial activities. - Industrial ecosystems optimize energy and material consumption and minimize waste through links between industrial processes.	- This entry does not indicate that an industrial ecosystem is part of the natural system. - This entry does not imply the need to cross industrial boundaries for IE.
	- An industrial ecosystem is a closed-loop or nearly closed-loop system.	- It raises two questions: What is the global industrial ecosystem, and what is its boundary?
The traditional model of industrial activity... should be transformed into a more integrated model: an industrial ecosystem. In such a system, energy and material consumption is optimized, waste production minimized, and effluents from one process... serve as raw materials for another process	- How the inputs and outputs of individual processes are linked within the global industrial ecosystem is equally important. This link is crucial to building a closed or nearly closed system.	- IE focuses on the integration of various components within a system. - IE reduces net resource inputs and pollutant and waste outputs from a system.
IE considers the principles of biological ecosystems when designing and redesigning industrial systems to	- IE considers the principles of biological ecosystems.	- Focuses on the consideration of biological ecosystem principles in IE but does not specify them.

create more effective interactions both within industrial systems and between industrial systems and natural systems	- IE designs and redesigns industrial systems. - IE enhances interaction efficiency within and between industrial systems and natural systems.	- Emphasizes interactions between industrial and natural systems. - The development of the closed-loop ecosystem needs to be specified.

The development of IE has relied on the understanding of related concepts/domains such as the industrial ecosystem, IS, and industrial metabolism (IM). However, definitions of IS were rarely provided before 2000, using Kalundborg as a case to explore IE in practice. The intensity of IS study began at the start of this century. Since 2000, there has been an increasing number of studies exploring IS and its applications. Chertow (2000) considered eco-industrial parks (EIPs) as a "concrete realization" of IS. On the other hand, some IS applications have neglected IS relevance to IE in terms of its ultimate goal of developing nearly closed-loop industrial ecosystems. The main definitions of IS and associated features, followed by comments, are presented in Table 3.2.

Early definitions of IS focused on the efficiency and optimization of resource flows without emphasizing the eco aspect or the novelty of exchanges based on establishing symbiotic relationships. The definition by Domenech and Davies (2011) made a breakthrough by highlighting the need for a knowledge network to facilitate the establishment of physical resource exchanges between various organizations. This emphasizes the importance of knowledge in the development of IS. Lombardi and Laybourn's (2012) definition further specifies that the exchanges must be new. These definitions clearly confirm that IS is part of IE. However, most definitions should clarify that IS must fulfill the goal of IE, which is to develop high levels of nearly closed-loop industrial ecosystems. These definitions should also address the system boundary aspect.

Industrial Symbiosis (IS) requires the integration of the following functionalities:

1. A knowledge network,
2. A network of diverse organizations,
3. A new supply of inputs,
4. Value-added destinations for outputs other than products (and other end-of-life products),
5. Improvement of business and technical processes, and
6. A collective approach to the system as a whole.

Table 3.2: Definitions of Industrial Symbiosis (IS), Key Features, and Comments

Definitions: Industrial Symbiosis (IS)	Key Features	Comments
Industrial symbiosis, within the emerging field of industrial ecology, demands focused attention on the flow of materials and energy through local and regional economies	- IS is part of IE, which deals with the flow of materials and energy through local and regional economies, not the global economy.	- This is a well-cited definition. However, it raises a crucial question about whether IS and IE should be distinguished by the scale of the economy. - IS is part of IE. - Emphasizes the importance of crossing industrial boundaries in a collective approach to IS. - Adds value by considering different physical exchanges, not just waste and by-products for IS. - This definition raises another crucial question about whether geographical proximity is essential for IS. (Numerous symbiotic exchanges between businesses across regions have been reported in the literature.)
Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving the physical exchange of materials, energy, water, and/or by-products. Key elements of industrial symbiosis are collaboration and synergies offered by geographical proximity	- IS engages traditionally separate industries. - Key elements of IS are collaboration and synergies. - IS is conditioned by geographical proximity.	
IS applies the ecological metaphor of IE to create a collective approach among companies and industries traditionally viewed as distinct entities and considers the whole system concerning the physical exchange of materials, energy, water, and by-products	- IS applies the ecological metaphor of IE. - IS creates a collective approach. - IS considers the entire system.	- Emphasizes the importance of the IE principle of the ecological metaphor required in IS. - Focuses on the entire system for examining IS. - The system boundary remains unanswered.

3.3.3. Histories of Industrial Ecology and Industrial Symbiosis Development

As we began to recognize the severity of the long-term negative impact of human industrial activities on the Earth, some of us began actively comparing our industrial systems to biological systems. Learning to support our human activities on Earth for our generation and future generations has been the key. The comparison of our industrial systems with biological systems led to the formal initiation and development of Industrial Ecology (IE) and its related fields, including Industrial Symbiosis (IS), and their applications.

The history of IE development confirms that the understanding of IE has not yet converged. The characteristics of biological ecosystems that an industrial system can imitate to become an industrial ecosystem still need to be explored. Some common features of industrial ecosystems identified in the history of IE development are:

- Material exchanges in almost a closed loop,
- Balance between production and decomposition,
- Diversity of industrial units/processes/organizations, and
- Wholeness, which is an extended system view.

The history of IS development clearly recognizes that IS is part of the field of IE. However, there are a number of debatable concepts presented in the history of IS development. This includes geographical proximity, self-organization, the required number of entities and resources involved in an IS exchange. Some of these debatable concepts have been brought to attention when examining IS definitions. Therefore, no repetition is given here. The focus here is that IS focuses on establishing symbiotic relationships to achieve the ultimate goal of IE, which is the development of nearly closed-loop industrial ecosystems. However, the history of IS development does not always reflect this goal of IE and contains some subjective and misleading concepts.

The term "industrial symbiosis" (IS) was mentioned many years before 2000. For example, Tibbs (1992) considered IS as one of the concepts within IE. The classic example of Kalundborg in Denmark was used to illustrate the applications of IE and IS in the literature. These studies frequently emphasized the unplanned collaborations established in Kalundborg over the years for the exchange of materials, waste, by-products, and cross-industrial energy in a local community. However, more recent synergies in Kalundborg have been facilitated by the Kalundborg Symbiosis Centre, created in 1996.

Moreover, the success of the UK's national IS program (NISP) was a planned and facilitated IS program, coordinated by NISP centers in different regions and its central NISP team. Several researchers have highlighted the importance of various industries in establishing symbiotic relationships in IS practice. However, some researchers have suggested that IS could also be applied within individual companies.

Some studies have focused on IS solely in terms of its role in establishing symbiotic relationships between different industrial companies without considering the development of closed-loop industrial ecosystems. Developing symbiotic relationships is an important step toward the closed-loop principle of IE. However, it is the totality of IE that should be reflected in the development of these symbiotic relationships in relation to IS. Exploring the relationships between IE and IS and other areas within the field of IE facilitates this understanding.

3.3.4. The Kalundborg Symbiosis

Located on the shores of the North Sea, about 100 kilometers from Copenhagen, Kalundborg is a small town with twenty thousand inhabitants. Kalundborg owes its fortune primarily to its fjord, one of the main ports accessible in the winter at this latitude in the Northern Hemisphere. It is precisely the accessibility of this port throughout the year that is the origin of Kalundborg's industrial development. Since the 1950s, the town has seen the establishment of a power plant and an oil refinery. Over time, the main companies based there began exchanging waste, steam, water (at different temperatures and levels of purity), and various products. By the late 1980s, local development officials realized that they had gradually and spontaneously created a system they called "industrial symbiosis."

3.3.4.1. How the Ecosystem Works

The Kalundborg symbiosis includes six industrial partners and one public entity, located only a few hundred meters apart and connected by a network of ad hoc pipelines (Christensen 2006). The Asnaes Power Plant is the largest in Denmark, with a capacity of 1500 MW. It was originally fueled by oil and later by coal (after the first oil crisis). It employs nearly 250 people. Statoil is the largest oil refinery in Denmark, with a capacity of over three million tons of oil per year and employing 350 people. Novo Nordisk is the largest Danish biotechnology company, a major producer of industrial enzymes and insulin, employing about 3500 people. Gyproc is a Swedish company with a factory in Kalundborg that produces gypsum construction panels (14 million m^2 per year), employing 165 people.

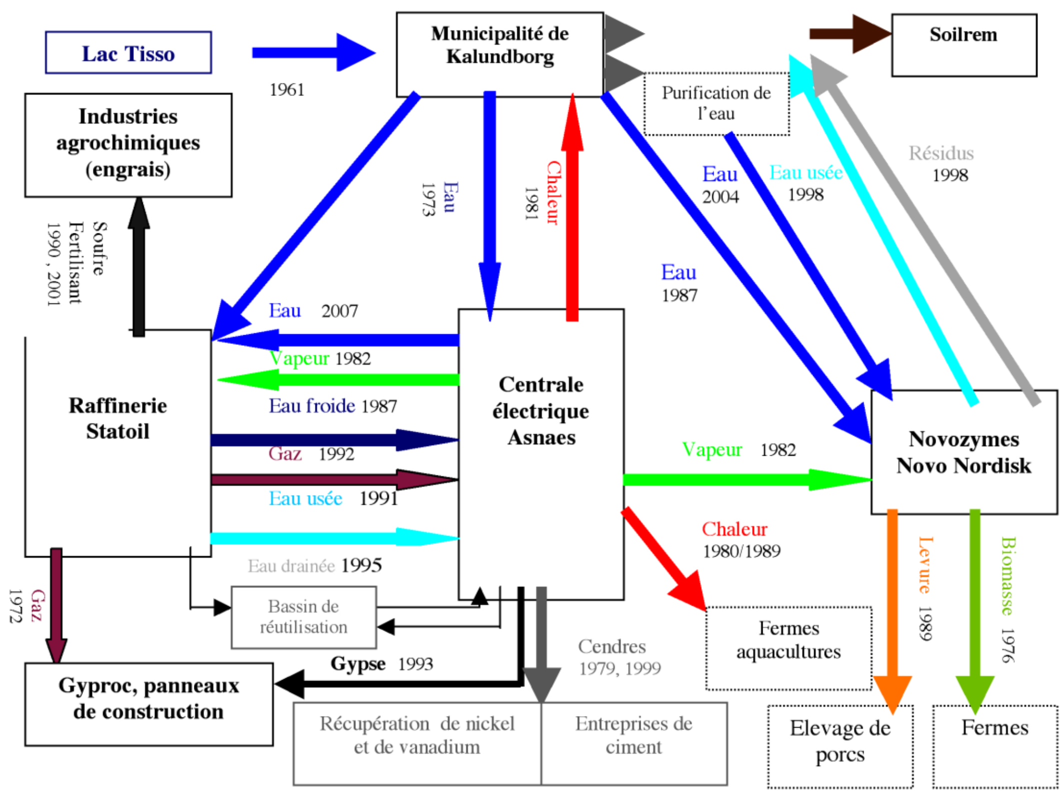

Figure 3.4: The Kalundborg Industrial Symbiosis

Soilrem is a facility for the remediation of soils contaminated by heavy metals and hydrocarbons, employing 65 people. Noveren is owned by nine municipalities and processes about 126,000 tons of waste per year. Finally, the Municipality of Kalundborg is a public entity that actively participates in the industrial project. The Kalundborg ecosystem operates as follows (Nahapétian 2002).

Water, in liquid or steam form, is the most systematically valorized waste (Keckler, Allen 1998). It comes directly from Lake Tisso, about 15 kilometers either away, or from the municipal water supply. Statoil's refinery provides wastewater to cool the Asnaes Power Plant, which then sells steam to Statoil's refinery, to Novo Nordisk (for its fermentation towers), to Gyproc, and to the municipality of Kalundborg for its district heating network. The power plant even sells hot water to an aquaculture farm raising turbot.

Based on available information in 1999, the Kalundborg system offered several environmental and economic benefits (Erkman 2004).

Environmentally, the industrial ecosystem showed a positive balance: a reduction in resource consumption (45,000 tons of oil per year, 15,000 tons of coal per year, and 600,000 m^3 of water per year, a scarce resource in the region); a reduction in greenhouse gas emissions and pollutants (175,000 tons of CO_2 per year, 10,200 tons of sulfur dioxide per year); and waste reuse (130,000 tons of ash for road construction, 4,500 tons of sulfur for sulfuric acid production, 90,000 tons of gypsum, 1,440 tons of nitrogen, and 600 tons of phosphorus per year).

Brings Jacobsen (2006) updated the figures a few years later, seeking to quantify water and steam exchanges. From 1992 to 2002, replacing surface water (lake) with recycled water amounted to nearly 1.1 million m^3. From 1997 to 2002, reductions in CO_2 and nitrogen oxide emissions were estimated at 154,000 tons and 389 tons, respectively (compared to the production of the Asnaes plant with a natural gas facility).

Economically, the investments needed to complete the twenty-five operations exceeded 75 million dollars. With annual savings close to 15 million dollars, the return on investment would be around four to five years for major projects (two years for others).

Beyond its many benefits, the Kalundborg system should not be "idealized" (Erkman 2004, p. 4) but rather serve as an example. Some observers (Sterr, Ott 2004) have noted two disadvantages: a certain rigidity of exchanges and a systemic risk in the event of one of the partners withdrawing.

3.3.4.2. Lessons from Kalundborg

The Kalundborg symbiosis provides three key lessons. First, a spontaneous process developed on commercial bases that satisfy all the companies (a win-win scenario). Suren Erkman notes, "The exchanges obey the laws of the market" (1998, p. 26). Each delivery of "waste" between partners is subject to separate, confidential negotiation. The industrial symbiosis in Kalundborg appears as an "environmental network" of more than 20 bilateral commercial agreements between six firms and a municipality.

Three types of projects have emerged water recycling (12 projects), energy exchange (6 projects), and waste treatment (7 projects). Since 1996, the "Symbiosis Institute" has been the living memory of this industrial success. Next, the success of the system relies on good communication between partners. Christensen (2006, p. 47-48) highlights three key factors: mutual trust ("Participants must fit, but be different"), geographical proximity ("There has to be a short physical distance between the participants"), and management style (sharing certain values), "There has to be a short mental distance between the participants."

Finally, for the system to become operational, it must be integrated into the organizational structure of companies. In management, industrial ecology has major consequences. On one hand, it challenges the focus of the company on the product. In fact, it gives equal importance to waste valorization. On the other hand, companies need to establish a form of "management over the fence," a collaborative chain to ensure optimal resource management (Esty, Porter, 1998).

Optimizing all material and energy flows mobilized by companies (from raw material to finished product) leads "eventually to improved performance and competitiveness" (Erkman, 1998, p. 33). To improve the efficiency of such a system, it will be necessary to encourage certain industrial mixes (industrial biocenoses) conducive to waste and resource exchanges (Brings, Jacobsen, Anderberg, 2001).

3.4. Conclusion

By critically examining various definitions of industrial ecology (IE) and industrial symbiosis (IS), the relationship between industrial ecology and industrial symbiosis, and the areas of study within industrial ecology:

- **Industrial Ecology (IE)** is an interdisciplinary field of study that encompasses interconnected areas of industrial ecosystems, industrial symbiosis (IS), industrial metabolism (IM), and legislation and regulation for the development and applications of IE. IE adopts and develops various approaches, both technical and managerial, to design industrial ecosystems and transform industrial systems into industrial ecosystems by mimicking the appropriate characteristics of biological ecosystems. IE aims to develop industrial ecosystems that are nearly closed-loop, balanced, diversified, and evolutionary in terms of material exchanges and energy cascades.

- **Industrial Symbiosis (IS)** explores ways to establish knowledge networks on new exchanges of materials, energy, and waste, and the core business processes that facilitate the development of synergy networks within and between different companies. This supports the development of high levels of material exchange in near-closed loops and cascading energy efficiency within and across industrial ecosystems.

The four IE domains should not be applied in isolation, as none of them alone can claim to be IE. It is the integrated effect of these applications that leads to the ultimate goal of IE: the development of nearly closed-loop industrial ecosystems. IS explores different ways to establish knowledge networks of innovative ideas and networks of potential industrial partners in order to maximize opportunities for innovative exchanges within and between different organizations to achieve the goals of IE.

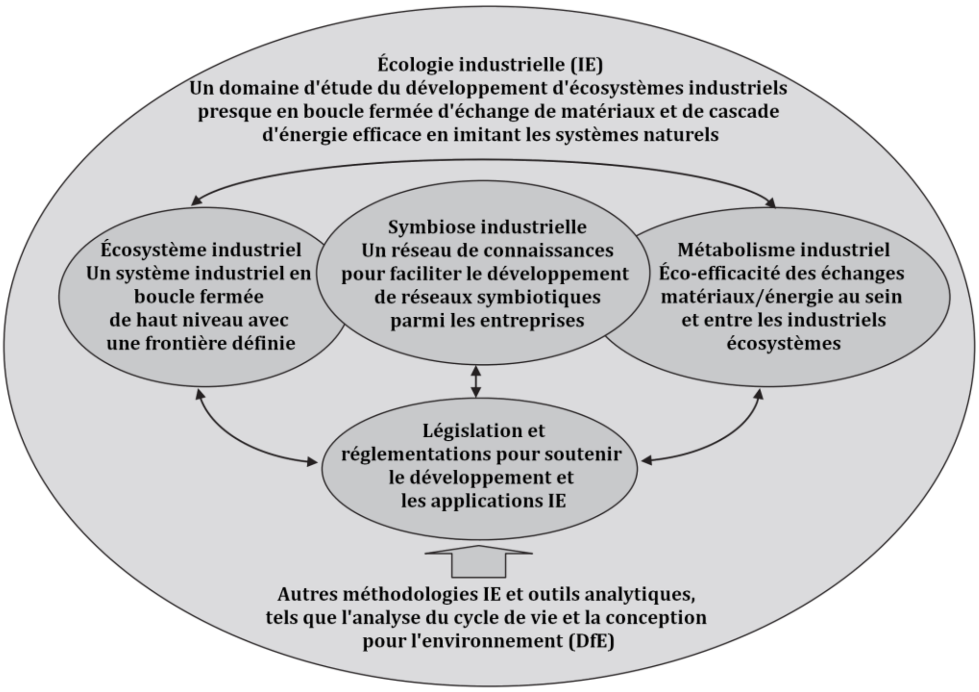

Figure 3.4: Industrial ecology and its four interrelated fields of study

Industrial ecology (IE) must "attract theorists and practitioners from many disciplines or fields that have been separated by the inexorable processes of modernist epistemology."

IE is an interdisciplinary field of study that presents challenges in integrating different academic disciplines. Operations management must be supported by IE thinking and consider processes and systems in closed loops rather than linear representations.

Closed-loop thinking for business decisions can have a significant impact on reducing the input of raw materials and the elimination of waste into the natural environment. In the development of IE and IS, economic gains as a driving factor for companies to engage in developing symbiotic relationships have been strongly emphasized, as seen in the classic example of Kalundborg, Denmark. Emphasizing economic gains as the primary driver for these exchanges, however, should not overshadow the importance of environmental benefits in practice.

Environmental gains need to be more prominently featured in practice. Related fields of IE and their integration across disciplines should be incorporated into the development of environmental sustainability. The world needs much more from IE and IS to maintain industrial activities and our standard of living.

The idea that industrial systems, as a form of industrial ecosystems, are part of the Earth's larger ecosystem must be embedded in our thinking on activity planning and decision-making. For businesses and industries to thrive in the long term, our business decisions must follow or more closely mimic the rules of nature. IE and IS contribute to transforming this mindset and business practice.