Chang Yu

Eco-transformation of industrial parks in China

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Eco-transformation of industrial parks in China

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Chang Yu – June 2014, Delft, the Netherlands

It was the best of times, it was the worst of times,
it was the age of wisdom, it was the age of foolishness,
it was the epoch of belief, it was the epoch of incredulity,
it was the season of Light, it was the season of Darkness,
it was the spring of hope, it was the winter of despair,
we had everything before us, we had nothing before us,
we were all going direct to Heaven, we were all going direct
the other way.
.

Charles Dickens – A Tale of Two Cities, 1859
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Part I

Theoretical research

1
Introduction

1.1 Environmental issues in China

1.1.1 Pollution associated with China's rapid industrialization

During the last three decades, China has accomplished an impressive economic development. Thanks to rapid industrialization of the economy, the average annual growth rate of GDP reached 9.9% (from 1978 to 2012). However, China's economic growth came at the price of dramatic pollution and resource depletion. Severe environmental issues such as ecosystem degradation, groundwater contamination and smog have become visible crises. One in five cities suffers from serious air pollution and one third of groundwater is too contaminated to be directly used (Yong, 2007). According to China Statistical Yearbook (2010), China contributed 9.5% of world total GDP in 2010, at the cost of 48.4% of world coal consumption and 44% of world steel consumption. Although the energy intensity of China was reduced between 2000 and 2011 (shown in Figure 1.1), it is still 49% higher than India's and 3.6 times as large as the US energy intensity. In 2012 the coal consumption in China accounted for 67% of its total energy consumption (Figure 1.2). This ratio was over 3 times of those in the developed countries like the US and Japan. The consequence of relying on coal power in industrial activities is the enormous emission of CO_2 and SO_2 due to lacking of treatment technologies and regulations. In 2013, the dense haze that blanketed over

China has exposed the severity of air pollution. More than 100 cities in 25 provinces suffered from frequent smog. The index of PM2.5[1] has kept hitting a record high of over 10 times as much as the standard requires, which indicates a threat to the people's health. It reminds us of another significant air pollution event, "Great Smog", happened in London in 1952. It caused more than 4000 deaths in one week and hundred thousand people fell ill in the following month. This smog in London was caused by large-scale coal-fired industrial activities due to rapid economic growth after the industrial revolution. It was just like the current status of the industrialization in China. The "Great Smog" triggered a series of strong environmental policy interventions, involving legislations, economic incentives and new technologies to reduce pollution. In China, relevant environmental regulations and legislation have been gradually issued since the 1990s, however, the environment has continuously deteriorated. The root cause is the GDP-oriented evaluation system, which drives local governments to promote economic growth at all costs. The pollution and resource consumption caused by industrial growth overweights pollution control and treatment (Yong, 2007). The new leadership of China has clearly proposed to revise the evaluation solely by GDP growth and emphasize social development and environmental issues. However, it will take a long time and considerable efforts to change the prevailing mode of industrial production and recover the environment.

1.1.2 Environmental management in China

Since the 1990s, China has been striving to cope with its severe environmental issues. End-of-pipe treatment was applied to reduce the pollution at the end of the production processes. However, this approach cannot solve the intensive resource consumption and prevent the generation of pollution at the source. Moreover, it may cause new types of pollution when treating the pollutant specifically required by regulations. In 1998, the idea of Circular Economy (CE) was introduced into China (Zhu, 1998), referring to concepts developed in Germany and Japan. It concentrates on the closed-loop of materials and "3R" principles - Reduce, Reuse and Recycle (Fang et al., 2007; Yuan et al., 2006). The focus of CE has been shifted from waste recycling to efficiency improvement in the life cycle of production, distribution and consumption (Su et al., 2013). Soon after, CE has become a priority to balance the economic growth and ecological conservation both in academia and government. Since 2002, CE has been officially accepted by China's central

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[1] PM2.5 means the particulates with a diameter of 2.5 micrometers or below. The standard from the World Health Organization is that people should not be exposed to air containing more than 25 micrograms per cubic meter in 24 hours.

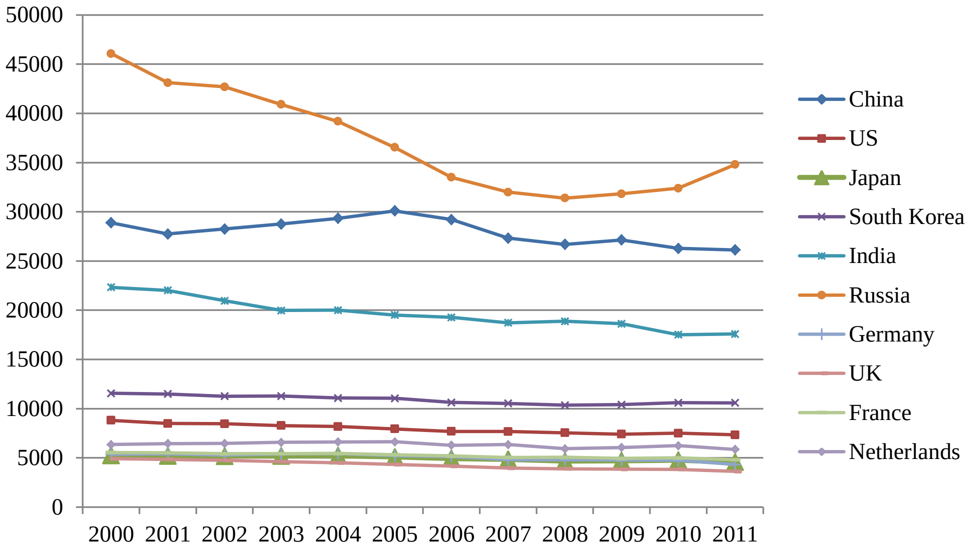

Figure 1.1 – Energy intensity in the different countries between 2000 and 2011. Unit: Btu (British thermal units) per US dollar. Note: It is calculated as total primary energy consumption per dollar of GDP and uses market exchange rates to unify GDP. Source: US Energy Information Administration.

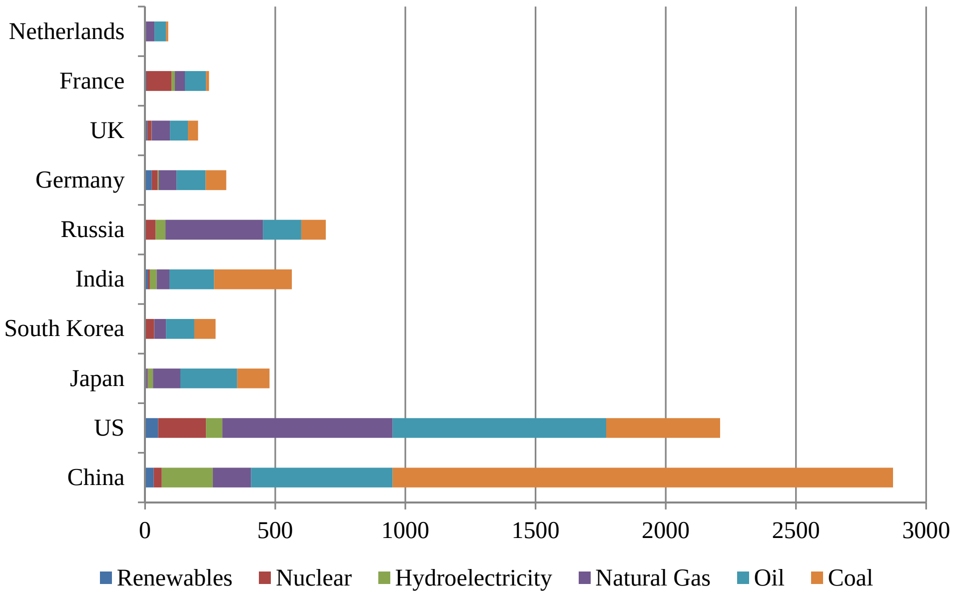

Figure 1.2 – Amount of the different types of energy consumption in 2012. Unit: million tons of oil equivalent (MTOE). Data source: (BP, 2013)

government as a new pattern of economic growth and underpinning strategy. In 2005, China's 11th Five-Year Plan prioritized resource conservation as one of the fundamental national policies through promoting the CE. The Circular Economy Promotion Law was officially issued in 2008. In its practical implementation, CE is carried out mainly at three levels (see Figure 1.3): intra-company (i.e., cleaner production and environmental management system), inter-company in industrial clusters (i.e., eco-industrial park (EIP)) and regions (i.e., eco-city and eco-province). Moreover, other environmental laws have been issued, such as the Cleaner Production Promotion Law (2003), Environmental Impact Assessment Law (2003), Law on the Prevention and Control of Environmental Pollution by Solid Wastes (2004), and Energy Conservation Law (revised in 2007). For all engineering construction projects and resources exploitation projects, the Environmental Impact Report must be approved by the local Environmental Protection Bureau before starting construction. After approval, the related environmental protection facilities must be designed, constructed and operated together with the whole project (also called the principle of "three synchronization"). Additionally, supporting policies and investment have been enforced to improve environmental performance, involving adjustment of industrial structure, market access for energy intensive and polluting industries, and stricter environmental standards. In 2011, the investment for all industrial waste treatment reached 44.4 billion RMB[2], an increase by 89% compared with that of 2000. As Figure 1.4 shows, the industrial wastewater and waste gas have been the

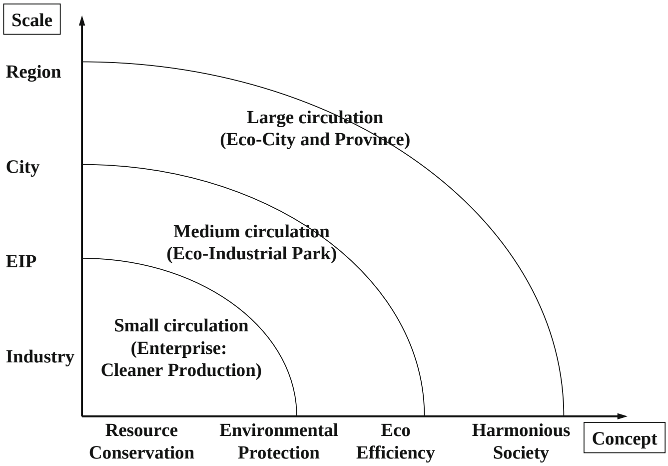

Figure 1.3 – Three levels of implementing CE. Source: (Zhang et.al, 2009a).

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[2] RMB is the currency of China. 100 RMB is approximately equal to 16 US dollars.

targets in the pollution treatment. The investment of wastewater and waste gas accounted for 35.5% and 47.6%, respectively, in 2011.

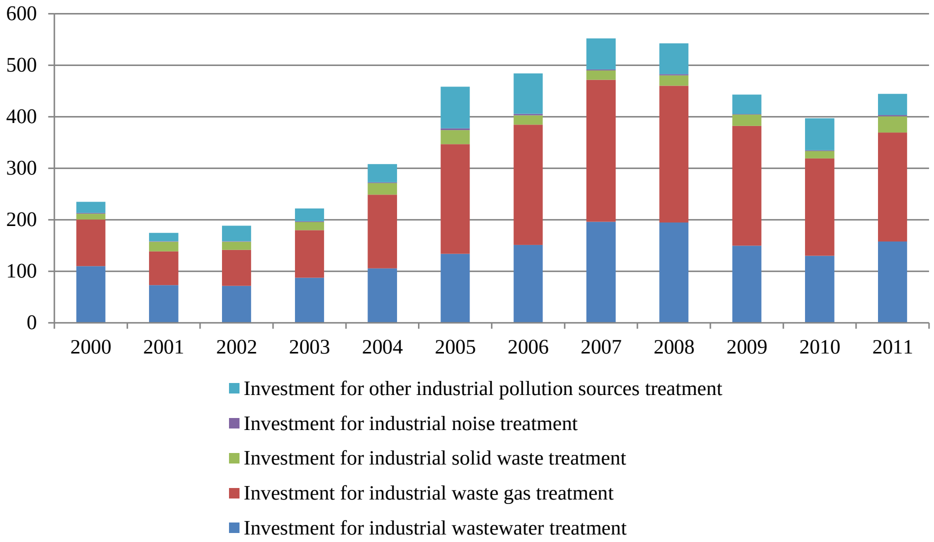

Figure 1.4 – The investment for industrial waste treatment between 2000 and 2011 in China. Unit: 100 million RMB. Data source: China Statistical Yearbook (issues from 2000 to 2011).

The performance of Circular Economy can be reflected by indicators in four domains: 1) wastewater (including discharge amount, chemical oxygen demand (COD) and ammonia nitrogen (AN)), 2) waste gas (including SO_2 and NO_x), 3) solid waste (including discharge amount and reuse rate) and 4) energy intensity (i.e., energy consumption per unit of GDP). We have examined the progress made in environmental management in China in terms of these four aspects. Table 1.1 shows the performance of the main pollutant in 2011 and the targets of 2015. Compared with 2010, the discharge of wastewater and NO_x increased by 6.7% and 5.74%, which needs more concern from government. The pollution reduction mainly made progress on COD, AN and SO_2 which were 2.04%, 1.55% and 2.2% lower than those of 2010. Table 1.1 also reveals that industrial activities take the largest amount of emissions in terms of waste gas and solid waste. Thus efforts need to be made in industries to reduce the pollution.

Moreover, according to the China Statistical Yearbooks, energy intensity in China in 2011 was 1012 tons of coal equivalent (tce)/10,000 RMB which was 2.01% lower than that of 2005. The average annual growth rate of energy intensity was -3.78% between 2005 and 2011. Apart from the national performance of energy consumption, regional data also show the progress and

Main pollution indicators (Unit: 10 thousand tons)		**Amount of 2011**				**Total growth rate**	**Goal of growth rate in 2015**
		Industrial	Agricultural	Residential	Other		
Wastewater	Wastewater discharge (billion tons)	23.09	---	42.79	---	6.7%	
	COD discharge	354.8	1186.1	938.8	---	-2.04%	-8%
	AN discharge	28.1	82.7	147.7	---	-1.55%	-10%
Waste gas	SO_2 discharge	2017.2	---	200.4	---	-2.2%	-8%
	NOx discharge	1729.7	---	36.6	637.6*	5.74%	-10%
	Smoke and dust discharge	1100.9	---	114.8	62.9*	0.08%	
Solid waste		Discharge	Comprehensive use rate	Storage	Treatment	Dumping	
	General industrial solid waste	32300	59.9%	60000	70000	433	
	Industrial hazardous waste	3431.2	76.5%	823.5	916.5	0.01	

Table 1.1 – The performance of the main pollution indicators in 2011 in China. Note: The total growth rate and the goal of growth rate in 2015 are based on 2010. The star (*) represents the discharge from motor vehicles. Data source: (MEP, 2013a; State-Council, 2011).

the distribution of energy intensity (see Figure 1.5 and Figure 1.6). Overall, the regions that have the lowest energy intensity are mostly located in the Pearl River Delta and Yangtze River Delta. The advanced economic development in these regions provides more supportive policies and investment on environmental management and technologies. Moreover, as the adjustment of industrial structure, the heavy industries with intensive energy consumption and pollution are being transferred to the west. Both Figure 1.5 and 1.6 reveal that western China has the highest energy intensity. Ningxia autonomous region made the highest energy intensity of 4.14 and 2.279 tce per 10,000 RMB in 2005 and 2011, respectively. As the new goals proposed in the 12^{th} Five-Year Plan (State-Council, 2011) by 2015, the energy intensity aims to reduce to 0.869 tce/10,000 RMB, 16% lower than that of 2010. The major targets lie in the industrial energy usage which accounts for approximately 73% of total energy consumption. Thus, the tasks to reduce pollution and energy intensity should focus on industries, especially industrial parks that have intensive industrial activities.

Figure 1.5 – Energy intensity of 30 provinces, autonomous regions, and municipalities (directly under the central government) in 2005. Unit: ton coal equivalent (tce)/10,000 RMB. Data source: China Statistical Yearbook (2006). Note: Energy intensity is calculated as energy consumption per unit of GDP. Data of Tibet and Taiwan are not available.

Figure 1.6 – Energy intensity of 30 provinces, autonomous regions, and municipalities (directly under the central government) in 2011. Unit: ton coal equivalent (tce)/10,000 RMB. Data source: China Statistical Yearbook (2012). Note: Energy intensity is calculated as energy consumption per unit of GDP. Data of Tibet and Taiwan are not available.

1.1.3 Progress of eco-industrial park program in China

At the industrial park level, the promotion of eco-industrial park (EIP) is the main approach to bring the "3R" principles into practice. In theory, EIP is in the research field of industrial symbiosis that is defined as engaging separate industries in a collective approach involving physical exchange of materials, energy, water and by-products (Chertow, 2000). In practice, EIP aims to promote the closed-loop materials and energy cascading through resource-service sharing, by-product exchange and environmental management (MEP, 2009). It aims to improve the environmental performance at the level of entire industrial park.

In 2001, the State Environmental Protection Agency (known as the former Ministry of Environmental Protection (MEP)) of China launched the program of National Demonstration Eco-industrial Parks. This national EIP program specifically focuses on the eco-transformation of National level Economic and Technological Development Zones (established since 1984) and Hi-tech Development Zones (established since 1992). The background of these national industrial zones can be traced back to the 1970s when China started to implement the reform and open door policy. At the time, these special industrial zones, as experimental fields for economic reform, were given various preferential policies to explore the approaches for institutional innovation, economic growth and technology development. The goal of these national development zones was to attract foreign investment and improve export. In the early stages, the national industrial zones were mainly dominated by manufacturing industries that process supplied materials with low added-value. Local authorities sought sheer GDP growth without considering the environmental cost and the efficiency of land use. Due to the absence of environmental management, some projects for pollution transfer were even allowed because of the short-term economic benefits. Furthermore, the location and relocation of companies depended on the preferential policies from the authorities rather than on the fit between activity and location or industrial agglomeration effects (Dijkema et al., 2005). The result is a weak network among companies and a wide range of fragmented industrial sectors. These national industrial zones have contributed a huge economic outcome. In 2010, the total GDP of the 90 national industrial zones achieved 2.68 trillion RMB. Their average GDP growth rate in 2010 was 25.8%. While the national industrial zones have immensely contributed to China's GDP, the intensive industrial activities also generate severe pollution and result in high energy consumption. To some extent, they even jeopardize the ecological security and health of local communities (for instance, land degradation, drinking water contamination and air pollution) (Geng and Zhao, 2009). The

EIP program provides new opportunities for these industrial zones to adjust their industrial structure and improve the environmental situation. It intends to stimulate intra-firm cleaner production and environmental management, and promotes inter-firm networks for sharing resource and exchanging waste.

The national EIP standards were issued in 2006 (revised in 2009 and 2013) for three types of EIPs: "sector-integrated" (i.e., mixed sectors), "sector-specific" (i.e., single industry center in anchor tenant), and "venous industry based" (i.e., recycling industries). Three ministries (including the Ministry of Environmental Protection, Ministry of Commerce, Ministry of Science and Technology) jointly evaluate the performance of the pilot EIPs according to the national EIP standard. The EIP standards have four groups of indicators: economic development, material reduction and recycling, pollution control, administration and management. Each group has sub-indicators and criteria. Appendix A shows the national standard for sector-integrated EIP. It should be noticed that the indicator of "average annual growth rate of industrial added value" is no longer mandatory since the latest revision in 2013. It implies that the requirements for economic growth are no longer the priority in the pilot national EIPs, but concentrate on environmental performance.

Until July 2013, 22 industrial parks had passed the evaluation and acquired the label of National Demonstration EIP, and the initiative of another 62 pilot national EIPs had been approved (MEP, 2013b). As the geographic location shown in Figure 1.7, 73% of the EIPs are located in eastern China. The rest are located in the central and western China, having 17% and 10% respectively. Among all the initiative and the approved EIPs, 82% are sector-integrate and 14% are sector-specific. One industrial park undertakes venous industry (i.e., recycling industry).

1.2 Problem description

So far, the national EIP program has been in force in China for over a decade. The practice of the national EIP program in China has shown that new EIPs built from scratch are less successful, which is the reason that the policy focus has been shifted to transform existing industrial parks (Shi et al., 2012b). Driven by government, the existing industrial parks are transformed in line with particular plans to improve their environmental performance (Shi et al., 2012b). In this planned model, local authorities propose the EIP planning that details how to match the flows around anchor tenants and build or retrofit public utilities, aiming to reduce pollution and resource consumption. This is a common EIP development model in China, especially in the national industrial zones. However, scholars are concerned that such planned

Figure 1.7 – Geographic distribution of the National Demonstration EIPs by 2013.

EIPs entail the risk that companies are not actually engaged, even though they are located nearby (Chertow and Ehrenfeld, 2012). Moreover, relying on command-and-control and mandatory environmental standards can only solve specific pollution problems, because it does not improve companies' attitude towards environmental responsibility (Geng and Zhao, 2009). The participating industrial parks have adopted various measures to implement EIP projects, while the effectiveness of the policy instruments differs (Tian et al., 2013; Zhang et al., 2010). Many pilot EIPs have made progress to improve environmental performance and energy efficiency, while there are also pilots that have shelved the program of eco-transformation. In some industrial parks, the policy instruments for EIP projects led to conflicts with other policies due to inefficient coordination by local authorities. In some cases, the necessary financial support was missing, which constrained the key projects and influenced company participation. In addition, some pilot EIPs overemphasize new technologies for pollution treatment. However, the technologies are bought but not appropriately used, which causes inefficient investments and disappointing environmental performance. Indeed, eco-transformation of an industrial park is more complicated than "matching and optimizing flows" because of the wider socio-technical context. As an economic and industrial site, an EIP is a system that involves various actors and interactions influenced by a set of rules. Even the same environmental policy instruments may get different results. We are curious about the underlying factors that determine an EIP's development. Empirical research from case studies would provide us substantial evidence to understand the mechanisms. To this end, an analytical framework is necessary to discover the required elements to frame the analysis of EIP research, aiming at generating useful insights to diagnose current EIP policies or make new ones. Moreover, lessons learned from ongoing EIP practices are crucial for other latecomer industrial parks to deploy environmental management.

1.3 Research questions

As we discussed above, an EIP involves various actors and their interactions. Besides, it is embedded in an institutional and a physical environment. The progress of pollution reduction and resource conservation is achieved by the system's performance as a whole. To steer such a system, we need to understand the features of an EIP and its mechanisms, in order to provide tailored policy intervention. Thus, in this thesis our central research question is:

How can industrial parks be eco-transformed in China?

Our research scope is at the park level and focuses on the activities and performance within the region of an industrial park. To answer the central research question, we also raise a set of sub questions that can guide us during the theoretical and empirical exploration. The sub research questions include:

1. How has the research on EIP evolved?
2. What elements are required to frame the analysis of an EIP?
3. How can the key activities that effectively shape the evolution of EIP systems be structured? How can the process of system development be tracked over time?
4. What policy instruments can stimulate the emergence of viable EIPs in China? How can the effects of policy instruments be evaluated?
5. What is the future of mature EIPs?

1.4 Thesis outline

The structure of the thesis is shown in Figure 1.8. In chapter 2, we intend to answer the first sub question. Since the EIP's research resides in the industrial symbiosis (IS) research field, we first track the evolution of the research

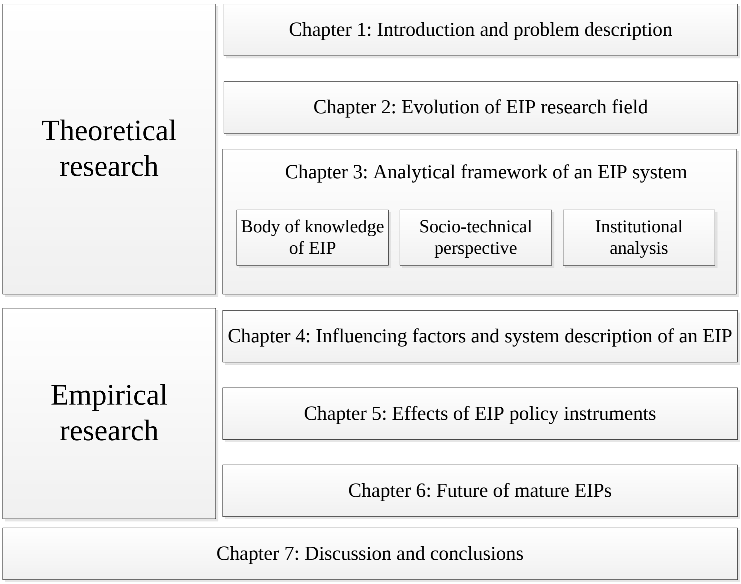

Figure 1.8 – Structure of the thesis.

on IS and EIP through bibliometric analysis. We elucidate its embeddedness in industrial ecology, trace the development of research themes and reveal the evolution of the research network through analysis of the core literature and journals that appeared from 1997 to 2012 by citation analysis, co-citation analysis and network analysis. Chapter 2 provides a knowledge map for the research on EIP and IS. It gives researchers an underpinned overview and may help to identify new directions in this research field.

The bibliometric analysis in chapter 2 has indicated the knowledge map regarding EIP's research. Then the coming question is: how can we bring the knowledge together to facilitate an EIP's development? Chapter 3 aims to discover the required elements to frame the analysis of an EIP. We intend to develop an analytical framework, aiming to integrate related knowledge from different perspectives. This framework can capture the representative features of an EIP and structures the analysis of an EIP's development process. In search of the analytical framework, we start from systems perspective and build a conceptual model to illustrate the actors and their interactions in an EIP. Moreover, we explore the institutional frameworks for analyzing socio-technical systems. In the end of this chapter, we synthesize a new analytical framework to direct our case studies of EIPs, with the aim to generate useful insights into the effectiveness of EIP policies. The analytical framework comprises of four building blocks: 1) influencing factors, 2) EIP system description, 3) system performance, and 4) evaluation. In the next chapters, we follow this framework to structure our empirical research on three Chinese industrial parks. The analysis in each chapter has different focal points directed at different sub research questions, thus the different components of the framework will be emphasized in the three case studies. Nevertheless, the analysis in each chapter is linked to the central research question from different perspectives: how can industrial parks be eco-transformed in China?

In chapter 4, to answer the third sub question, we present a process analysis approach that enables analysts to trace and structure the key activities that influence changes in an EIP system. This approach rests on five key activities that affect EIP changes and development: (1) institutional activity (2) technical facilitation (3) economic and financial enablers (4) informational activity and (5) company activity. We apply this approach to an ongoing case - the Tianjin Economic-technological Development Area (TEDA) in China, which allows us to build a structured database of activities to analyze its eco-transformation from 2000 to 2011. Moreover, we also use the conceptual model developed in chapter 3 to sketch out the EIP system structure of TEDA in two stages. In this way, the different roles of actors are presented to show how the system changes.

Chapter 5 focuses on the effects of policy instruments for developing viable EIPs in China. We study the general instruments available for local authorities to shape and promote eco-industrial development. Empirical research in two cases, TEDA and Dalian Development Area (DDA), identifies the activities and actions conducted by local authorities. A quantitative method for comparative analysis, TOPSIS, is adopted to reveal the effects of policy instruments.

Chapter 6 answers the question: What is the future of mature EIPs? Is it possible that eco-cities may be the next generation of eco-industrial parks? We aim at understanding what conditions that an eco-industrial park may provide for eco-city development. To this end, empirical research is conducted in Suzhou Industrial Park (SIP), where we analyze how it has been transformed to an EIP and what effect this has on the associated urban functions. The policy instruments and environmental infrastructures are inventoried and analyzed to deduce how SIP improves energy efficiency and reduces pollution. Furthermore, we analyze the eco-efficiency and use decoupling theory to evaluate the environmental performance relative to economic growth.

The synthesis of the empirical research in three EIPs is discussed in chapter 7. The three cases had several similar features when they started the EIP program. However, during the eco-transformation, the three industrial parks have revealed different trajectories and performance. Section 7.1 elaborates what insights we can draw from the EIP development in TEDA, DDA and SIP. Recommendations for making policies of eco-transformation are proposed in section 7.2. In the end of chapter 7, we conclude to answer each research question. Furthermore, we also reflect on the limitations and formulate a future research agenda.

2

Understanding the evolution of industrial symbiosis research: a bibliometric and network analysis (1997-2012)

This chapter has been published as Yu, C., Davis, C., Dijkema, G.P.J., 2014. Understanding the Evolution of Industrial Symbiosis Research. Journal of Industrial Ecology 18,2.

2.1 Introduction

Eco-industrial park is in the research field of industrial symbiosis (IS). IS is one of the key concepts and research areas within Industrial Ecology (IE) (Lombardi et al., 2012). The most cited definition is from Chertow (2000, pp.314) who pointed out that IS:

"engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and by-products."

As the field emerges in theory and in practice, IS activities are not limited by geographic proximity. Indeed, Lombardi and Laybourn (2012, pp.31) proposed a new definition emphasizing that:

"IS engages diverse organizations in a network to foster eco-innovation and long-term culture change. Creating and sharing knowledge 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."

As with the interdiscipline of IE, it appears that the IS idea and subsequent research started from the inspiration of biology and ecology, and from a drive to develop more sustainable production systems (e.g., (Allenby and Cooper, 1994; Côté and Hall, 1995)). The early publications mentioning IS can be traced back to 1990s. These were mostly inspired by eco-industrial park (EIP) projects especially the one in Kalundborg. According to the Eco-efficiency Task Force Report by the US President's Council (1997) on sustainable development, an EIP is defined as:

"a holistic community of businesses that cooperate with each other and with the local community to efficiently share resources (information, materials, energy, infrastructure and natural habitat), leading to economic gains, improvements in environmental quality and equitable enhancement of human resources for business and the local community."

In line with the principles of IE and economics of industrial clusters, the publications discussed co-siting, planning and designing of EIPs, exchanging wastes, "islands of sustainability" and the successful recipe of Kalundborg (e.g., (Lifset, 1997; Erkman, 1997; Engberg, 1992; Lowe et al., 1996)). These researches employed the existing theories at the time to explain the new forms of industrial activities and further brought out new questions about intra/inter firms' environmental management and regional development.

Almost two decades have passed and IS has also matured from case-by-case research towards a field that is more theoretical, systematic and diverse. There is attention given to IS-theory building and the issue of local versus worldwide applicability and reproducibility of IS concepts for practical implementation. The *Journal of Industrial Ecology* (JIE) devoted a special issue to Industrial Symbiosis in 2012, which represents a thorough overview of the status of IS research. In the special issue, the definition of IS was re-interpreted based on the progress in IS research and practice as a tool to affect innovative green growth (Lombardi and Laybourn, 2012), and a three-stage model of IS development was synthesized (Chertow and Ehrenfeld, 2012). The editorial article summarizes the latest research about IS in the special issue into four aspects: testing the boundaries of IS, the role of information and other social factors, designing IS networks, and implementation of IS (Lombardi et al., 2012).

2.2 Research goals and research questions

With the general overview above, we wonder how the research field of IS has evolved in detail. Thus this study aims to obtain a holistic and quantitative overview of IS and to trace its evolution from 1997 to 2012. Meanwhile, the study will also inspect the research topics about IS summarized by the special issue and previous research align with those emerging from our analysis, and to what extent our analysis can complement it. We have addressed four research questions:

- What are the core literature and journals about industrial symbiosis?
- How is industrial symbiosis embedded in the field of industrial ecology?
- How have the research themes evolved in the last fifteen years?
- Who are the key authors and what is their collaboration network?

To answer these questions, we have used bibliometrics, a suite of approaches and quantitative methods to analyze the patterns in scientific literature. Together, these provide a holistic perspective to objectively classify and analyze literature. Citation analysis and co-citation analysis are the common techniques used to reveal the impact of a literature or an author (Garfield, 1979). The overview is augmented by a network analysis of the authors that together constitute the IS research community. We will continue with an introduction about the methods mentioned, data acquisition and detailing the research tools. Second, we will present and interpret the results of the citation analysis of core literature and journals, co-citation of literature, keywords and author networks. To conclude, we will discuss the results with an emphasis on past, present and future IS research themes and directions.

2.3 Methods

2.3.1 Bibliometric methods

Citation analysis is a widely used method of bibliometrics (Pilkington and Meredith, 2009). When writing a scientific article, authors cite the related literature to support their arguments. Thus citation implies a relationship between citing and cited works in a particular research area. It is argued that the more frequently cited an article is, the greater impact it has (Garfield, 1979). Currently, citation analysis allows one to identify core literature, journals, authors, source countries, institutions, etc. We used citation analysis to provide an overview of the core literature and journals about IS.

Co-citation analysis shows the frequency that two works are cited together in the same literature (Kessler, 1963). Frequent co-citation of two works is an indicator that they share the related subjects. Co-citation analysis thus can point out how articles are related within a body-of-literature and how strong these relationships are (Pilkington and Meredith, 2009). In other words, co-citation analysis can map the intellectual structure of a research field (Pilkington and Meredith, 2009). The core themes of a research field can be identified through analysis of the links in a cluster of articles, mapping these links and establishing the importance and proximity of topics (Chai and Xiao, 2012). As a research field develops, co-citation patterns change as the themes addressed by and interests of researchers change (Small, 1973). Furthermore, author co-citation analysis reveals the cognitive realm of a field by showing the consensus of citers to important contributors and works, as well as schools of thought (White, 1990). In this study, we analyzed core literature co-citation and keywords co-occurrence to understand the evolution of the main research themes.

Co-authorship analysis can imply a strong social bond of the researchers who share similar interests compared with citation and co-citation networks, because the latter can happen without authors knowing each other (Liu et al., 2005). Thus a co-authorship network is used to discover the academic collaboration and schools of thoughts (White, 1990). We used co-authorship analysis to demonstrate the research groups and international collaboration in the area of IS.

Network analysis maps and measures the relationships among interacting units (Wasserman and Faust, 1994). It serves as a lens on the insights underlying a network of nodes and links through which information or social relationships travels. We applied it to a network established with the nodes that represented articles, keywords or authors, to evaluate the importance and influence of a node by means of measuring the centrality of a node in the network. Thus employing the advantages of network analysis, we mainly used degree centrality as a metric. Degree centrality is defined as the number of direct links that a node has and indicates the importance of a node in the network (Wasserman and Faust, 1994). The larger the degree centrality, the more important the node is and the more it can plays the role of a “hub”. By sorting the degree centrality, the importance of articles, keywords and authors has been determined.

2.3.2 Data acquisition and clean-up

We used the literature exported from Scopus[1] to compile our literature dataset. While we focused on these, other sources could also have been used to collect the literature data, such as Web of Knowledge[2] and Google Scholar[3]. Our preliminary study showed that the data from Scopus is the most comprehensive and standardized when exporting data. The Scopus data we used consisted of all the results returned by searching for the keywords "Industrial ecology" OR "Eco-Industrial Park" OR "Industrial Symbiosis" in the "article title, abstract and keywords". The data spans the period from 1997 to 2012. The terms of the exported data can cover rich details from citation information, bibliographical information to funding details. The information we selected for the data set includes author data, keywords, article metadata, references and citations.

Several techniques were used in order to clean up the data. One issue encountered is that the keywords listed in articles do not adhere to a standard. As a consequence, many slightly different variants of what are in essence the same keywords are found, such as "Life Cycle Assessment" and "Life Cycle Analysis", "Eco-industrial park" and "Eco industrial parks". To address this, the "Cluster and Edit" feature of Google Refine[4] was used. This is a sophisticated data evaluation and cleanup utility that has been made available for download by Google. It employs various fuzzy string matching algorithms that can identify clusters of keywords like these and allow for a standard preferred keyword form to be chosen. The same technique was applied to author names and the titles of references. A further issue was that a reference to an article may have two or more different forms that could not be identified as being the same via this technique. We therefore transformed the form for all those references that share the same Digital Object Identifier (DOI) into a single standard form. A similar strategy was employed for all references with the same title, but for which only some had a DOI specified.

This post processing of the literature data was necessary to reduce the number of duplicated entities that occurred in the analysis. Without clean-up, it is possible that a reference, keyword or author is seen as being less popular than it really is due to the dilution caused by remaining present as more than a single instance in the data.

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[1] http://www.scopus.com/home.url

[2] http://apps.webofknowledge.com

[3] http://scholar.google.com/

[4] http://code.google.com/p/google-refine/

2.3.3 Research tools

We used BibExcel[5] to analyze bibliometric data and used Gephi[6] to visualize the data network.

First, we imported the data from Scopus into BibExcel, a program designed for the analysis of bibliographic data, or any data of a textual nature that is formatted in a similar manner (Persson et al., 2009). With BibExcel one can complete a co-citation analysis by making pairs of the selected items, such as frequently cited literature and authors. To analyze the literature co-citations, we retrieved the references of the source articles. Visualizing the entire networks is not directly insightful as there are too many connections which make it difficult to see the underlying structure. Therefore, for producing the graphs, we selected only those references that were cited together more than twice to get the cleaner visualization. Then the co-occurrence function in BibExcel was used to pair the co-cited literature.

Second, the resulting data about the connections between literature, authors and keywords was imported to Gephi to compute and visualize the network of core literature, the layout, degree centrality and clustering. Gephi is an open source software for network analysis (Bastian et al., 2009). Aside from just showing the network in a graph, the size of the nodes was used to indicate degree centrality, meaning that larger nodes are the articles that are more frequently cited. The width of the links illustrates the strength of the tie between co-cited articles. The thicker a link is, the more frequently the two articles are cited together, indicating that their research is related. When being clustered, articles are located closer on the graph if they are frequently co-cited.

We applied the same method to analyze keywords co-occurrence and co-authorship networks. Just as we filtered the nodes and edges for co-citation analysis, the keywords from the source articles were selected where the two keywords about IS were used together more than three times. Moreover, the tag cloud (Halvey and Keane, 2007) is employed to visualize the importance of keywords. The bigger font size of a tag is, the more frequently this keyword appears. The co-authorship network was filtered to show only links between people who were co-authors more than twice. The larger a node is, the more frequently this author publishes articles with others. The tie strength between nodes represents the frequency of co-authorship. Thus a thicker link between two authors indicates that the authors have more in common in their research interests, and a higher frequency of collaboration.

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[5] http://www8.umu.se/inforsk/Bibexcel/

[6] https://gephi.org/

2.4 Results and analysis

2.4.1 Core literature

The first fifteen highest cited articles about industrial symbiosis are listed in the Appendix B. Chertow (2000) proposed the concept of IS and its position in the area of IE. At the inter-firm level, industrial symbiosis engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products (Chertow, 2000). Since the appearance of this article, the term industrial symbiosis has become widely used and IS has gradually developed into a research domain of industrial ecology. In the article, Chertow also reviewed EIP projects in terms of 5 types: through waste exchanges, within an organization, among firms in a planned EIP, among firms in an unplanned EIP, and a virtual EIP across a broader region. This classification provided a basic typology of EIPs. About how to stimulate an EIP, Chertow (2007) argued that "uncovering" existing symbiosis has led to more sustainable industrial development than attempts to design and build EIPs only considering physical exchanges. For either planned or spontaneous EIPs, three policy ideas were proposed to move IS forward during different stages of discovery: 1) bring to light kernels of cooperative activity that are still hidden; 2) assist the kernels that are taking shape; 3) provide incentives to catalyze new kernels by identifying "precursors to symbiosis" (Chertow, 2007). Frosch and Gallopoulos (1989) first raised the concept of industrial ecosystem and the analogy from biological ecosystem. The goal of IE is to create closed integrated industrial ecosystems (Frosch and Gallopoulos, 1989), unlike the linear production systems with no re-use or recycling. The research and practice of IS aims to flesh out this idea through establishing the synergies of waste and by-products exchange in an industrial cluster. As observed from the Appendix B, most of the frequently cited articles were based on practical EIP initiatives. Worldwide, the cases include Kalundborg in Denmark, EIPs approved by US President Council, the National Industrial Symbiosis Program (NISP) in the UK, national level EIPs in China and the port industrial areas in Netherlands. It has been clear that the creation of EIPs has become a strategic policy to reduce environmental impact in regional economic development. These articles described the process of implementing IS in various regions and reflected the experiences in material flow analysis, industrial park management and policy instruments.

2.4.2 Core journals

Appendix B shows the number of IS articles in the top 6 relevant journals. It shows an increasing trend of the number of IS articles overall. Currently, the core journals in IS are the *Journal of Cleaner Production* (total 58 articles), the *Journal of Industrial Ecology* (total 56 articles), and *Resources Conservation and Recycling* (total 13 articles). *Progress in Industrial Ecology* had 22 IS articles but has ceased publication since 2011. In the first period, the total number of publications was small and the only core journals were *Journal of Industrial Ecology* and *Journal of Cleaner Production*, each having 13 articles. As more articles were published about IS, the publications became more professional and centralized on four core journals. A rise in the number of articles in the *Journal of Industrial Ecology* appears in 2012 because of the special issue about IS. It implies that the academic community of IS has evolved, which is also indicated by that Industrial Symbiosis/Eco-Industrial Development (IS/EIDC) has become a section of the International Society for Industrial Ecology (ISIE).

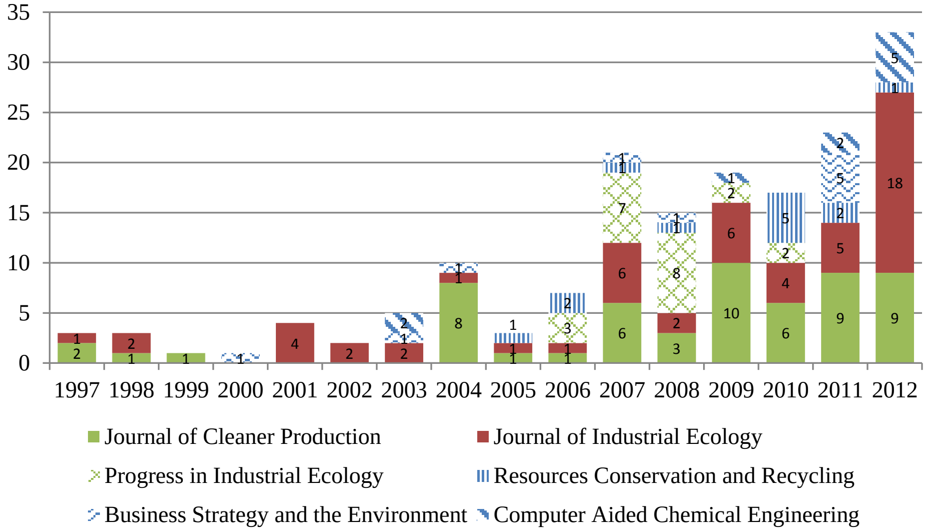

Figure 2.1 – Number of the articles about industrial symbiosis in the relevant journals from 1997 to 2012 (Top six journals). Source: Scopus.

2.4.3 Research themes in the two periods

The last section sketched the highest cited literature and core journals from 1997 to 2012. This section will focus on the changes of research themes in the field of IS in period 1 and 2, through analyzing the literature co-citation and keywords co-occurrence networks.

The research themes were discovered by co-citation analysis through checking two articles co-cited by another article. Thus we used the reference data of the source articles. A total of 1339 source articles and the corresponding 39122 references were extracted for the period from 1997 to 2012. Preliminary research using Scopus revealed a significant increase in the growth of the number of citations since 2006. In addition, the number of the IS articles in Figure 2.1 also shows the increasing trend from 2006. Therefore, we decided to divide the development of IS into two periods, 1997-2005 and 2006-2012. The first period has 383 articles including 9445 references and the second period has 956 articles including 29677 references. This section will discuss the changes of research themes and the underlying explanations.

We visualized the data in two steps. First, the entire dataset was used to show how IS is embedded in the field of IE. Subsequently, we zoomed in to the data only about IS to observe the research themes in this domain of IE. As mentioned above, we have used Google Refine to standardize the keywords. The fact remains, however, that co-citation analysis of keywords is influenced by the wording habit of authors. Nevertheless, keywords still reflect how researchers define and position their work in the field of IS. Therefore we used the keywords co-occurrence analysis to augment literature co-citation analysis.

Period 1

Figure 2.2 shows the research clusters in the network of the entire Industrial Ecology literature as revealed by co-citation analysis. The cluster of IS (the red nodes) is relatively scattered and close to Waste Minimization and Recycling and Industrial Ecosystem. The early research of IS incorporated the ideas from waste treatment and recycling which can be traced back to the 1860s (e.g., (Simmonds, 1862) and (Koller and Stocks, 1918)). The theories about industrial ecosystems were adopted to define an eco-industrial park system, illustrated by the links between (Korhonen, 2001) and (Chertow, 2000) and between (Allenby and Cooper, 1994) and (Ehrenfeld and Gertler, 1997). Besides, IS is loosely and indirectly connected with other research themes of IE, such as Supply Chain Management, Life Cycle Assessment (LCA) and Material Flow Analysis (MFA), Exergy and Entropy. The connection is linked through the nodes of Strategies for Manufacturing from Frosch and Gallopoulos (1989) and the research about the synthesis theory of IE (e.g., (Erkman, 1997; Graedel et al., 1995)).

As we focus on the research themes within the industrial symbiosis do-

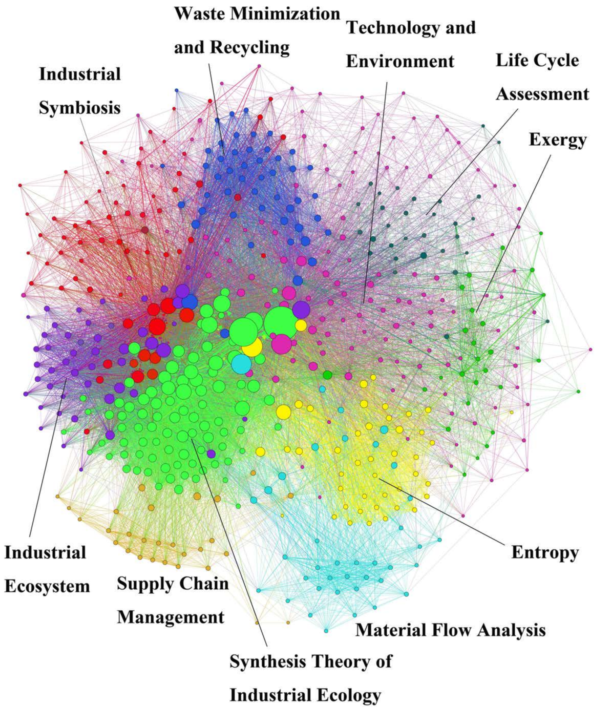

Figure 2.2 – Position of industrial symbiosis (red nodes) in period 1 among the research clusters of industrial ecology.

main, Figure 2.3 illustrates how the core literature about IS in period 1 relate through co-citation analysis. In the starting period, IS had neither become a systematic concept nor a widely used body-of-knowledge by researchers. Scholars were looking for the theoretical input from IE at large to explain their observations from industry about the exchange of waste, by-products and energy. Waste minimization and recycling, industrial ecosystem and eco-industrial parks constitute the dominant network in Figure 2.3. The biggest node in the center is Chertow (2000). As mentioned before, this article proposed the concept of IS and it was often co-cited with early articles. The Kalundborg EIP in Denmark, as a typical case in the early period, drew the attention from academia and industry alike about its ecosystem, initiative, conditions, evolution and duplicability. After critically examining Kalundborg, Ehrenfeld and Gertler (1997) pointed out that the case of Kalundborg was not easily transferred to other locations due to several barriers, involving the transaction costs of searching for suitable waste or by-products, profits on the material flows, the technical problem of continuous sources of feedstock, and the cognitive capability of firms. In the meantime, the features of an EIP were debated based on the projects mainly in US and Canada (Chertow, 2000; Lowe et al., 1996; Côté and Cohen-Rosenthal, 1998; Lowe, 1997). Either for Kalundborg or for developing other EIPs, a detailed study of the material flows and a thorough evaluation of the economic and policy aspects appeared necessary (Erkman, 1997; Côté and Cohen-Rosenthal, 1998).

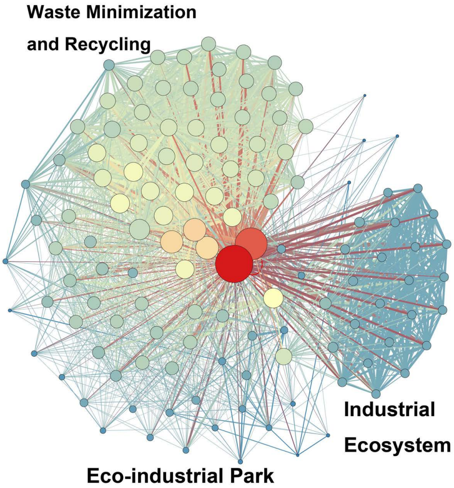

Figure 2.3 – Network of the core literatures about industrial symbiosis in period 1.

The tag cloud (Figure 2.4(a)) shows the frequency of keywords related to EIP/IS in period 1. The top five were IE, EIP, ecology, LCA and environmental impact. The connection of research themes is indicated by the keywords co-occurrence in Figure 2.4(b). The biggest nodes are LCA, MFA and IE, which means that these three keywords were frequently used with other keywords. The second important group has the nodes of "environmental impact", "recycling" and "ecology". The keywords of IS and EIP were not the most frequently used with others. The size of IS is relatively small, which implies that the term of IS was not widely used yet and it had not become an individually recognized research domain in IE. The thickest links reveal that the popular topics in period 1 were "practical EIP projects" and "principles of IE and sustainable development". Other research themes around EIP and IS involved "waste management", "ecosystems" and "industrial economics".

Period 2

In period 2, the domain of IS was tightly gathered together while at the same time became connected with more diverse research clusters. Apart from LCA, MFA and ecosystem in IE, some new theories were particularly incorporated

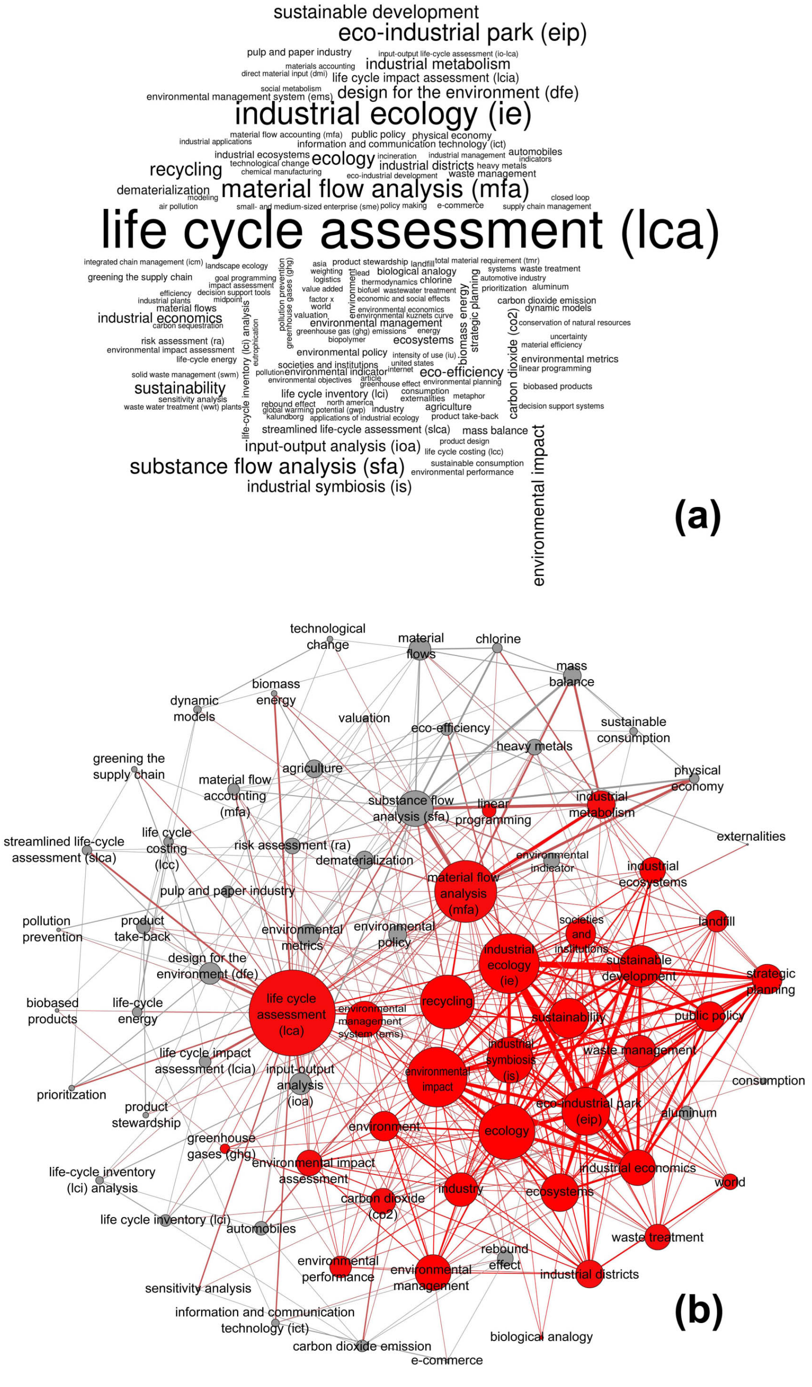

Figure 2.4 – Keywords occurrence (a) and co-occurrence (b) related to eco-industrial park / industrial symbiosis in period 1. The red nodes in (b) are directly connected with industrial symbiosis and eco-industrial park.

by IS (see Figure 2.5). Regional Economy and Economic Geography explain the agglomeration effect of co-location and the role of EIPs in regional development and environmental performance (e.g., (Porter, 1998; Harrison, 1992; Desrochers, 2002)). Theories from social science appear on the scene. Researchers address EIP management and how to stimulate symbiosis networks through organization management, regulation and policy (e.g., (Boons and Howard-Grenville, 2009; Korhonen et al., 2004; Ashton, 2008)). Moreover, wastewater management has become a theme related to the design of water systems for an EIP.

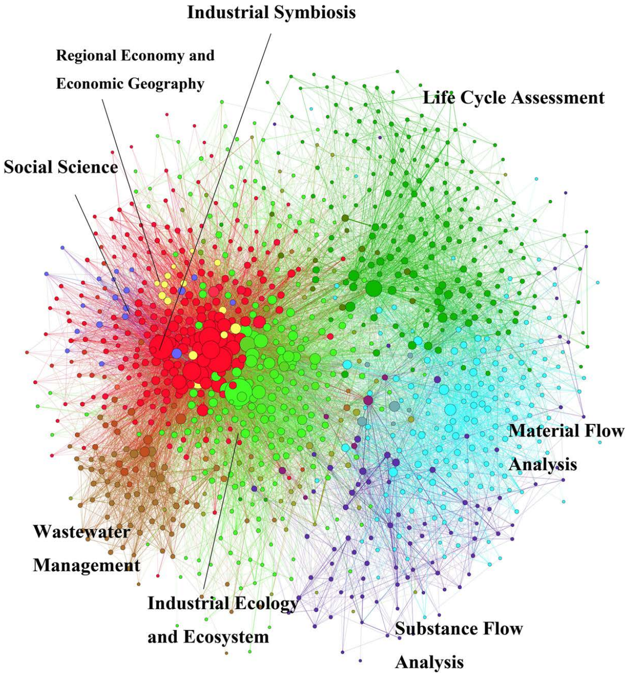

Figure 2.5 – Position of industrial symbiosis (red nodes) in period 2 among the research clusters of industrial ecology.

Figure 2.6 shows the network of IS literature co-citation is dominated by eight clusters in period 2. The new central nodes and connections reflect the research progress and the adoption of more diverse research themes. In this period, Chertow (2007) has become one of the largest nodes. In this article, Chertow addressed the importance of uncovering existing IS. Based on the cross case studies of planned and self-organized EIPs, the work reported by Chertow (2007) has a central position in the co-citation network. In retrospect, this may be because it pointed out two important points of IS research: the unsuccessful planned model of EIP from scratch and the role of kernels of symbiosis represented by business links as preconditions for further symbiosis opportunities. Moreover, Chertow's article suggested to adopt a policy of identifying and nurturing early-stage precursors of IS, which influenced other research themes, especially the research on assessing EIP-related policies and how to stimulate synergies through policy instruments. This is indicated by the strong connections with (Jacobsen, 2006), (Heeres et al., 2004), (Gibbs and Deutz, 2007) and (Mirata, 2004). More symbiosis cases were unveiled in period 2, for instance, the Australian minerals industry (van Beers et al., 2007), Ulsan EIP in Korea (Park and Won, 2007), national level EIPs in China (Shi et al., 2010; Geng, Zhang, Côté and Fujita, 2009), NISP in the UK (Paquin and Howard-Grenville, 2009) and the eco-town program in Japan (Ohnishi et al., 2012). These empirical studies about EIP practice provided more evidence and various models to establish the theories for IS. Wastewater management, another significant cluster in Figure 2.6, was adopted to optimize and design the water systems in EIPs (Chew et al., 2009; Aviso et al., 2010). In period 1, the question about how to measure and evaluate IS was raised. As the research evolved, the methods from environmental standards, optimization, LCA, MFA were applied to quantify and evaluate IS on economic performance, resource and energy efficiency (Ohnishi et al., 2012; Chen et al., 2012; Geng et al., 2008; Mattila et al., 2010). New research themes emerged, such as social network analysis and the circular economy in China. The strong connections between (Boons and Howard-Grenville, 2009), (Ashton, 2008), (Chertow and Ehrenfeld, 2012), (Mirata, 2004), (Baas and Boons, 2004) and (Costa and Ferrão, 2010) indicate that researchers started to focus on trust, common understanding, the role of coordinator and government after examining the drivers and barriers of various EIP projects. The circular economy in China was officially legislated in 2008, involving three levels: intra-firm, inter-firms (EIPs), municipal and provincial level (eco-cities). The research about Chinese EIPs has accumulated plenty of lessons and knowledge to formulate the Circular Economy (Geng and Zhao, 2009; Liang et al., 2011; Yuan et al., 2006).

The keywords occurrence and co-occurrence in period 2 also present a booming of IS research (see Figure 2.7). Figure 2.7(a) shows the 5 most frequent keywords are IE, IS, EIP, industry and sustainable development. The network of co-occurrence in Figure 2.7(b) illustrates the research themes in period 2. IS, EIP and IE have turned into the biggest nodes, which indicates that IS has become widely used with other keywords in this period. The thick links tell that the biggest three nodes are frequently used together with circular economy, industrial ecosystem, LCA, MFA, recycling, and optimization. Around the central keywords, several new keywords have emerged to study

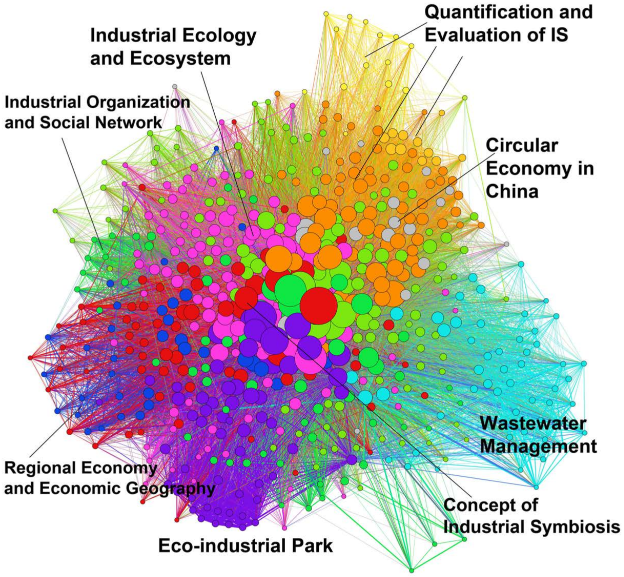

Figure 2.6 – Network of the core literatures about industrial symbiosis in period 2.

IS, for instance, wastewater reclamation, quantitative assessment, emergy, energy efficiency and game theory. One may note that names of particular regions appear in period 2 (see Figure 2.7), including China, United States, Finland, Sweden, United Kingdom, Kalundborg, Australia and Korea. They are directly linked with IS, EIP, and IE, which points out that an abundance of case studies have been done in these regions.

2.4.4 Co-authorship analysis

The visualization in Figure 2.8 presents a scattered network of the IS domain with eleven groups from nine countries. The three largest author nodes are Yong Geng, Yuichi Moriguchi and Tsuyoshi Fujita. They frequently co-author with other researchers. One cooperative cluster is centralized in Yong Geng and Tsuyoshi Fujita. This research group focuses on Asian eco-industrial development. The cooperation between Yong Geng and Tsuyoshi Fujita connects Chinese and Japanese research on waste recycling policy, waste management and CO_2 reduction. Additionally, the active collaboration among Asian researchers was also reflected in the third ISIE Asia Pacific Meeting in China, 2012. Another cluster consists of the UK and the US researchers. The specialty of the UK group is economic geography and regional industrial symbiosis. The US group, Marian Chertow and Weslynne Ashton from Yale University, has overlap with the UK group on agglomera-

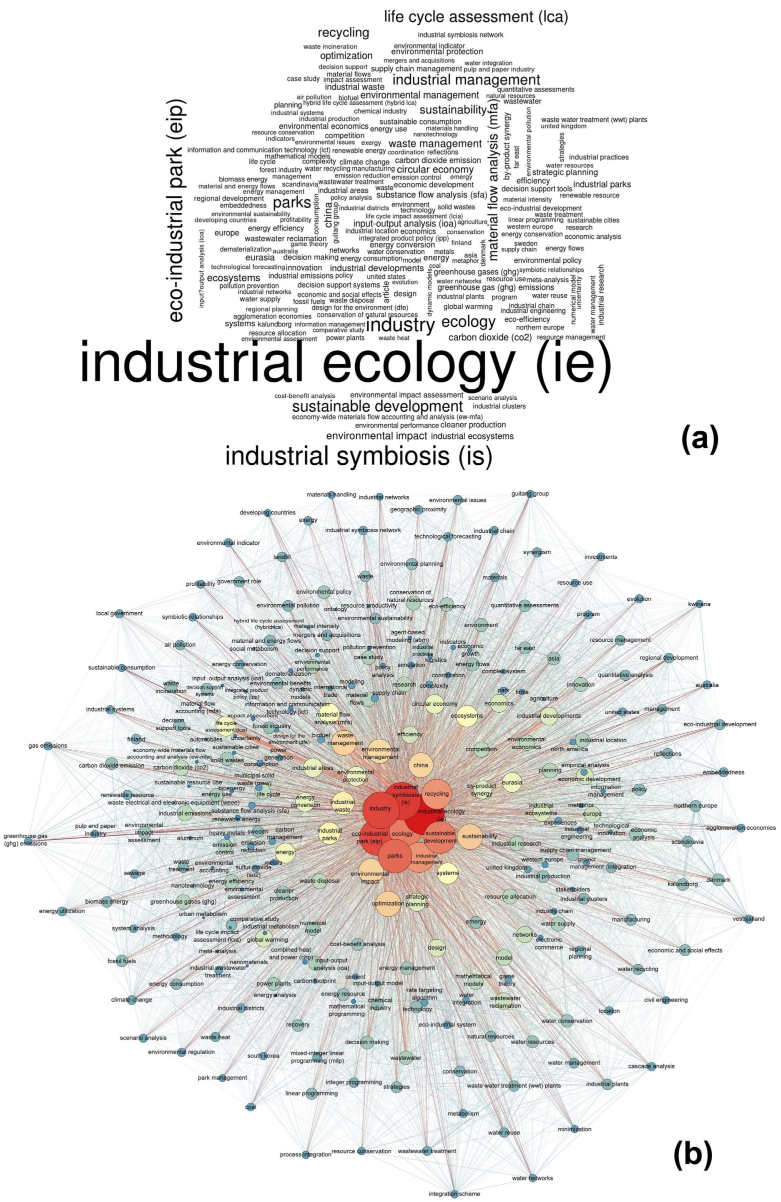

Figure 2.7 – Keywords occurrence (a) and co-occurrence (b) related to eco-industrial park / industrial symbiosis in period 2.

tion economies and regional industrial development. Besides, the group from the Finnish Environment Institute (SYKE) reveals the cooperation within the cluster. They analyze the IS activities in Finland through IS-type policy evaluation, LCA, and greenhouse gas emissions. Moreover, we checked the countries of authors' affiliations and indicated this in Figure 2.8. Indeed, the analysis confirms that research about IS is done by an international community spread over Europe, Asia, the US and Australia, where authors from different countries have communication and collaboration. Furthermore, all countries with a strong IS research community such as the UK, China and Japan, are also the ones that implement EIP programs or IS-related policies. Therefore plentiful demands and cases are provided for academics to explore and examine.

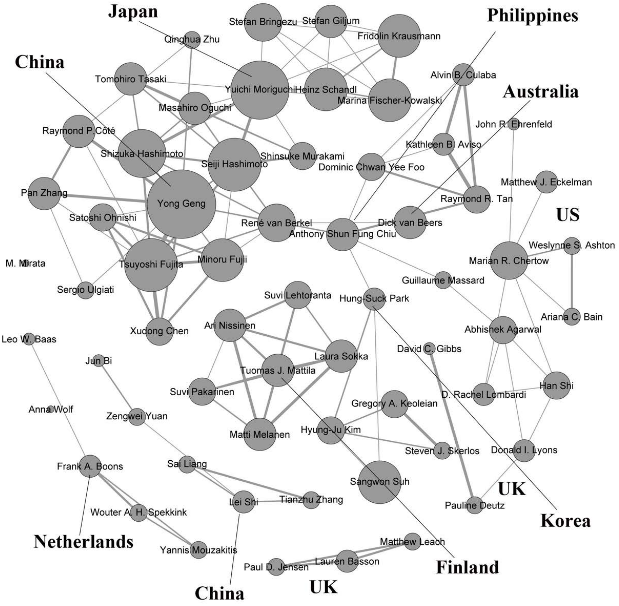

Figure 2.8 – Network of co-authorship and countries of authors' affiliations.

2.5 Conclusions

The body-of-knowledge on industrial symbiosis today is vast. Dividing the time into two distinct periods helped to map and elucidate the development of IS as a domain, the research themes explored and the emergence of a tightly connected international research community.

The analysis revealed that IS is a growing, diversifying and advancing research field. The top three cited articles, Chertow (2000), Chertow (2007) and Frosch and Gallopoulos (1989) remain essential reading. Chertow's articles brought up the concept of IS and the key of uncovering IS. Frosch and Gallopoulos proposed the goal of IE and the metaphor of industrial ecosystem. Next, the analysis of core journals revealed that in phase 1 the *Journal* *of Industrial Ecology* and the *Journal of Cleaner Production* were the core journals; these remain leading in phase 2 accompanied by two other journals, a development that indicates the growth of the academic community of IS.

Integrating the analysis results of literature co-citation and keywords co-occurrence, we conclude that in phase 1 IS held a minority share of research in IE while being only loosely connected with the two major concepts (LCA and MFA). The research themes were about the concept of IS, assessment of EIP projects, waste treatment and recycling. The topics about IS in the early phase were practice-oriented, based on the experience and observation from empirical projects. In phase 2, the term of industrial symbiosis gradually became widely accepted and new research approaches and theories enriched the field to analyze and stimulate IS. Amongst others, these include Economic Geography, the methods of LCA and MFA, policy intervention and evaluation, social network analysis, complexity and self-organization.

The analysis reveals the evolution of the IS field from practice-oriented research towards more systematic and diverse topics in theory building and worldwide practical implementation. It is an exploration that ranges from phenomenon description to underlying mechanisms. The academic communities about IS are distributed worldwide and have international collaboration. Our results confirm the summary of Lombardi et al. (2012) on the research and progress of IS in the special issue of JIE. The field is growing in breadth and is increasing the pace of integration between the social and natural sciences' approaches and literature both in theory building and tools (Lombardi et al., 2012). The trend from our analysis shows that the domain of IS is subdivided into five main disciplines: wastewater treatment and management, energy efficiency, solid waste management, self-organization of IS systems, and policy making and evaluation for IS and EIP projects.

Finally, this first use of the techniques of bibliometric shows that these methods and associated tools provide an overview of the IS research domain and contribute to our understanding thereof. We believe this kind of analysis will help researchers identify the academic community and relevant research articles and aid them in choosing the research topics and direction. However, the limitations still remain in this study. We searched the terms of IE, IS and EIP to identify and extract the source articles, which might miss the related ones which do not use these keywords. Additionally, Scopus does not cover all types of sources, such as theses and books. Further work can be conducted to compile more sources and use different bibliometric methods to compare the results. Nevertheless, our work provides a starting point for understanding the status and progress of IS research community. To further share the knowledge, we have made the procedure of data processing and results available online for discussion[7]. As the field of IS develops, we expect that the domain will grow to become even more diverse, advanced and topical.

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[7] http://enipedia.tudelft.nl/wiki/Bibliometric_Analysis_IS

3

An analytical framework for an EIP system

3.1 Introduction

In the previous chapter, we have discussed the evolution of the research field of EIP and IS. It shows that the definition and research themes have been enriched as more empirical research has been conducted in industrial parks. Those figures of research themes in chapter 2 have clearly indicated that understanding the research questions needs multidisciplinary perspectives from material flow analysis, regional economics, economic geography, environmental science, etc. Meanwhile, it also implies that the knowledge needs to be further synthesized to integrate social and technical disciplines.

Thus, as we have the knowledge map, the coming question is: how can we bring the knowledge together from different perspectives to facilitate an EIP's development? Several researchers have mentioned that a systemic view is necessary to integrate social and technical elements. As Haskins (2006) and Erkman (2001) argued that a holistic sustainable development should account for the dimensions of social and cultural regimes, apart from considering the technologies to reduce pollution. Chertow and Ehrenfeld (2012) and Ashton (2009) proposed to link complex system theory, agglomeration economics and organizational theory to analyze an EIP in terms of its features and motivations. The theory building should lead to understand the mechanisms of self-organizing systems where actors accept norms that can enable collaboration, which can result in an IS network through interactions between system elements (Chertow and Ehrenfeld, 2012; Boons, 2008).

Indeed, in the real world, the realization of an EIP is more complicated than "matching and optimizing flows". As an economic and industrial site, an EIP is a system that involves various actors and interactions determined by a set of rules in a wider social, technical and economic context. Besides evaluating the data of economic and environmental performance, we also would like to understand the actors who can make changes in an EIP system and how to disentangle them in order to steer the system. Furthermore, as a dynamic system, EIP has different features in the different stages. The strategies need to be adjusted along with the system changes in order to provide tailored policy intervention.

Thus, chapter 3 aims to discover what elements are required to frame the analysis of an EIP. We intend to establish an analytical framework that can guide one to characterize an EIP system in terms of structures and analytical approaches. This framework can capture the representative features of an EIP and structures the analysis of an EIP's development process. In search of the analytical framework, we start from systems perspective and build a conceptual model to illustrate the actors and their interactions in an EIP. Then the long-term process of eco-transformation is portrayed from an evolutionary perspective. Moreover, we explore the institutional frameworks for analyzing socio-technical systems to build up the analytical framework for an EIP system. Finally, we elaborate how to apply this framework to direct our empirical case studies in the following chapters.

3.2 EIP from a systems perspective

Erkman (1997) summarized three key elements from various definitions of industrial ecology, including 1) a systemic view of all the components and their relations with the industrial economy and biosphere; 2) complex patterns of material flows and human activities within and outside the industrial system; 3) influence of technologies on the transition to a viable industrial ecosystem. Compared with traditional approaches of environmental issues, industrial ecology does not only concern the reduction of pollution in an individual company through technical solutions, but equally emphasizes the inter-relationships of business and society, and the influence of overall government policy (Erkman, 2001). Similarly, Wallner (1999) proposed that the most critical innovation of the industrial ecology concept is the level of inter-firm collaboration within the network of region-wide settled companies. In this respect, eco-industrial parks apparently provide an ideal research object to materialize the concept of industrial ecology as a whole system.

The goal of such a system should be to combine the ecological, economic and socio-cultural spheres and develop a culture of collaboration (Wallner, 1999). Towards this goal, a systemic network approach and interdisciplinary methodologies appear to be useful to accomplish regional sustainable development (Wallner, 1999). Haskins (2006, 2007) suggested to apply systems engineering to create a framework for analyzing an EIP's formation. Systems thinking provides an integrative way to quest how system results emerge from the interaction among various components within the system and between system and system environment (Asbjornsen and Hamann, 2000; Chappin, 2011). Systems perspective is useful because industrial symbiosis intends to generate larger systemic efficiency of material and energy use by interactions among diverse industrial actors. According to Haskins (2007), systems engineering can contribute to EIP's formation mainly in the following ways: 1) a unifying framework of a straightforward process to guide the formation; 2) coordination of diverse stakeholders who must collaborate to realize the final goals; 3) integration of the insights of experts from various disciplines; 4) monitoring trends, risk and opportunities.

Dijkema and Basson (2009) sketched the complexity of industrial ecology from the perspective of a socio-technical networks, as Figure 3.1(a) shows. "The dynamic connections between the social domain (including humans; their values, behavior; organizations and governance structures) and the technical or physical systems in which they operate and that they continue to bring into being (e.g., industries, infrastructure, markets)" should be considered to frame eco-industrial parks, industrial regions (Dijkema and Basson, 2009). They fleshed out the holistic roles of social actors, rules and physical elements in an industrial system integrating the principles of industrial ecology. Regarding the internal and external relationships of an EIP, Romero and Ruiz (2013) conceptualized a nested system to illustrate an EIP that is ruled by economic, social and natural systems (see Figure 3.1(b)). Influenced by these rules, companies in an EIP make decisions for their benefits, change the evolution of industrial networks and the systems where they are embedded in. Following a similar line of thought, Chertow and Ehrenfeld (2012) emphasized that the essence of a successful EIP is a self-organizing industrial network that can be pursued within a complex adaptive framework. In such a framework, systems of diverse components form stable structures as an industrial ecosystem with many interactive links that pass energy, materials, information and capitals. What is more important is the institutional setting to foster actor participation, otherwise the EIP projects may get hindered and hardly move forward. As Chertow and Ehrenfeld (2012) pointed out, the success of an EIP model depends on the degree to which member companies

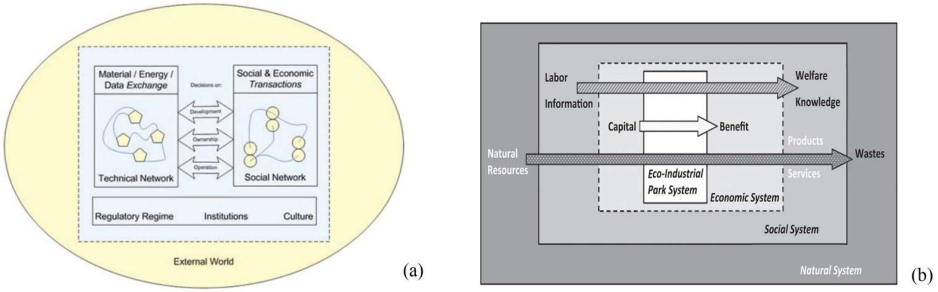


Figure 3.1 – (a) A socio-technical network - an interconnected complex network (Dijkema and Basson, 2009). (b) Industrial systems and its nested environment (Romero and Ruiz, 2013).

come to accept the norms and values that enable collaboration and inter-firm exchange.

Compared with systems engineering, the theory of socio-technical systems provides a comprehensive guidance to analyze an EIP which is a man-made industrial system following a set of rules and which is embedded in the natural, economic and social systems. A socio-technical system evolves through the interactions among a group of actors influenced by institutions (Ghorbani, 2013). Institutions are a set of rules that create incentives for behavior and structure behavior and interaction (North, 1990; Ostrom et al., 1994; Scharpf, 1997). Formal institutions are rules in the form of laws and regulations. Informal institutions are social norms, protocol or habits. Both formal and informal institutions can be effective as long as the institutions are enforced. These institutions, which are rules of the game, influence actors' decisions and shape their interactions.

The research mentioned above reveals that understanding how to realize an EIP first requires knowledge of its system configuration and the connections between system elements. It is the foundation to further analyze the mechanisms for steering an EIP's development. We are enlightened by the perspective of socio-technical systems to extract the elements and their relationships of an EIP. Table 3.1 summarizes the EIP system components found in the literature. Liwarska-Bizukojc et al. (2009) presented a model to conceptualize the minimal conditions required for establishing EIPs. Similarly, Costa and Ferrão (2010) used a set of parameters to structure IS development. Romero and Ruiz (2013, 2014) presented the building blocks and influential factors of an EIP system. Comparing these categories of an EIP's system components, we find that the former two research groups share similarities regarding the actors in an EIP. They both pointed out the essential actors (i.e., companies) and other related actors in the industrial community. Liwarska-Bizukojc et al. (2009) classified companies into producers, consumers and decomposers, thus illustrating an EIP as an industrial eco-system that can circulate and minimize resources and waste. The classification by Costa and Ferrão (2010) is more comprehensive, because it also includes policy makers, business associations and networks, and research institutes like universities. This conforms to the essential elements for initiating a general industrial cluster. In terms of interactive relationships, Liwarska-Bizukojc et al. (2009) summarized the material exchanges through mass and energy flow, as well as the business relationships of collaboration and competition. Romero and Ruiz (2013, 2014) proposed to analyze the companies' interactions through their properties of adaptive ability and behavioral rules. Moreover, they clearly pointed out the influential factors from multiple dimensions (see Table 3.1).

Liwarska-Bizukojc et al. (2009)	**Costa and Ferrão (2010)**	**Romero and Ruiz (2013, 2014)**
Structure of ecosystems: • Industrial community (organizations such as companies and associations) • Industrial habitat (infrastructures and resources)	Companies	Building blocks of an EIP system: • Companies (defined by specific properties or behavioral rules) • Groups of companies (to show the variability and heterogeneity) • Adaptive ability (companies assimilate and adapt to changes in surroundings) • Interactions among companies (to form a cooperative network)
	Government (e.g., economic incentives, regulations)	
Classification of enterprises: • Industrial producers • Consumers • Decomposers	Government organizations	Influential flows: • Environmental factors (natural environment, resources, waste stream) • Social factors (legislative and political, organizational, formative) • Economic factors (market, innovation and competitiveness) • Technical factors (infrastructural, technological and procedural)
Mass and energy flow	Private associations (e.g., business or environment associations)	
Interactions in the ecosystems (e.g., symbiosis and competition)	Universities	
	Business	

Table 3.1 – Components to conceptualize an EIP system (Costa and Ferrão, 2010; Liwarska-Bizukojc et al., 2009; Romero and Ruiz, 2013, 2014)

Based on the survey in the literature, we establish a conceptual model for an EIP system to illustrate the actors and the interactions following the perspective of a socio-technical system (see Figure 3.2). The design of this conceptual model is in line with the perspectives of Dijkema and Basson (2009) and Chertow and Ehrenfeld (2012) in terms of system configuration and the effect of institutions in an industrial ecology system. Our conceptual model intends to identify all actors and their internal and external relationships in an EIP system. This model integrates the classification of actors from Liwarska-Bizukojc et al. (2009) and Costa and Ferrão (2010) and adds more types of actors from our own observations in the field. In general, the actors of an EIP mainly consist of company, policy maker, coordinating body and research institute. Actors are embedded in the institutional environment that influences their decisions and actions. Thus, the institutions (i.e., formal and informal rules) are indispensable in the system configuration. Moreover, an EIP system is also nested in the external natural and economic environment. It needs to adapt to the changes in the external environment. This conceptual model of an EIP system is further explained as follows.

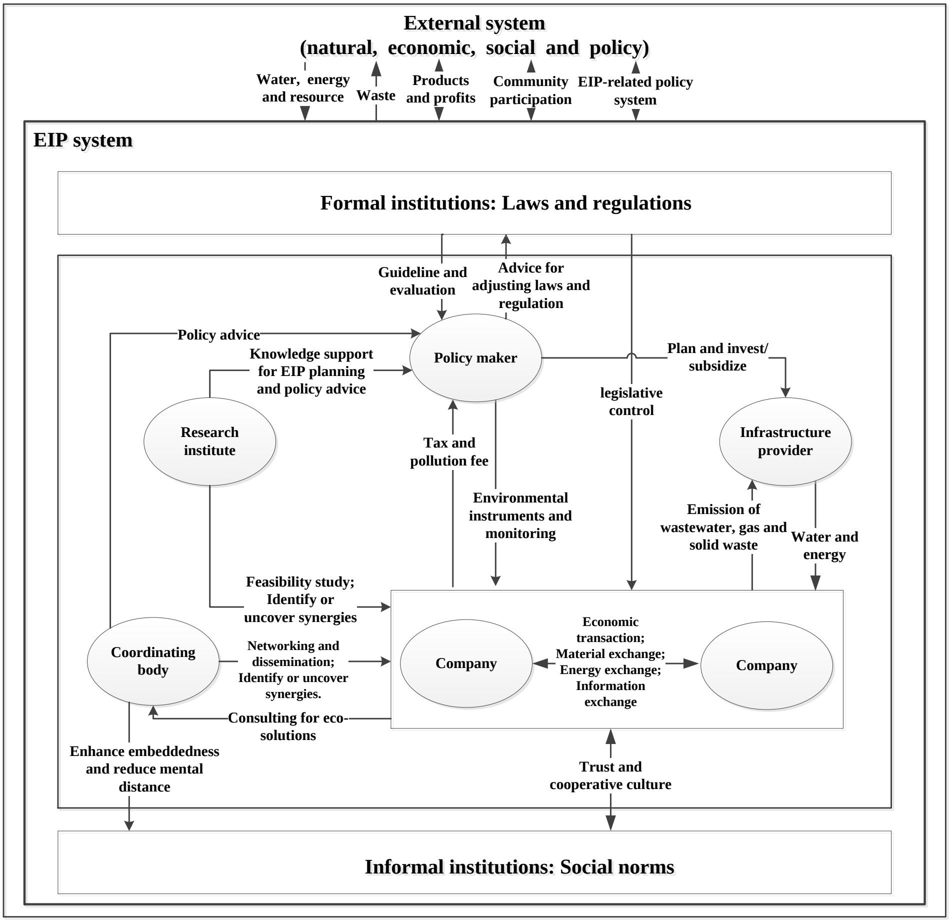


Figure 3.2 – A conceptual model to sketch an EIP system.

Actors in an EIP system

1. **Companies.** Companies are the core actors of an industrial site. The ultimate goal of environmental performance needs to be realized by companies who make decisions according to market rules and their own business routines. Thus, active company participation determines an EIP's realization and its continuous development. The implementation of an EIP needs to be operated as a profitable business project that the participating companies would like to spontaneously join, rather than the show-cases that only focus on environmental performance.

   According to the literature, four types of companies may play the key roles in an EIP system: industrial scavenger, industrial decomposer, anchor tenant and infrastructure provider (Geng and Côté, 2002; Korhonen, 2001; Liwarska-Bizukojc et al., 2009; Lowe, 1997; Tudor et al., 2007). An industrial scavenger is company that collects waste or reuses materials without extra treatment. An industrial decomposer is a recycling company that recycles materials to produce by-products or safely disposes of waste. From the perspective of industrial ecosystems, scavengers and decomposers are key actors to make the materials cycled in an industrial system (Geng and Côté, 2002). An anchor tenant is the large or leading company which provides the critical mass of materials or technologies that other related companies would like to locate around. It can influence the stability of an EIP. Furthermore, the infrastructure provider, as another type of companies in an EIP system, needs to be separately explained. The infrastructure provider is the company which constructs or operates infrastructures, such as wastewater plants and cogeneration plants. These infrastructures are the indispensable physical conditions for member companies to share utilities and improve the efficiency of energy and water usage. Infrastructure providers may receive subsidies from the government due to the large upfront investments in the early stage of building utilities. In some industrial parks, the infrastructures (e.g., cogeneration plant) can play the role of anchor tenant because the regional industrial ecosystem relies on the energy or water flows from the plants (Korhonen, 2001). The relationships among companies may involve competition and collaboration. The interactions of companies are in the forms of economic transaction, material and energy exchanges through business contracts. Meanwhile, information exchange (e.g., the collaborative opportunities of waste treatment) may also influence the occurrence and success of an EIP project.

2. **Policy maker.** A policy maker is the park management board or local authority that is responsible for recruiting tenants, managing and supervising economic, industrial development and environmental issues. The impact of policy makers may differ in different regimes. In an EIP system, policy makers can facilitate the investment in infrastructures (e.g., water, energy and transportation) that are vital criteria for companies when selecting a site to settle down. Furthermore, policy makers can steer the industrial site to adopt environmental principles through various policy instruments (e.g., tax reduction, subsidies, funding, regulation, performance standards) (Costa et al., 2010; Goulder and Parry, 2008). Meanwhile, monitoring and evaluation of environmental performance is necessary to enforce environmental principles and ensure pollution prevention performance.

3. **Coordinating body.** A coordinating body can be a business association or other organization that provides a platform for companies to exchange information and explore network. Using a coordinating body is an effective approach to disseminate and facilitate EIP projects (Boons and Howard-Grenville, 2009; Paquin and Howard-Grenville, 2012). Coordinators can play the role of catalysts to engage companies in joining EIP projects and strengthen the shared norms and perceptions (Chertow and Ehrenfeld, 2012).

4. **Research institute.** A research institute supports an EIP with knowledge input for the feasibility or environmental assessment to analyze the potential economic and environmental outcomes of synergies or technologies. Like a policy adviser, a research institute is often involved in EIP planning and policy design based on scientific research. Moreover, uncovering existing synergies may be assisted by experts through investigation and material flow analysis (Chertow, 2007).

Institutions

1. **Laws and regulations.** An EIP system has mutual impact with the external formal institutions. The environmental laws and regulations that are outside the system boundary still have legislative control on companies. The pressure from strict regulations or penalty fines will trigger companies to change their business models or industrial production. For instance, a higher landfill fee will stimulate companies to recycle waste in order to reduce costs. Meanwhile more recycling companies will appear in the system. In addition, many EIP programs are initiated by policies or political directives from the government (Gibbs

et al., 2005). The policy makers in an EIP system carry out the guidelines from higher level government through deploying localized policy instruments. At the same time, the results are assessed and fed back to improve the related higher level policies.

2. **Social norms.** Social norms in an EIP constitute a shared belief among all the actors that the efficiency of energy use and pollution prevention are necessary for the regional industrial system. Scholars have proven that social norms, such as trust and common understanding, are vital to establish and maintain an industrial network (Ashton, 2008; Boons and Howard-Grenville, 2009; Chertow and Ehrenfeld, 2012). The success of Kalundborg mostly benefited from the informal social relationships among managers, which reduced the "mental distance" and transaction costs (Ashton, 2008; Jacobsen and Anderberg, 2004). Company participation and collaboration can be stimulated if the norms are accepted by companies. Consensus about social norms can be facilitated by such as training and dissemination organized by coordinators.

External system

1. **Natural environment.** In an industrial site, industrial activities need to acquire water, energy and other resources from the natural environment for production. Wastewater, gas and solid waste are discharged to the natural environment. An ideal industrial ecosystem should be a closed-loop that can recycle and reuse the waste as resources in the system without external environmental influence (Graedel et al., 1995). Although many industrial sites cannot currently realize the complete closed-loop or zero emission, treatment facilities and recycling companies can significantly reduce the pollution of the natural environment. In addition, change in the natural environment (e.g., the aggravating air pollution and water scarcity) may push actors to take measures, such as adjusting environmental laws or policies and applying new technologies for better environment performance.

2. **Economic environment.** The external economic environment, such as the regional and global economy, has leverage to improve the environmental performance of companies in an EIP. The market is usually the interface across which an EIP system interacts with the external economic environment. For instance, the preference of consumers for environment-friendly products (e.g., products with eco-labels) is an

important driver for companies to improve their environmental performance in order to make economic benefits. Macro-economic development, such as the global financial crisis, also influences the economic activities in an industrial park.

3. **Social community.** Industrial parks are not isolated islands that only contain industrial activities. In terms of spatial location, they either become complexes of industrial and urban functions, or well connected with mother cities due to convenient transportation. Moreover, the pollution caused by industrial parks, especially in water and air, has regional diffusion that can influence nearby residents. As the awareness of environmental protection rises, people's concern for a safe and healthy environment will influence their choices to find jobs or select neighborhoods. Thus, the demand of residents needs to be considered in an EIP's development, which requires community participation in the policy making and the assessment of industrial projects.

4. **Policy system.** The policy system we refer to involves the formal institutions mentioned above (e.g., environmental laws and regulations) and the administrative organizations in the government that enforce these policies. These governmental organizations are in charge of supervising an EIPs' planning and evaluation. It is a comprehensive project that needs the joint work of various departments, such as environmental protection, finance, resource and land use, innovation and technology. Efficient collaboration and clear guidelines are necessary to facilitate EIPs. Furthermore, institutional capacity to enforce EIP-related policies is also critical. Some pilot EIPs are hardly initiated without substantial policy support. Moreover, some EIPs slack off after they get the titles of EIP due to a lack of continued supervision is lacking (Zhang et al., 2010).

3.3 EIP from an evolutionary perspective

Eco-transformation of an industrial park does not happen overnight. It is a process of change that involves interactions among actors nested in the institutional, natural and economic environments, as our conceptual model shows in Figure 3.2. During this dynamic process, the decisions of actors to exchange materials, share knowledge or adopt technologies to reduce pollution depend on certain preconditions and evolutionary mechanisms. From the perspective of evolutionary economics, a long-term development of economic activities emerges from the behavior of economic actors who select strategies to survive and adapt to the continuously changing environment with new technologies and organizations (Nelson and Winter, 1982). Lambooy and Boschma (2001) made efforts to link evolutionary economics to regional policy and elaborated what factors can influence the formation of an industrial cluster and how to make tailored regional policy. To steer a regional economic system, we need to be aware of the essential features that affect the decision making of economic actors: routines, path-dependency and selection mechanisms. Routines are the conventions that develop in social networks of people or organizations in a region (Storper, 1995). Making decisions is within the boundaries of existing routines and the accumulation of knowledge and experience, which forms path-dependency and influences the further trajectory (Lambooy and Boschma, 2001). When selecting strategies (e.g., to accept collaboration or not), companies follow both market rules (e.g., cost and benefit) and non-market factors (norms such as trust and common understanding) (Dosi and Nelson, 1994; Lambooy and Boschma, 2001). When making regional policies, policy makers should think about the preconditions of an industrial cluster and provide context-sensitive policy instruments (Asheim et al., 2013).

In the light of the concepts of evolutionary economics, EIPs also can be observed as evolutionary systems. Indeed, in the literature of EIP and IS, researchers have been studying the mechanisms to steer actors to realize IS networks in different development stages. Table 3.2 summarizes the stages, triggers and outcomes from the literature. It shows that the development of IS networks has relatively identifiable stages that are characterized by patterns of interactions among actors and policy interventions. We may get more generic insights through interpreting this from evolutionary perspective. When making incentive policies to foster IS networks, one needs to first dive into the analysis of the existing conditions. For instance, analysts may investigate the features of the industrial region (e.g., geographical location and industrial structure), resource scarcity and regulatory pressures that the local companies are confronted with. This information is useful to design localized policies. Then policy makers or coordinating bodies organize potential participants to build up a common understanding through disseminating knowledge and networking. This preparation stage ensures that the projects are in line with the routines of local companies, which makes it more logical for participants to accept collaboration or new technologies. Pilot projects should be short-term and easy to operate. Positive outcomes after evaluation would reinforce trust and increase the chances that companies select to continue the projects. In addition, it can also make demonstration effects to attract new participants. Such an evolutionary process can be recognized and analyzed to make suitable rules to steer the development.

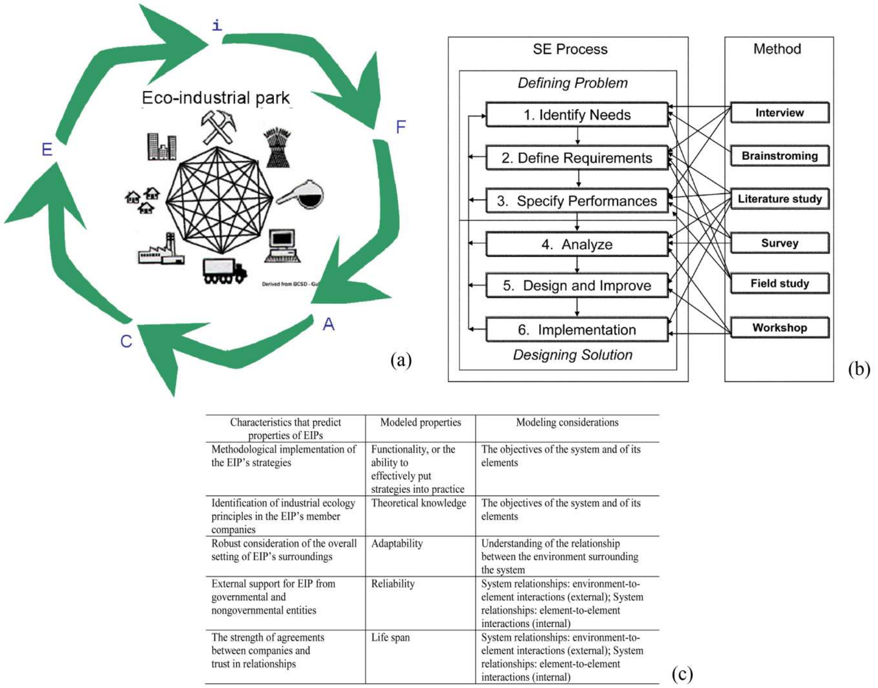
	Stages	Triggers	Outcomes
Three-stage model (Chertow and Ehrenfeld, 2012).	Sprouting	Economic efficiency. Regulatory pressure. Social relationships. Resource security. Supply chains of firms.	Firms begin to randomly exchange resources.
	Uncovering	An actor (e.g., a coordinator or local authority) whose focus is beyond the private transactional network observes and uncovers.	The realization of positive environmental externalities becomes consciously uncovered and pursued.
	Embeddedness and institutionalization	A coordinator engages potential symbiotic partners and strengthens the shared norms which can facilitate more complex exchanges.	Further expansion of the network becomes intentionally driven.
Stages of a facilitated IS network (Paquin and Howard-Grenville, 2012).	Primarily serendipitous processes	Taking strategic view of region's resources. Using pre-existing contacts to engage firms. Facilitating interaction spaces.	Firm's interest is captured and led to broader institutional awareness. Potential exchanges are found through workshops.
	Mix of serendipitous and goal-directed processes	Strategically introducing relevant firms around low-hanging fruit. Deepening involvement with firms and projects.	Deeper relationships, trust are developed. Firms are re-engaged in new exchanges.
	Increasingly goal-directed processes	Replicating high-value exchanges. Developing capacity around key regional resources.	Selected firms increasingly engaged around replicable exchanges. Selected complex projects to support future IS exchanges.
Building trust and embeddedness in the IS development (Doménech and Davies, 2011)	Emergence	Stringent regulations. Limited resources. Policy actors' initiatives. High coordination.	Formation of the network. Some straightforward cooperation opportunities are explored.
	Probation	Learning by doing. Implicit and explicit negotiation and cooperation. Potential IS exchanges are unveiled and tested.	Realization of first IS exchange projects. Generation of dynamics of cooperation and building trust. IS is gradually integrated in the decision-making.
	Development and expansion	Continuous and frequent interaction generates trust and builds a shard vision to develop embeddedness. Learning from past experience and tacit knowledge. Joint problem solving and exchange of fine-grained information assists to identify new IS exchanges.	Deeper embeddedness in the network. Attracting new members and opening up the potential for new exchanges. Diversifying the material and organizational base of the network.

Table 3.2 – Stages of IS development in the literature.

3.4 Frameworks for analyzing an EIP

The discussion above has revealed that analyzing an EIP system requires various aspects to be considered. We need an analytical framework which can guide analysts to identify an EIP's system components, influencing factors and mechanisms, and to evaluate the outcomes. Some frameworks for analyzing EIPs have been discussed as Figure 3.3 shows. Haskins (2007) raised an iFACE framework for the formation of EIPs. i represents "identify stakeholders and their needs"; F is "Frame the problems"; A is "Alternatives and options"; C is "Choose and implement a course of action"; E is "Evaluate continuously". The figures in the center of Figure 3.3(a) represent the diverse elements having interconnections in an EIP. Figure 3.3(b) demonstrates a framework for IS modeling proposed by Sopha et al. (2010). In line with the systems engineering process, they summarized 6 steps to create an industrial symbiosis model, including: identify needs, define requirements, specify performances, analyze, design and improve, and implementation. The underlying methodology of the two frameworks in Figure 3.3(a) and (b) is systems engineering that emphasizes the holistic thinking of system elements and their interactions, feedback loops, and redesign based on evaluation and adjustment. Romero and Ruiz (2013) described an integrated conceptual framework for modeling the operation of EIPs based on the understanding of complex adaptive systems, industrial ecology and the observation of existing EIPs. Figure 3.3(c) presents five key properties to be modeled to reveal an EIP as either a planned EIP or an evolved EIP through self-organization. It incorporates the features of complex adaptive systems that emerges from interactions among actors and adapts to changes in the surrounding environment.

These frameworks provide us with a systematic process to identify an EIP's system components. However, they have not yet revealed how to analyze the mechanisms that determine an EIP's realization. Apart from the system configuration, policy analysts also need to know the rules that influence actors' decisions in order to make appropriate policies for eco-transformation. As we have analyzed in the previous sections, the evolution of an EIP system emerges from the interactions among actors who are motivated by various rules. The strategies they select favor their own economic objectives and also bring about less pollution and resource consumption. These mechanisms need to be considered when we select various policy instruments and explain the underlying reasons of policy results. Thus, to study an EIP which is a socio-technical system, an analytical framework should be both rooted in the systems perspective and institutional analysis. Our contribution is the



Characteristics that predict properties of EIPs	Modeled properties	Modeling considerations
Methodological implementation of the EIP's strategies	Functionality, or the ability to effectively put strategies into practice	The objectives of the system and of its elements
Identification of industrial ecology principles in the EIP's member companies	Theoretical knowledge	The objectives of the system and of its elements
Robust consideration of the overall setting of EIP's surroundings	Adaptability	Understanding of the relationship between the environment surrounding the system
External support for EIP from governmental and nongovernmental entities	Reliability	System relationships: environment-to-element interactions (external); System relationships: element-to-element interactions (internal)
The strength of agreements between companies and trust in relationships	Life span	System relationships: environment-to-element interactions (external); System relationships: element-to-element interactions (internal)

Figure 3.3 – Frameworks in the literature for analyzing an EIP. (a) iFACE framework for EIP formation (Haskins, 2007). (b) Framework to create a model of industrial symbiosis (Sopha et al., 2010). SE process means Systems Engineering process. (c) Properties to be modeled and modeling considerations for an EIP. The system is the EIP and the elements are companies within the EIP (Romero and Ruiz, 2013).

combination of institutional analysis with the analytical framework for EIP development.

To conduct institutional analysis, Williamson (1990) proposed a three-layer schema for analyzing the economic organization. It consists of three levels: institutional environment, governance and individual actors. The schema also presents the mutual relationships how components influence each other. Later, this three-layer schema was expanded to four layers through further dividing up the institutional environment into informal institutions (social embeddedness) and formal institutions (Williamson, 1998). Williamson's frameworks pointed out the focal points and the related theories for economic institutions at the different levels.

Emphasizing actor behavior, Scharpf (1997) and Ostrom et al. (1994) analyzed how institutions affect the decision making of actors and how actors in turn change the institutional environment. The framework of actor-centered institutionalism proposed by Scharpf (1997) highlights the role of actors who can determine the outcome of policies by their choices. It assumes that actors have action orientations and capabilities to make purposeful choices. In addition, actors have both rational strategies and irrational preferences. Actor-centered institutionalism is used as an analytical framework for conducting empirical study on governance and self-organization, especially in the field involving state intervention (Scharpf, 1997). The intention of this framework is to distinguish the analysis of actor-related factors and the effects of institutions. When analyzing policy issues, Scharpf (1997) suggested to start from identifying the interactions of actors and then move to analyze the institutions that influence actor behavior.

Also focusing on actors and institutions, the Institutional Analysis and Development (IAD) framework of Elinor Ostrom is more comprehensive because it connects these concepts with other aspects of a socio-technical system (Ghorbani, 2013), such as the physical world and the community. As Figure 3.4 illustrates, the components of IAD can decompose a social, technical and ecological system. The action arena, where the actual interactions of actors happen, is the core of IAD and also the focal point of policy analysis and design. It consists of actors who have certain preferences in action situations. Action situation is the social space where actors interact, exchange goods and services, solve problems and dominate one another (Ostrom, 2005). The action arena is affected by three exogenous variables: 1) the rules used by actors to direct their behavior, 2) the physical world and 3) the more general community where a particular arena is placed. The patterns of interactions and outcomes can be identified and evaluated after analyzing the action arena. Furthermore, the outcomes are fed back to influence the exogenous variables and arena.

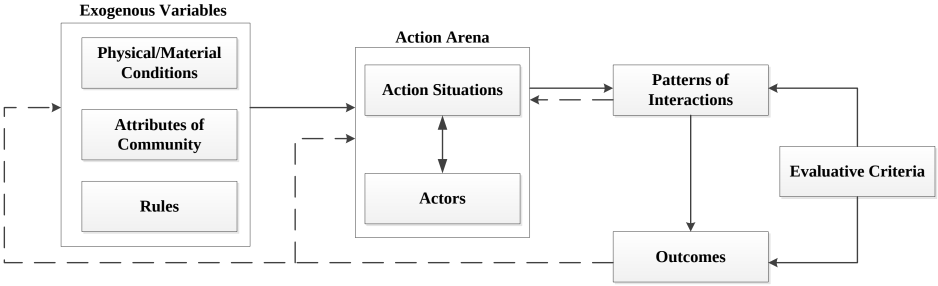


Figure 3.4 – Institutional Analysis and Development (IAD) framework (Ostrom, 2005).

As we have analyzed, the debates on realization of EIPs focus on how to build up effective and appropriate institutions in a particular physical and social environment to steer the actors to incorporate the goals of an EIP in their decision making. Our conceptual model in Figure 3.2 also indicates the connections with the external system, such as nature and social community. Therefore, the IAD framework is suitable to guide our exploration. In policy analysis, IAD can be used as a tool for policy analysts who need to design new policy interventions, evaluate policy effectiveness, or initiate policy reform (Ostrom et al., 1994; Polski and Ostrom, 1999). Following IAD in a systematic way, policy analysts need to keep each component in mind, which may avoid the oversights and simplifications that lead to policy failures (Polski and Ostrom, 1999). Polski and Ostrom (1999) proposed two approaches on how to apply IAD to the different objectives of policy analysis. The first approach is for designing new policy initiatives or comparing alternative policies. It starts from investigating exogenous variables (i.e., the physical world, community and rules) and works forward through the IAD diagram. Table 3.3 shows 7 steps involved in conducting a policy analysis by this approach. Also, several questions are listed in Table 3.3 to specify the research questions in each step. The second approach uses the framework as a diagnostic tool and starts from outcomes. Then it works backwards through the flow diagram. It can be used to evaluate policy outcomes and revise policy objectives. In this approach, analysts may first observe some policy outcomes and question how these results occur. Then the analysis moves on to identify patterns of interactions, description of the policy action situations and the actors involved in the action situation. Subsequently, rules-in-use, physical conditions and social community are investigated to understand how these variables affect the action arena and policy outcomes. Sometimes, the problem may be so complicated that we need to flexibly use IAD. Using which approach depends on the concrete research objectives and research stages. Nevertheless, the two approaches provide us with a basic outline for analyzing policy issues.

3.5 Synthetic framework for EIP system analysis

In this section, we would like to propose a synthetic framework to guide policy analysts to analyze an EIP's formation and development. It will help us to answer the research question how to eco-transform industrial parks through policy intervention. Inspired by the IAD in guiding policy analysis of a socio-technical system, we use it as the underlying theoretical foundation. Figure 3.5 presents our analytical framework that integrates the underlying questions of "what" and "how" to understand the policy issues about EIPs.

Steps	Examples
Step 1: Define the policy analysis objective and specify the analytic approach	
Step 2: Analyze physical and material conditions	What is the economic nature of the policy activity? What physical and human resources are required? What is the scale and scope of provision and production activity?
Step 3: Analyze community attributes	What is the size of the community and who is in it? What knowledge and information do members have? What are members' values and preferences?
Step 4: Analyze rules-in-use	Position, boundary, authority, aggregation, payoff. What are the rules at three levels: operational, collective choice and constitutional choice?
Step 5: Integrate the analysis	Action situation: Who are the participants? What are the positions or roles that actors play in this situation? What actions can participants take, and how are actions linked to outcomes? Actors: What are the resources that an actor brings to a situation? What are the valuations actors assign to actions? How do actors acquire, process and use knowledge contingencies and information? What are the processes that actors use for selection of particular course of action?
Step 6: Analyze patterns of interaction	Structure of economic and political participation, information flows.
Step 7: Analyze outcomes	How do observed outcomes compare to policy objectives? What are the physical results obtained as a result of actors' actions? What are the material rewards or costs by payoff rules? How do actors value the combination of the physical and material results? How are the efficiency, fiscal equivalence, sustainability and adaptability?

Table 3.3 – Steps for policy analysis based on IAD (Polski and Ostrom, 1999).

This framework integrates our comprehension of the features of EIP systems and in the institutional analysis. It mainly covers four aspects: 1) influencing factors, 2) EIP system description, 3) system performance, and 4) evaluation. Each aspect has focal points to sort out. Furthermore, the time span is taken into account to illustrate the changes across the different stages. The framework can be used to guide policy analysis regarding EIPs.

1) Influencing factors

When analyzing an EIP system, one needs to find out what the influencing factors are. The attributes of the industrial site need to be clarified, such as geographical location, current industrial structure, water and material resources. This information does not only provide the background, but also presents the resource endowments that may decide the path of an industrial park's development. For instance, if an industrial park suffers from water scarcity, the priority of implementing EIP projects would first be to improve utilities for reclaiming water and efficiency of water usage. Furthermore, we need to capture the key activities that affect an EIP's changes and development. The set of these key activities and their corresponding indicators

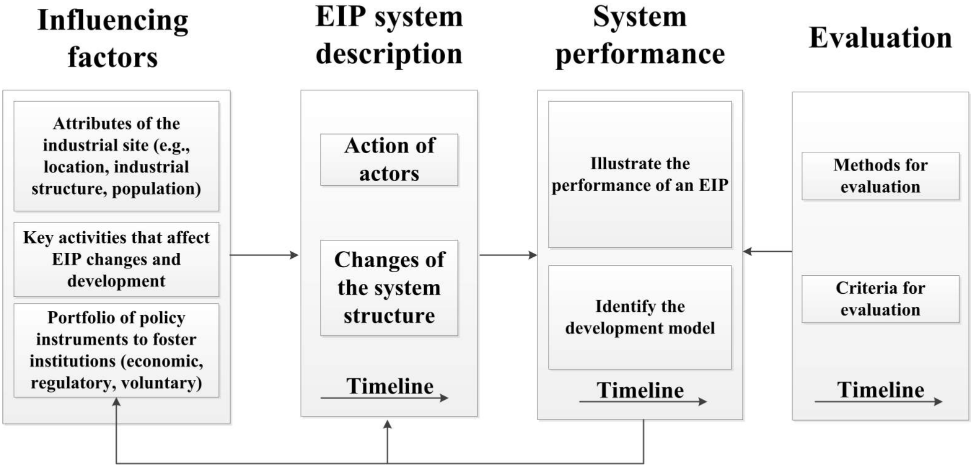


Figure 3.5 – An analytical framework for an EIP system.

could be extracted from a literature review, in order to ensure the generic application to analyze different EIPs or trace one EIP over time. Moreover, a portfolio of policy instruments for fostering the institutions needs to be clearly structured and elaborated, because it reveals the actions that can be used to steer the EIP system. The use of a combined instrument that integrates the features of various instruments is more effective than implementing a single one (Goulder and Parry, 2008). The toolkit of environmental policy has diverse instruments, mainly including incentive-based instruments (market-based instruments, e.g., tax, subsidies, funding), regulatory instruments (command-and-control instruments, e.g., technology mandates) and voluntary instruments (e.g., information disclosure and coordination program) (Arimura et al., 2008; Costa et al., 2010; Goulder and Parry, 2008). We roughly structure the instruments with respect to economic, regulatory and voluntary aspects. Analysts may review the historical policy instruments implemented in an industrial park in the past or trace the ongoing ones.

2) EIP system description

After identifying the influencing factors, we use the conceptual model in Figure 3.2 to sketch an EIP system. Each actor's actions should be analyzed to see the results of influencing factors within a time period. For instance, does this type of actor appear in this period? What actions do actors give to deal with the influencing factors (e.g., companies improve energy efficiency to get funding)? Furthermore, changes in system structure need to be identified through the interactions between actors. The interactions can be interpreted as various flows of capitals, materials, energy and information. In the system description, the milestone events should also be highlighted when we describe the changes of an EIP system. What is more important is companies' reactions, because they decide the effectiveness of policy instruments and system performance. Thus, in this step, the participation of company actors should be particularly focused in order to observe their intra-firm actions and inter-firm collaboration. Besides, it is necessary to investigate the energy and water flows to identify the conditions for utility sharing. In addition, we also need to observe the role of the coordinator. The appearance and functions of a coordinating body may influence company actors' decisions via networking and dissemination (Paquin and Howard-Grenville, 2012). Companies get more opportunities and occasions to become aware of environmental principles, useful funding and potential synergies in collaborating with other companies.

3) System performance

System performance reveals the outcomes of policy intervention and actors' decisions. It can be portrayed by the indicators that represent the occurrence of the key activities or the technical indicators of economy and environment. Using the indicators of the key activities (found in the influencing factors), we can code the events from the empirical evidence to capture "what happened or what is happening that may determine the system performance" in a time period. Moreover, the results of economy and environment can be measured by a series of technical indicators to show the progress. Industrial added value (IAV) and GDP are often used to show economic growth and to calculate energy efficiency and other environmental performance indicators. Using IAV or GDP depends on the research scope that focuses on the industrial site or the entire region. The environmental indicators are the most critical ones to reveal the environmental performance of an EIP. Thus, the selection of environmental indicators should be comprehensive to present the overall progress of pollution control and prevention, resource reduction and recycling. According to the research objectives, the indicators may cover raw materials, energy, water, air and waste. Furthermore, through analyzing the changes in the system structure, we can identify the EIP models and the corresponding performance in the different stages. This is useful to understand the status of the EIP and recognize the symptoms for prescribing the next move. For instance, if we find signs of self-organization, then more incentives should be given to help companies to strengthen such self-organizing activities.

4) Evaluation

System performance is evaluated and the results are used to assess whether the policy instruments are effective or whether the system development deviates from the policy objectives. Such analysis can help to adjust policy instruments to better steer the EIP system. Meanwhile, the policy objectives should also be adjusted and updated, aiming to deal with the new system structure as the development continues.

There are various methodologies for the evaluation of system performance. Quantitative methods in industrial ecology are often used to reveal the economic, environmental and social performance of an EIP based on multiple indicators, such as multi criteria decision making analysis, eco-efficiency, material flow analysis, emergy analysis (for instance, (Geng et al., 2010; Huppes and Ishikawa, 2005; Sendra et al., 2007; Yoon and Hwang, 1995)), etc. Sometimes, statistical methods based on surveys and questionnaires are used to collect micro data from actors and establish the relations among policies variables (for instance, (Ashton, 2008; Liu et al., 2009; Zhang et al., 2009)). The selection of evaluation methods depends on the research objective and data acquisition. In addition, the criteria should be appropriately chosen as benchmarks to assess whether the system performance meets the requirements of the policy objectives. Analysts may choose the criteria from acknowledged national or international standards, which is suitable to compare different cases.

3.6 Application of the analytical framework in this thesis

In this chapter, we have elaborated the framework to conceptualize and analyze an EIP system. We synthesized a new analytical framework, based on the body of knowledge of EIP and IS, a socio-technical perspective and the institutional analysis. In chapters 4, 5 and 6, we will apply the framework to the empirical research of three cases: Tianjin Economic-technological Development Area (TEDA), Dalian Development Area (DDA) and Suzhou Industrial Park (SIP). The case studies will follow the framework and structure the empirical work from these aspects: 1) influencing factors, 2) EIP system description, 3) system performance and 4) evaluation. The analysis in each chapter has different focal points to answer sub research questions, thus the different components of the framework will be emphasized in the different case studies.

Chapter 4 will focus on the influencing factors and EIP system description. We will extract the key activities that determine an EIP's development through literature review. Moreover, to illustrate how these key activities influence an EIP's development, the approach of process analysis will be used to trace and analyze the events of the key activities that took place in TEDA from 2000 to 2011. Process analysis aims to capture and explain the different types of forces and mechanisms that can influence the evolution of a firm or a network of firms (Poole et al., 2000). The event is used in process theories as the appropriate meaningful unit in which change can be detected (Poole et al., 2000). These events in a time line were significant during the changing process and had a critical impact on the system. This approach helps to identify the key activities of a sequence of events over time and recognize the underlying patterns. We will adapt process analysis to better understand what drives the changes of TEDA's eco-transformation and how the changes unfold during the development. Moreover, the system structure of TEDA will be analyzed in accordance with our EIP conceptual framework to show the changes in the different stages.

In chapter 5, we will emphasize the system performance and evaluation. Thus this chapter will reveal how to quantify policy effects and measure EIP performance. A comparative perspective will be used to assess the EIP models and their performance in TEDA and DDA. We will unravel the efficiency of policy instruments (economic, regulatory and voluntary) used to foster EIP development in the two industrial parks. The reactions of actors due to policy interventions will be investigated. Next, we will use China's National EIP Standard as a benchmark and adopt a multi-criteria decision making method to evaluate the effectiveness of environmental policy instruments in TEDA and DDA. Multi-criteria decision analysis is useful for complex and intractable environmental projects, because this methodology can rank the alternatives through a set of indicators of the inherent trade-offs between environmental, economic, social and political factors (Kiker et al., 2005). The results may indicate the effectiveness of a portfolio of policy instruments and the different models that can bring about a viable eco-transformation of Chinese industrial parks.

In chapter 6, our research scope will be expanded to explore the next step of EIP development in China. The policy goals and policy instruments need to be adjusted for the continuous development of EIPs as new features may emerge in terms of industrial structure, population, land use, etc. The empirical research in SIP will focus on how it has been transformed into an EIP and what effect this had on the associated urban functions. Following the analytical framework, the policy instruments and environmental infrastructures will be inventoried and analyzed to deduce how SIP improved energy efficiency and reduced pollution. Furthermore, we will analyze the eco-efficiency to evaluate the relation between environmental impact and economic growth in SIP. A set of eco-efficiency indicators (including energy, water and air) will be used to reflect how the regional environmental pressure changed during SIP's eco-transformation. From this chapter, we would like to obtain the insights about the potential directions of EIP policies as industrialization and urbanization proceed.

Some theoretical limitations may occur due to the research boundaries. In this thesis, we focus on the environmental issues in industrial sites or industrialized towns. Thus, the theory exploration mainly concentrates on the actors of companies, policy makers and coordinating organizations. Social community is currently belonging to the external system in our conceptual EIP model. As urbanization is happening in many industrial sites, industrial symbiosis may be extended to urban symbiosis. Social community in the residential areas would be involved as one of the main actors in terms of water and energy use. Furthermore, our current analytical framework tends to use explicit or quantifiable indicators to present system's changes and performance. However, some factors that cause or facilitate industrial symbiosis may be tacit knowledge. It requires deep investigations and long-time observations in companies.

Part II

Empirical research

4

Process analysis of eco-industrial park development - the case of Tianjin, China

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4.1 Introduction

The most famous eco-industrial park (EIP), Kalundborg in Denmark, demonstrates the feasibility of reconciling a profit orientation with environmental performance. Due to water scarcity, six major companies in Kalundborg spontaneously formed a symbiotic network that is deeply embedded in the regional context. In recent years, EIPs have become a policy-driven attempt to apply the principles of Industrial Ecology in specific locations (Gibbs, 2009) to reduce the environmental impact of industrial activities. The worldwide boom of EIP practices has been evidenced in the National Industrial Symbiosis Program (NISP) in the UK, the regional synergies in the Australian mineral industries and the Circular Economy program in Chinese industrial parks (Mirata, 2004; van Beers et al., 2007; Yuan et al., 2006). Meanwhile, abandoned projects in the US have revealed that regulatory and management complications may exist when realizing EIPs. Overemphasis on the technical aspects of matching material flows appears not sufficient to facilitate the emergence of symbiotic networks. Indeed, barriers created by existing regulations and distrust among actors have hindered the establishment of synergy in many US EIP projects (Gibbs and Deutz, 2007; Heeres et al., 2004). The variety of successful and unsuccessful cases raises the question "how to examine the determining factors of existing EIP cases and how to explore developmental paths for future EIPs".

The underlying idea of an EIP is industrial symbiosis (IS) that aims to engage otherwise separated industries in a collective approach to reduce their environmental impact (Chertow, 2000). It involves physical exchange of materials and by-products, shared management of common utilities and infrastructures for water, energy and waste (Chertow, 2000; van Berkel et al., 2009). Analysis of worldwide EIPs has revealed that most of the eco-initiatives have been deployed to transform already existing industrial parks (Mathews and Tan, 2011). In this article, the term "eco-transformation" is used to designate industrial park revitalization and transformation in accordance with IS principles. Eco-transformation of industrial parks does not come about overnight. Rather, it is a process that spans years and unfolds in a wider socio-technical context wherein changes emerge from the co-evolution of technology, institutions and social systems (Chertow, 2000; Dijkema and Basson, 2009). Many scholars have sought to understand the patterns and mechanisms for EIP inception and development over time, based on the experiences from various historical and current cases. However, a knowledge gap remains, *how to trace the determining factors that unfold over time and elicit their integrative effect at the EIP systems level?* Thus, this research aims to develop a generic approach which allows analysts (1) to structure the key activities that influence changes of EIP systems, and (2) to track the process of the system development over time.

This chapter will unfold as follows. Section 4.2 introduces process analysis and how it can be adapted to study an EIP's development. Such an approach requires a set of indicators to detect the key activities from the events in a given time span. Consequently, a literature review is provided on the topics of EIP and IS, which culminates in a list of the key activities that promote or hinder the development of an EIP. Meanwhile, a set of indicators is identified to trace these activities over time. In section 4.3, the approach is applied to an ongoing case - the Tianjin Economic-technological Development Area (TEDA) in China. The authority of TEDA initiated the eco-transformation in 2000 as one of the earliest participants in the China National EIP Program. The overview of this national program has been discussed (see (Fang et al., 2007; Geng, Zhang, Côté and Fujita, 2009; Mathews and Tan, 2011)). This article focuses on the practical implementation at the park level. Evidence shows that IS networks are indeed emerging in TEDA, stimulated by several institutional and management instruments (Shi et al., 2010). Thus, TEDA's eco-transformation during the last decade provides real-life lessons to uncover insights as to how EIP development can successfully evolve. Section 4.3 first details how the process analysis approach is used and the necessary data has been collected. Subsequently, the approach is applied to make sense of the transformation process of the TEDA case. In the fourth and concluding section, the research findings and insights are discussed and their wider implications are addressed.

4.2 Process analysis of an EIP system

4.2.1 Analysis of EIP

Generally, chronological narrative analysis is used to describe the process of EIP evolution. Ehrenfeld and Gertler (1997) analyzed the evolution of company interdependence at Kalundborg from 1959 to 1993 in terms of business interests, organizational arrangements, technical factors and regulations. A discontinuous three-stage IS model was extracted by Chertow and Ehrenfeld (2012) (i.e., sprouting, uncovering, embeddedness and institutionalization). This three-stage model was subsequently used to examine ten industrial ecosystems. Domnech and Davies (2011) explored the main mechanisms that forge trust and embeddedness during the three IS stages: emergence, probation, and development and expansion. They then characterized three cases (including Kalundborg, NISP, and Sagunto) to examine the trajectories of their embeddedness in IS networks. A cross-case study was made by Mathews and Tan (2011) through discussing the drivers and inhibitors in an evolutionary framework. These authors analyzed in detail what happened in various IS projects during a period. Their work, however, points out a knowledge gap: how to trace the determining factors unfolding over time and elicit their integrative effect at the EIP system level. Furthermore, narrative analysis is context-specific, which lacks a generic approach to discern the determinants for success and failure. It is limited to extract the patterns for comparison and generalization.

4.2.2 Process analysis

Process analysis aims to capture and explain the different types of forces and mechanisms that can influence the evolution of a firm or a network of firms (Poole et al., 2000). In this chapter, process analysis is adapted to better understand the drivers of change of an EIP, and how changes unfold over time.

A *Process* is defined as a sequence of events that describe how things change over time (Ven and Poole, 1995). The point of process analysis is to obtain meaningful insight into the changes unfolding over the duration of a central subject's existence (Poole et al., 2000), here being an EIP. In process theories, the event is used as the appropriate meaningful unit by which change can be detected (Poole et al., 2000). Activities in a certain subject are mapped as events. Thus, a historical database is constructed in which all relevant events related to a specific developmental process are mapped (Hekkert et al., 2007). Hence, development and change can be studied by analyzing the sequence of events (Poole et al., 2000). The advantage of event analysis is that rich qualitative information about the development processes can be obtained. Furthermore, the structured and quantitative characteristics are useful to interpret and compare case studies. As Poole et al. (2000) emphasized, the goal of the process approach is to develop explanations with more general applicability; in the meantime, it stresses the systematic investigation and evaluation of narrative explanation. Process analysis was used to collect the events and study the Dutch stimulation program for EIPs (Boons and Spekkink, 2012). The data were employed to test the theory of institutional capacity for IS. Their work has inspired us to use process analysis to analyze the changes during the eco-transformation of industrial parks from a system perspective.

4.2.3 Towards a lens on EIP development

The study of EIP development requires us to tailor process analysis. We first need to develop a framework that consists of the key activities as variables that determine the development of EIP/IS, and specify the corresponding indicators for each variable. Second, the framework is applied to detect the events from the empirical data to build the database. Then the system analysis of EIPs' development is delivered based on the main events description and event sequence analysis.

A literature study has been conducted to identify the determining factors that promote or prohibit an EIP's evolution. We searched item "eco industrial park symbiosis" for journal articles in Hub-SciVerse, which spans ScienceDirect and Wiley-Blackwell. The results included 167 articles in the subject areas: Environmental Sciences, Energy, Agricultural and Biological Sciences, Social Sciences, Economics and Econometrics and Finance, Business and Management and Accounting, and Decision Sciences. After initial inspection, we identified 46 articles that address drivers and barriers of EIPs/IS projects. A comprehensive overview of the determining factors is extracted and given in Appendix C.

The classification criteria of the factors are based on review-type articles. Mirata (2004) categorized the determining factors for IS networks into technical, political, economic and financial, informational, organizational and motivational. Sakr et al. (2011) classified the EIP success and limiting factors as symbiotic business relationships, economic value-added, awareness and information sharing, policy and regulatory frameworks, organizational and institutional setups, technical factors. When comparing the drivers and barriers of Australian IS projects, van Beers et al. (2007) used six categories including economics, information availability, corporate citizenship and business strategy, region-specific issues, regulation, and technical issues. Considering the need for mutual-exclusiveness of the criteria, we concluded that the determining factors elicited from the literature review best fit the classification criteria by Mirata (2004). Consequently, we use the following criteria in our tailored process analysis approach for EIPs: 1) institutional activity, 2) technical facilitation, 3) economic and financial enablers, 4) informational activity and 5) company activity. The next section further details the lens on these five groups of key activities.

Institutional activity

Having an appropriate institutional setting in a region is one of the most important elements for IS programs (Mirata, 2004). Ehrenfeld and Gertler (1997) pointed out that policies may enable or preclude EIP development. In many EIP cases, policy interventions motivate the development of new EIPs or the transformation of existing industrial areas (Boons et al., 2011; Lehtoranta et al., 2011; Mathews and Tan, 2011). Examples are the national level EIP program in China, NISP in the UK, and the special industrial park in Ulsan, South Korea. The formal institutional regime consists of laws and regulations (e.g., environmental protection law and water quality standards). Policies and guidance can create appropriate conditions that enable infrastructure sharing and company interaction, which increases the synergy opportunities (Mirata, 2004). If strict environmental regulation is in place, the financial burden imposed on resource consumption and waste disposal urges companies to reduce and recycle their waste and by-products. Regarding the policy direction, Chertow (2007) argued that for self-organizing or planned EIPs, three policy ideas can move IS forward: 1) bring to light kernels of cooperative activity that are still hidden; 2) assist the kernels that are taking shape; 3) provide incentives to catalyze new kernels by identifying "precursors to symbiosis". When investigating the evolution of Kalundborg, Ehrenfeld and Gertler (1997) and Desrochers (2001) highlighted that the flexibility of regulatory requirements on performance standards is the key to stimulate companies to innovate and explore creative arrangements to meet pollution-reduction targets. In contrast, regulatory requirements may preclude the material exchanges due to high transaction costs or inflexible planning (Mirata, 2004). Additionally, regular monitoring and evaluation of EIPs is necessary to ensure that ecological and economic goals are reached (Geng, Zhu, Doberstein and Fujita, 2009).

Technical facilitation

The second criterion is the availability of infrastructure for pooled use and joint management of resources (Chertow et al., 2008). Besides, information and communication technology (ICT) tools also may facilitate the realization of potential synergies. Although the type of specialized infrastructure depends on local industrial characteristics, the regional public utilities (e.g., co-generation and wastewater plants) can play the role of anchor tenant, around which the main material and energy flows of a regional industrial system could be arranged (Korhonen, 2001). Lastly, ICT can support IS networks through information acquisition and analysis of material flows for potential synergies, and for monitoring the performance of the network (Mirata, 2004).

Economic and financial enablers

Economic benefit is the main driver for the emergence of IS/EIP projects (Ehrenfeld and Gertler, 1997; Lehtoranta et al., 2011; Roberts, 2004; Tudor et al., 2007). Companies may hesitate when considering the transaction cost and risk in symbiosis projects. Subsidies and funds can stimulate the collaboration, and guide the adopting technologies and infrastructures. Market-driven actions, such as price mechanisms for energy and resources, are crucial to make symbiosis economically attractive (Desrochers, 2001; Mathews and Tan, 2011). Mirata (2004) reviewed the fiscal incentive policies relevant for IS programs in the UK, viz. landfill taxes and climate change levies. The former provides incentives to reduce and recover waste streams and to find alternative ways for waste treatment. The latter provides tax reductions or exemptions for inter-organizational synergies such as co-generation. And heat, steam and waste as defined by statute are non-taxable carriers of energy (Mirata, 2004).

Informational activity

During the eco-transformation of an industrial park, information is essential to identify and establish various types of synergies (Heeres et al., 2004).

Absent or incomplete information may lead to difficulties even when companies share one geographical space (Tudor et al., 2007). First, professional knowledge may be lacking to turn waste into a profitable product (Chiu and Yong, 2004). Second, while companies may know what by-product exchanges they are engaged in, they do not have complete information about who their neighbors are, what industry and activity they are engaged in, and thus what by-products they may have or need (Chertow, 2007). In the context of EIPs, three aspects of informational activity are involved: 1) dissemination and training, to generate a common understanding of IS; 2) networking activity, to engage companies in and to collect information for potential synergies; 3) feasibility studies, to analyze potential synergies. Informational activities may benefit from the input of coordination bodies, such as entrepreneurs association and non-governmental organization (NGO). Coordinators can catalyze IS through organizing training or workshops and research on IS feasibility and thereby engage key parties. Frequent encounters can reduce "mental distance" and cognitive barriers (Mirata, 2004; Roberts, 2004; Sterr and Ott, 2004). Even if actors decide not to pursue a joint project, their thinking may have changed to give preference to IS projects when the conditions for a partnership are favorable (Paquin and Howard-Grenville, 2009).

Company activity

The bottom-line of industrial symbiosis is company participation in the exchange of physical by-products and utility sharing (e.g., steam, wastewater treatment and joint provision of ancillary services) (Chertow et al., 2008; Tudor et al., 2007). Heeres et al. (2004) compared the Dutch and North American EIP projects and concluded that active company participation is crucial for success, as the EIP plans are ultimately implemented by companies. Companies must invest time, money and other resources in IS projects. Trust and willingness to participate often determine whether the initiatives can eventually lead to the implementation of an IS project (Gibbs and Deutz, 2007; Mirata, 2004). The main reasons for Kalundborg's success are the "culture of cooperation", the "short mental distance" and a shared cooperative attitude (Ashton, 2008; Ehrenfeld and Chertow, 2002; Gibbs and Deutz, 2007; Sterr and Ott, 2004). Self-organization by companies for IS is a pivotal factor for the emergence of symbiosis possibilities, and appears to be the missing link in many unsuccessful planned EIPs (Chertow, 2007; Gibbs et al., 2005).

4.2.4 Approach to identify the key activities for event tracking

Above, we have summarized our findings from a literature review and grouped the results into institutional, technical, economic and financial, informational and company activity. As we are interested in the process of EIP development, we use a list of indicators (Table 4.1) to represent what drives the changes of an EIP, in order to identify these activities from empirical material. The set of indicators as a minimum should cover the determining factors under each subject of the key activity in Appendix C. The institutional activities concern formal institutions such as regulations, laws, planning and evaluation, as well as informal institutions like voluntary agreements or shared norms. For technical facilitation, we focus on the public utilities such as cogeneration plants and wastewater recycling plants. Regarding economic and financial enablers, although the funding sources of companies are diverse, we pay particular attention to local government's subsidies and funds for encouraging companies to join symbiosis networks. The informational activity can be mapped through the number of training sessions, feasibility studies, workshops and networking events. And we use the started IS projects to map the events about company activity. Finally, the participation in the information exchange and information disclosure can be counted as a proxy, because these imply willingness of companies to engage in IS projects.

Key activities	**Indicators**
Institutional activity	• Policies, regulations, planning, voluntary agreement and evaluation for EIP/IS (+1)
Technical facilitation	• Projects of infrastructures and utilities for enabling IS (+1)
Economic and financial enabler	• Financial incentives (funding and subsidies) (+1)
Informational activity	• Training and educational programs (+1) • Feasibility/assessment research projects (+1) • Workshops, conferences, seminars and forums for networking (+1)
Company activity	• IS projects started (+1) • Join the information exchange activities for seeking synergy partners (+1) • Environmental information disclosure (+1)

Table 4.1 – Framework for identifying the events of key activities

The framework can help to detect the events from raw data (e.g., news, archives and interviews) related to EIP/IS development. Once a related event appears, it will be counted with value 1 in this type of key activities. The events are stored in a historical database to create a time series. Consequently, the trends of the 5 key activities influencing an EIP's development are illustrated and analyzed. Through this approach, the process of EIP's development is tracked and systematically analyzed over time. The approach requires case study to testify whether it is adequate, which will be presented in the next section.

4.3 Case study on process analysis about the eco-transformation of TEDA

4.3.1 Method of applying process analysis and data collection

In the following sections, the approach outlined above is used to illustrate TEDA's development and to analyze its evolution process. First, we describe the milestone events that had profound impacts in terms of institutional activity, technical facilitation, economic and financial enablers, informational activity and company activity. Second, a system analysis is presented based on the database that has been compiled by collecting historical events from 2000 to 2011. The database is set up in accordance with the indicators in Table 4.1. Data collection follows Hekkert et al. (2007) who tracked events reported at the system level. Thus, we focus on the data sources available to give us information at the park level of TEDA's eco-transformation. These include news and annual reports of TEDA from 2000 to 2011, mainly from the websites of TEDA government (http://www.teda.gov.cn), TEDA's Eco-center (http://www.ecoteda.org), and TEDA's Environment Protection Bureau (EPB) (http://www.teda.gov.cn/html/hjbhj/portal/index/index.htm). The events are counted over time with the same weight and plotted in the figures. The trends of the 5 key activities through time are analyzed to explain the dynamics of TEDA's eco-transformation. Moreover, during data collection in the field, we conducted seven semi-structured interviews with the key departments in TEDA. These interviews lasted 1-3 hours and the findings largely served as triangulation of data obtained by other means (yearbooks, policy documents, our measurements of the key activities). The interviews also provided necessary background information about the drivers and barriers during TEDA's eco-transformation. Appendix D gives an overview of the departments and positions of the respondents and questions in the interviews.

4.3.2 General introduction of TEDA

Tianjin Economic-technological Development Area (TEDA) was established in 1984 as one of the first Chinese national level economic development zones. Connected with Tianjin Port, TEDA's developed land occupies approximately 98 km^2, including 46 km^2 of industrial area and an employed population of 484 thousand. The geographical location of TEDA is shown in Figure 4.1. In 2010, TEDA's GDP was 154.586 billion RMB, an increase of 25.1% compared with the previous year (TEDA, 2010a). In total, TEDA has approved 4,870 foreign companies involving US dollar 62.207 billion of project investment, and 9,546 domestic-funded enterprises with a total registered capital of 177.069 billion RMB (TEDA, 2010a). As a mixed industrial park with diverse industries, TEDA has seven main industries and their relative share is shown in Figure 4.2.

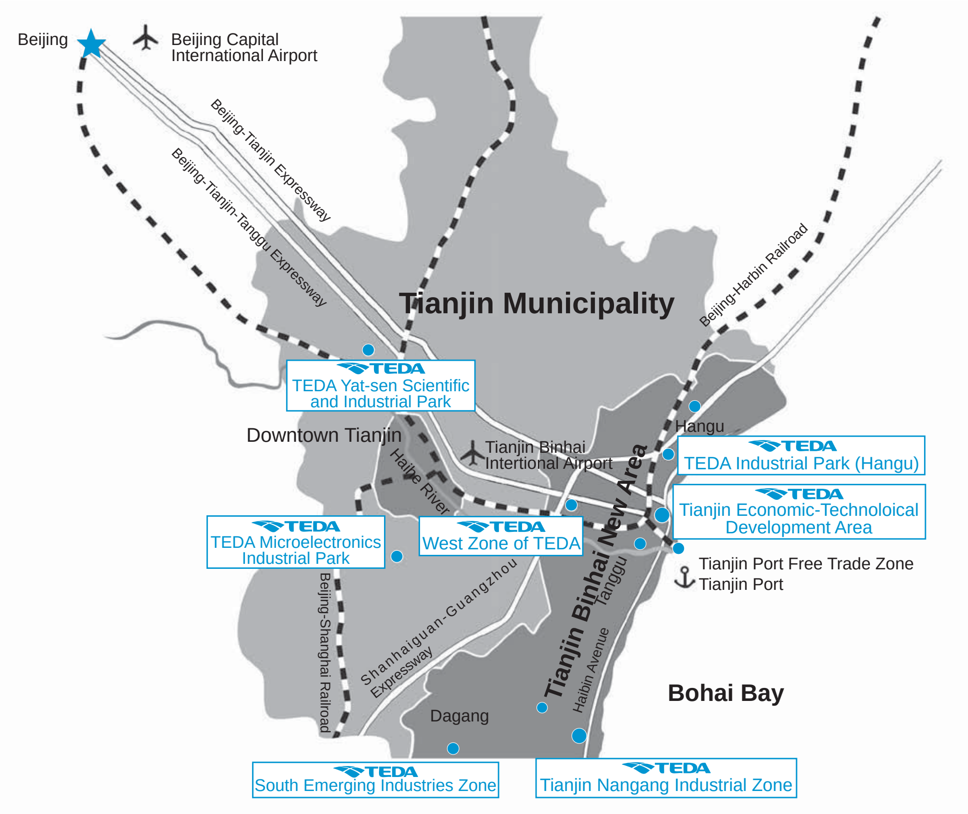

Figure 4.1 – Geographical location of TEDA.

TEDA's eco-transformation dates back to the year of 2000 when TEDA started to prepare for the ISO14001 certification. The diversity of industries brings TEDA the possibility of by-product exchanges as well as the challenges to connect different types of companies. Furthermore, Tianjin City relies on external energy and resources. Consequently, TEDA also suffers from the same problems, especially water scarcity. Considering the growing demand for resources from the rapid economic growth, it is indispensable to reduce and recycle energy, water and resources. After years of effort, TEDA

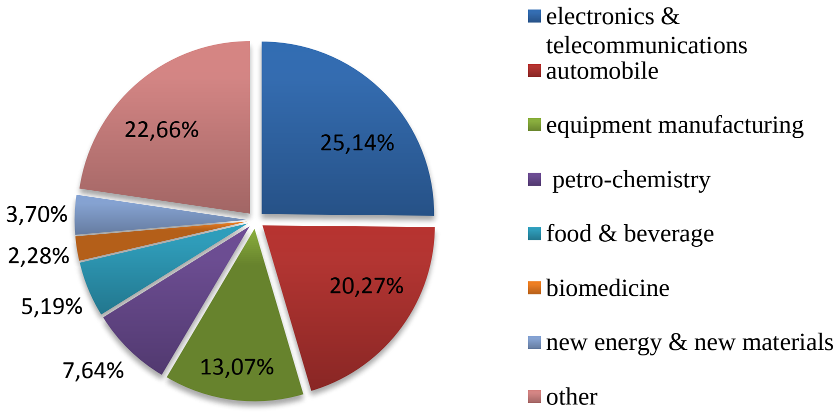

Figure 4.2 – Proportion of the industries in TEDA by 2010. Data source: website of TEDA Government.

was nominated as a National Pilot Industrial Area for Circular Economy in 2005 and it became one of the first three National Demonstration EIPs in 2008. Utility sharing has gradually increased in regional water supply and co-generation. Moreover, a symbiosis network of by-product exchanges is emerging. During TEDA's eco-transformation, various activities and changes took place in terms of institutional intervention, infrastructure provision and actor participation, which will be discussed in the following sections.

4.3.3 Description of main events

Institutional activity

TEDA's Administrative Committee (AC) (set up in 1984) is accredited by the Tianjin municipal government. The AC is in charge of administrative management, the drafting and supervising local regulations. Besides, it is also responsible for the auditing of investment projects, the planning of infrastructures and public utilities, and setting infrastructure charges. The multiple roles as a substitute local government give TEDA's AC considerable institutional capacity for economic development and environmental issues.

Various administrative instruments, including national laws, have stimulated TEDA's eco-transformation since 2000. Table 4.2 records the institutional activities stimulating EIP practices from 2000 to 2010 in TEDA and at the national level, respectively. At the park level, the institutional arrangements involve planning, incentive policies, monitoring and evaluation, which is in line with the goal of EIP and national laws. The focus in TEDA switched from using public utilities to companies' spontaneous IS behavior. Due to the worsening environmental situation and water scarcity, in 2000 TEDA initiated the regional ISO14001 certification and adopted its main principles on reducing sewage discharge and air pollution. When the first wastewater reclamation plant was operated, TEDA's AC formulated two measures: exemption from the sewage disposal fee in 2000; encouragement for the use of new water sources in 2002. According to these measures, if a company's wastewater meets the Grade II national standards or if its wastewater is reused, the company is exempt from the sewage disposal fee (1 RMB/ton) (TEDA, 2002). Furthermore, recycled water is 20% cheaper than tap water. These measures thus stimulate companies to improve their wastewater treatment and to use recycled water. In 2009, 25.29% of discharged water was recycled (Eco-center, 2010).

	Year	Institution	Type
TEDA	2000	TEDA Regional ISO14001.	Incentive policy
	2000	Measures for exempting from sewage disposal fee (On trial).	Incentive policy
	2002	TEDA National Level EIP Development Planning (Approved in 2004).	Planning
	2002	Measures for encouraging new water sources (On trial).	Incentive policy
	2005	Eco-labeling management system for industrial solid waste.	Incentive policy
	2006	Implementing Plan for TEDA Circular Economy Pilot.	Planning
	2007	The Guide for TEDA Environmental Information Disclosure. And the Catalogue for TEDA Environmental Information Disclosure, including government information disclosure, company voluntary and compulsory information disclosure.	Monitoring and evaluation
	2007	Provisional Regulation for Promoting Energy-saving, Cost-reducing and Environmental Protection.	Incentive policy
	2007	Initiated to quarterly publish the companies who failed the requirements for pollution discharge.	Monitoring and evaluation
	2008	Roadmap for TEDA circular economy (2010-2020) (Approved in 2009).	Planning
	2010	Provisional Measures on the High Energy Users in TEDA.	Monitoring and evaluation
National	2003	Cleaner Production Promotion Law.	Law
	2003	Environment Impacts Assessment Law.	Law
	2004	Law on the Prevention and Control of Environmental Pollution by Solid Wastes.	Law
	2006	National Standards for Eco-industrial Parks (On trial) (Revised in 2009).	Standard
	2008	Guild for Planning and Construction of Eco-industrial Parks.	Planning
	2009	Circular Economy Promotion Law.	Law

Table 4.2 – Main institutional activities stimulating EIP at TEDA and national levels

Life cycle use of materials and industrial symbiosis have been clearly proposed since 2002 in TEDA's National Level EIP Development Planning. This plan prioritized the complementary projects for closed-loop industrial chains on electronics and telecommunications, machinery manufacture, food and biomedicine (TEDA, 2004). In addition, environmental infrastructure projects were initiated, which involves the regional water cycle system and a co-generation plant. Moreover, due to the absence of national regulations on non-hazardous industrial waste, an eco-labeling management system was launched in 2005 to reduce solid waste. Companies that generate, recycle or treat solid waste can set up a waste management system and have it evaluated. If it passes the assessment, the company will receive an eco-management label as a certification (TEDA, 2007). Apart from the goal of solid waste reduction, the eco-labeling management system also traces the solid waste flow to search suitable waste recyclers and effective transport routes.

Although crucial regulations had been implemented for closed-loop chains and IS, many problems still persisted. For instance, the efficiency of energy utilization was low. 60% of the steam condensation water could be reused for heat energy instead of being discharged. The reclamation of materials was constrained by imperfect information and insufficient information services (TEDA, 2006). Considering these shortcomings, the Implementing Plan for the TEDA Circular Economy Pilot was promulgated in 2006. Following the main IS principles, this plan emphasized optimization of energy structure, reclamation of regional steam condensation water, and the establishment of an information platform for solid waste management. Furthermore, it stressed the incentive mechanisms to mobilize companies to disclose environmental information and join the IS network (TEDA, 2006). In retrospect, these new goals paved the way for IS-type projects. A company obtaining the eco-management label for 3 consecutive years can receive a reward of 30,000 RMB. Additionally, monitoring and evaluation have been strengthened since 2007. TEDA's EPB regularly publishes the names of companies that fail the requirements for pollution discharge.

The transition of China's national environmental policies also have impacts on TEDA's development. As the Cleaner Production Promotion Law was formulated in 2003, the shift from end-of-pipe to source control and life cycle management has been strengthened (Zhang and Wen, 2008). Besides, the national EIP standards and the Guide for Planning and Construction of EIPs provide a clear definition of IS and the associated regulatory instruments in the following domains: wastewater treatment and recycling, solid waste disposal and reclamation, and energy cascading. Furthermore, the Circular Economy Promotion Law (2009) states that the development of a green-field (building new parks with ecological principles) and a brown-field industrial park (revitalizing existing industrial parks) should follow the 3R principles: Reduce, Reuse and Recycle through the approaches of closed-loop chains and IS.

Environmental infrastructure facilitation

Several environmental infrastructures were built by TEDA Investment Holding Co. (a state-holding company authorized by TEDA's AC), according to the instructions of TEDA's National Level EIP Development Planning (2002) and the Implementation Plan for TEDA's Circular Economy Pilot Project (2005). The first wastewater reclamation plant was initiated in 2000. By 2007, the regional water cycle system had taken shape. The idea is to integrate wastewater in-situ regeneration, wastewater treatment plants, recycled water and ecological landscape restoration to provide high-quality water to the users in the whole industrial park. The New Water Sources Plant supplies high purity recycled water with the technologies of reverse osmosis and continuous micro-filtration for users demanding water of high purity.

In 2005, Binhai Energy Cogeneration Plants generated 2.04 million tons steam and 95570 kWh electricity (Binhai-Energy, 2005). The main steam users were Toyota, Tingyi Food, Chia Tai Group, Novozymes Biotechnology, Tingjin Food, Nanqiao Oil, Hartwell Textle, Zhongxin Pharmaceutical, Fuji Protein and Idemitsu Lube. Fly ash from the coal-fired production can be completely reused by TEDA Eco-landscaping Development Company. The problem of inefficient steam condensate reclamation persisted, however. By the year 2008, only one company reclaimed and transformed the condensate water back to Binhai Energy. The amount was only 7000 tons which accounted for 0.4% of the total steam consumption for industrial production. The rest was all discharged into the sewers. Moreover, only one-fifth of the steam can be consumed in summer, which means a capacity of 800 tons steam per hour is left unused. To improve the efficiency of the co-generation plants, TEDA has listed a number of key projects for condensate water reclamation and thermo electric air-conditioner by waste steam to stimulate companies and investors.

Economic and financial enablers

To further trigger and foster the spontaneous IS activities, since 2007 subsidies and funds have been provided for new water sources, reduction of resource and energy, and reclamation of solid waste. TEDA's AC issued the Provisional Regulation for Promoting Energy-saving, Cost-reducing and Environmental Protection in 2007. According to this guidance, a special fund of 1 hundred million RMB per year is provided to promote the usage of new water sources, by-product utilization and energy-saving projects. Figure 4.3 shows the amount of funds for environmental protection projects in 2007, 2008, 2009. In 2009, the total funds grew by 86% compared with 2007. A total of 143 environmental projects were funded. The number of projects and amount of funds for energy-saving is also growing. As shown in Figure 4.4, from 2008 to 2009, the total number of funded projects on energy-saving increased from 6 to 95 and the amount of the funds grew by 83.6%. Furthermore, in order to encourage environmental data disclosure among companies, in 2010 TEDA's AC awarded 30,000 RMB to every company that kept publishing environmental information for 3 consecutive years.

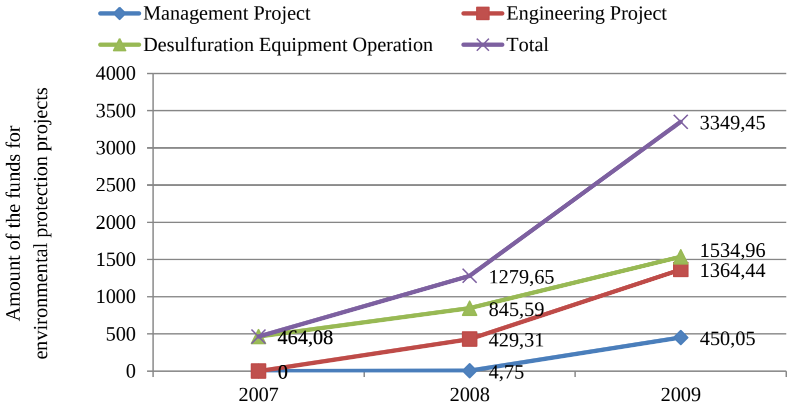

Figure 4.3 – Funds for environmental protection projects from TEDA's Administrative Committee. Management projects include cleaner production verification, ISO14001 certification, environmental labeling product certification, national environment-friendly company, ecological management logos for industrial waste, and annual corporate social responsibility reports or environment reports. Engineering projects include situ sewage reuse, resource comprehensive utilization, flue gas desulphurization and demonstration project. Unit: 10^4 RMB. Data source:(TEDA, 2010b)

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Informational activity

In April 2004, a Waste Minimization Club (WMC) was established in TEDA. As a NGO, the WMC was a sub-project of the EU-China Environmental Management Cooperation Program (EMCP) (2003-2005). The EMCP aimed to enhance company environmental awareness and to provide relevant knowledge and technology for facilitating waste exchange and recycling. The point of the WMC is to foster spontaneous action among pioneer companies

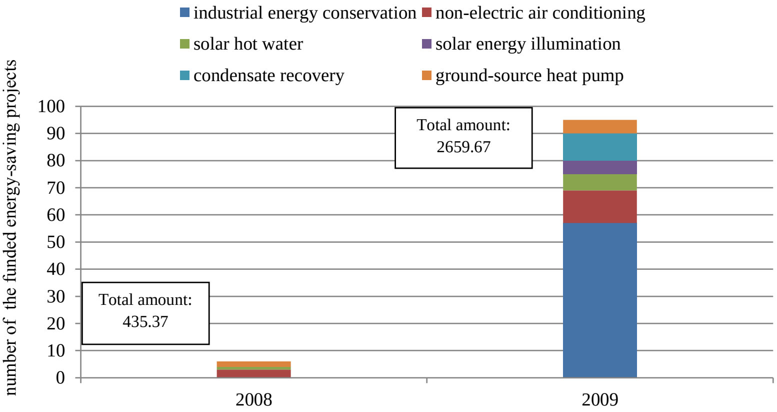

Figure 4.4 – Number of energy-saving projects funded by TEDA's Administrative Committee. Unit: 10^4 RMB. Data source: (TEDA, 2010b)

through profitable waste minimization, and then to gradually expand the effect to the whole industrial park. Although TEDA's AC provides only limited funding, the committee promises not to intervene during the projects. While the EMCP was running, experts organized by the EU and TEDA selected one company each month and investigated the efficiency of its energy and water usage. Then potential solutions were discussed with the company to minimize waste. From July 2004 to March 2005, the WMC's first term attracted 10 companies (e.g., Lafarge-Aluminates and GlaxoSmithKline). A total of 52 low/free-cost solutions were proposed to realize waste heat recovery, the reduction of energy/water/raw materials, waste recycling, and pollution treatment (Zhang et al., 2007). The payback period for most of these was less than a year. In the first term of WMC, the total capital saving was approximately 8.8 million RMB. TEDA WMC is still active even though the EMCP has ended. It is a platform for training and knowledge dissemination about waste minimization and IS. A problem, however, is that the main participants are either the leading or the problematic companies. How to attract the average companies to expand the good practices remains an issue (Zhang et al., 2007).

To trace TEDA's solid waste flow, a Solid Waste Management Information System (SWMIS) was developed by the EPB and EMCP group in 2004. It provided an online questionnaire for a waste information database. In addition, the online system can also analyze the data to assist the waste trade market. Also, several workshops were organized by the EPB to train companies to use the online system. During the EMCP, SWMIS implemented online surveys twice in 2004 and 2005, respectively. The surveys involved 62 solid waste producers (accounting for 85% of this type of companies in TEDA) and 57 recycling companies (Zhang et al., 2007).

In early 2010, another coordination body, TEDA's Low-Carbon Economy Promotion Center (called TEDA Eco-center) was set up by TEDA's AC. The center is a hub to explore and disseminate knowledge and information about IS, energy saving and environmental protection. It is responsible for engaging stakeholders to join eco-oriented business projects and to assist companies to identify synergy possibilities (TEDA, 2010b). The Eco-center hosts the Industrial Symbiosis and Environmental Management System Program under the EU Switch-Asia Project since 2010. Match-making workshops are the main platforms to discover potential synergies and company communication. At the workshops, participants are asked to fill in forms about their by-products, waste and spared resources. Afterwards, the Eco-center analyzes the data and identifies potential synergies. In this way, suppliers and receivers of materials can be connected. Additionally, the Eco-center provides consultancy services for alternative eco-solutions. Meanwhile, information about by-products, solid waste and waste energy can be better traced. By the end of 2011, TEDA's Eco-center had organized 6 match-making workshops and 8 IS conferences (Eco-center, 2011). It also undertakes training and educational services in collaboration with research institutes.

Company activity

Four recycling companies settled in TEDA in 2006, attracted by the large volume of solid waste from electronics and telecommunications, and the automobile industries. Taiding (Tianjin) Environmental Technology mainly works on e-waste recovery with a treatment capacity of 30,000 tons/year. Tianjin Toho Lead Recycling reuses the lead from battery manufacturing and auto parts to produce lead alloy. From 2008 to 2010, Tianjin Toho recycled 30,000 tons of lead waste in TEDA (TEDA, 2010a). The scrap steel produced by Toyota is disassembled by Tianjin Fengtong Recycling and then sent to Tianjin Rainbow Hills Cast Iron to make casting (TEDA, 2011c). The casting is reused by Toyota to produce grinding tools for auto parts. Thus, scrap steel is reclaimed as a resource in the automobile industrial chain.

Since the IS program (within the EU Switch-Asia Project) was launched in 2010, 536 companies within TEDA have been recruited in IS events. In 2010 and 2011, 13 and 14 by-product exchange projects have been completed, respectively. These involved packaging waste, scrap iron, wastewater treatment and waste oil. All synergies were one-to-one matches. Table 4.3 shows the environmental and economic results of these synergy projects. Meanwhile, the number of companies who publish environmental information was

14, 26, and 29 in the years of 2008, 2009, 2010 (TEDA-EPB, 2012).

However, one drawback of the strong government involvement in the IS project was that some companies only passively participated in the beginning (Sun et al., 2011). Many companies would have preferred to use existing logistics relationships for waste disposal rather than exchange their by-products or recovered resources, because the profit margins of these synergy projects are lower. Since company managers have been trained in traditional business models, their interest to join IS events has often been limited.

Number of recruited companies	Number of synergies	CO_2 reduction (10,000 tons)	Landfill diversion (10,000 tons)	Raw materials reduction (10,000 tons)	Revenue increase (RMB 10,000)
536	27	1.1	0.3	0.3	552

Table 4.3 – TThe environmental and economic results of the synergy projects within Switch-Asia Project by 2011.

4.3.4 System analysis

The system analysis is based on the event sequence analysis of the 5 key activities as Figure 4.5 illustrates. Basically, the years 2000-2005 were the initial era of TEDA's eco-transformation with the themes of cleaner production, ISO14001 and construction of environmental infrastructures. The era was characterized by the fact that IS-related company activities were not very significant (Figure 4.5(e)). During this era, the emphasis of the planning and guidance was on intra-firm cleaner production, building water treatment plants and co-generation plants, and connecting the industrial chains. Infrastructures were mainly launched before 2006 (Figure 4.5(b)). Figure 4.5(c) indicates that in this era few events related to economic and financial incentives targeting encouraging company activities, except for the WMC funding in 2004. The informational activities were at a stable and low level (Figure 4.5(d)) of no more than 5 events per year. Unlike the culture of cooperation in Kalundborg, the companies in TEDA lacked inter-firm communication most of the time (Sun et al., 2011). Furthermore, in this period there was no main coordinating body that could have improved the situation of incomplete information and fostered the dissemination of IS-related ideas to a wider business community. Consequently, by-product exchange and information disclosure were not substantial (Figure 4.5(e)). This type of events appeared only about 10 times per year.

The tide seems to have changed since 2006 when the Implementation Plan for TEDA's Circular Economy Pilot was carried out. In this emerging era, IS-related company activities increased markedly (Figure 4.5(e)) and physical synergies gradually emerged. Prevalent institutional incentives triggered companies to spontaneously share information and to join the IS network. Figure 4.5(a) shows a trend of growing institutional activity, which implies a positive governmental involvement in building up the institutional environment for IS in TEDA. The monitoring and evaluation of the environmental impacts were also strengthened (Figure 4.5(a)). The companies that failed the evaluations could be deprived of preferential policies. As the new environmental infrastructures were launched, more and more companies began to use recycled water and steam subsidized by TEDA's AC. The special funds in 2007 for environmental protection projects and energy saving gave an additional impetus to company participation. Ever since, the economic incentives have been consistently strengthened (Figure 4.5(c)). Financial rewards were also given to companies that continued publishing their environmental information. Meanwhile, the coordinating body, TEDA's Eco-center, functioned as a broker to provide the information and knowledge essential to build new IS relationships and to identify the potential synergies. These developments explain the growth in Figure 4.5(d) of informational activities since the establishment of the Eco-center in 2010. The number of events in 2011 increased by 85% compared with those in 2009. The awareness of IS and the inter-firm communication were enhanced through several conferences and training events organized by the Eco-center. Meanwhile, as economic incentives were offered, companies were encouraged to consider alternative solutions for solid waste reclamation and wastewater treatment. Figure 4.5(e) indicates that a surge of company activities occurred in 2010 on physical synergies, information exchange and disclosure. Networking activities created more opportunities for by-product exchanges, and strengthened the common understanding. 27 IS agreements were achieved for by-products and waste exchange. These successful practices led more company activities to join the IS program.

In spite of the progress in TEDA, no small number of barriers remains. In the interviews with local authorities and coordinators in TEDA, two main difficulties for TEDA's eco-transformation were mentioned:

- As a mixed industrial park, TEDA has a large number of companies from diverse industrial sectors which produce different types of waste. This is a consequence of the unplanned industrial structure of TEDA since its establishment in the 1980s. The fragmented industrial composition limits the possibilities for connecting industrial chains. The strategy of closed-loop chains was tried through inviting companies to settle down in TEDA, aiming to reclaim the waste in the industrial chains. This enforcement to create closed-loop chains may have had a

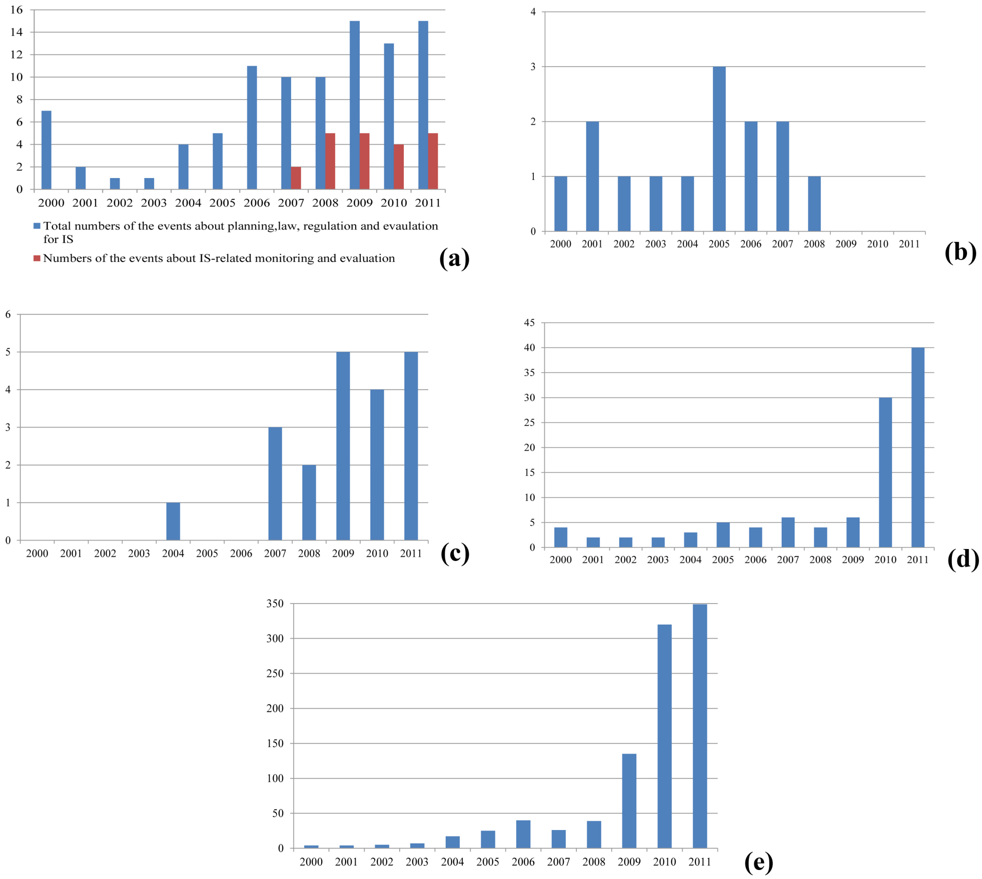

Figure 4.5 – Numbers of the five types of events per year. (a) is the numbers of the events of institutional activity. (b) is the numbers of the events of technical facilitation. (c) is numbers of the events of economic and financial enabler. (d) is the numbers of the events of informational activity. (e) is the numbers of the events of company activity. Data sources: TEDA Annual Yearbooks from 2000 to 2011; (Shi et al., 2010; TEDA, 2007); websites of TEDA Government, TEDA's Eco-center and TEDA's EPB.

short-term effect, but in reality the links did not evolve in a natural way, which resulted in incompatible and unstable couplings.

- There is no landfill tax nor Extended Producer Responsibility for general industrial waste in China, which results in a lack of pressure and motivation for companies to reduce, reuse and recycle. In addition, the current environmental regulation has an institutional barrier as it is lacking practical and standardized instructions. The regulations on industrial waste classification and reclamation are not systematic. The waste recycling market is immature and dominated by unqualified recyclers.

To overcome the first barrier, TEDA is operating the IS program in order to engage companies from various sectors in a symbiosis network that is flexible and can increase cooperation. The economic and environmental benefits from by-product exchange projects can be quantified and traced by TEDA's Eco-center. The combination of closed-loops within chains and networks of synergies between chains may be a solution for the eco-transformation of mixed industrial parks. Regarding the second barrier, TEDA can only guide companies to join the IS network through incentive policies and dissemination at the park level, the effect of which is still limited. The central government should issue clear and specific regulations to promote waste reclamation and waste recycling market. The relevant laws will also need to be strictly enforced.

TEDA's eco-transformation reveals a typical government-driven model in China where planning comes first, accompanied by other supporting policies (e.g., infrastructure services and economic incentives). Figure 4.6 and Figure 4.7 indicate the relevant actors mentioned above in 2000-2005 and 2006-2011. The arrows show how the actors influence each other in terms of institutional activity, technical facilitation, economic and financial enablers, informational activity, and company activity regarding IS (interpreted as material flow and energy/water flow). As revealed by these two figures, the role of TEDA's AC varied in different phases. It initially concentrated on planning and building infrastructures through investments and subsidies. Then the goals shifted to the incentive policies for IS and the evaluation and monitoring. The coordinating bodies in the business community and government, such as the WMC and the Eco-center, provide platforms for communication and consultation to assist policy implementation. Especially the Eco-center, as shown in Figure 4.7, plays the role of catalyst in generating a common understanding on eco-solutions. Figure 4.6 and Figure 4.7 also show how the main IS activities expanded over time from only utility sharing to more actual by-product exchanges and information sharing. Some companies in TEDA gradually evolved into material supplier, recycler and receiver. These findings suggest that the intervention at the park level can indeed facilitate the eco-transformation of industrial parks (e.g., adjustment of industrial structures, eco-labeling, rewarding solid waste reduction). However, TEDA, like many other EIPs, is also influenced by national institutional arrangements. Although current environmental and energy laws in China provide directive goals and guidance, the specific regulations have not been established yet. In other words, the gap between "what to do" and "how to do it" still needs to be bridged. Only a systematic institutional framework can thoroughly change the activity patterns toward actual eco-industrial development.

4.4 Discussion

4.4.1 Reflection on the approach

Process analysis has provided a novel view to grasp EIP development and to learn lessons from a historical case that continues to develop. By applying the framework, we assembled a database from individual events that enabled us to make a system analysis. We learned that understanding the eco-transformation of industrial parks requires dynamic systems thinking. When steering the eco-transformation, the strategies and decisions should be underpinned with a holistic understanding about what drives the transformation by what mechanisms, and how various drivers and mechanisms interact. We have deconstructed this web of drivers and mechanisms in five key activities: institutional activity, technical facilitation, economic and financial enablers, informational activity and company activity. The development in TEDA across the years has shown that each of these five activities does matter, but not equally in every phase. In this particular case, company activity was relatively weak compared with the others and the role of public authority was strong and dominant. In different phases, the intensity of various activities changed and the contributions made by various actors to these activities also varied. Across the board, a close reading of the qualitative and quantitative data indicates that TEDA shifted from a planned to a more facilitated model, with a positive outcome for the EIP's performance. It thus appears that one can draw valuable lessons from mapping the events using the approach we developed. Across case studies, one can check if similar or different patterns can be established, whether similar mechanisms and drivers have led to different outcomes. Eventually, EIP management can be compared and appropriately selected. Only when the mechanisms that determine changes have been captured and understood can we give underpinned policy advice on how to steer the system.

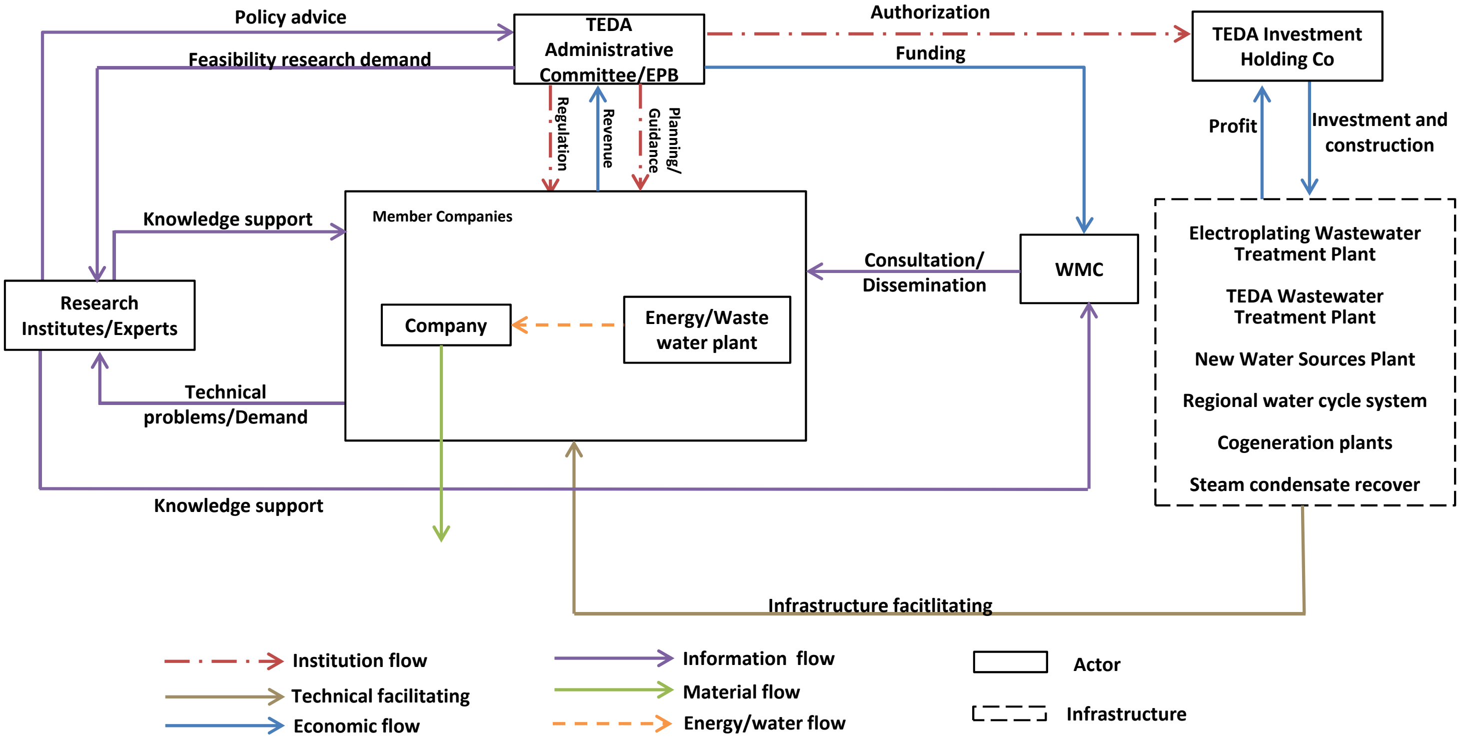

Figure 4.6 – TEDA's system structure in the initial era

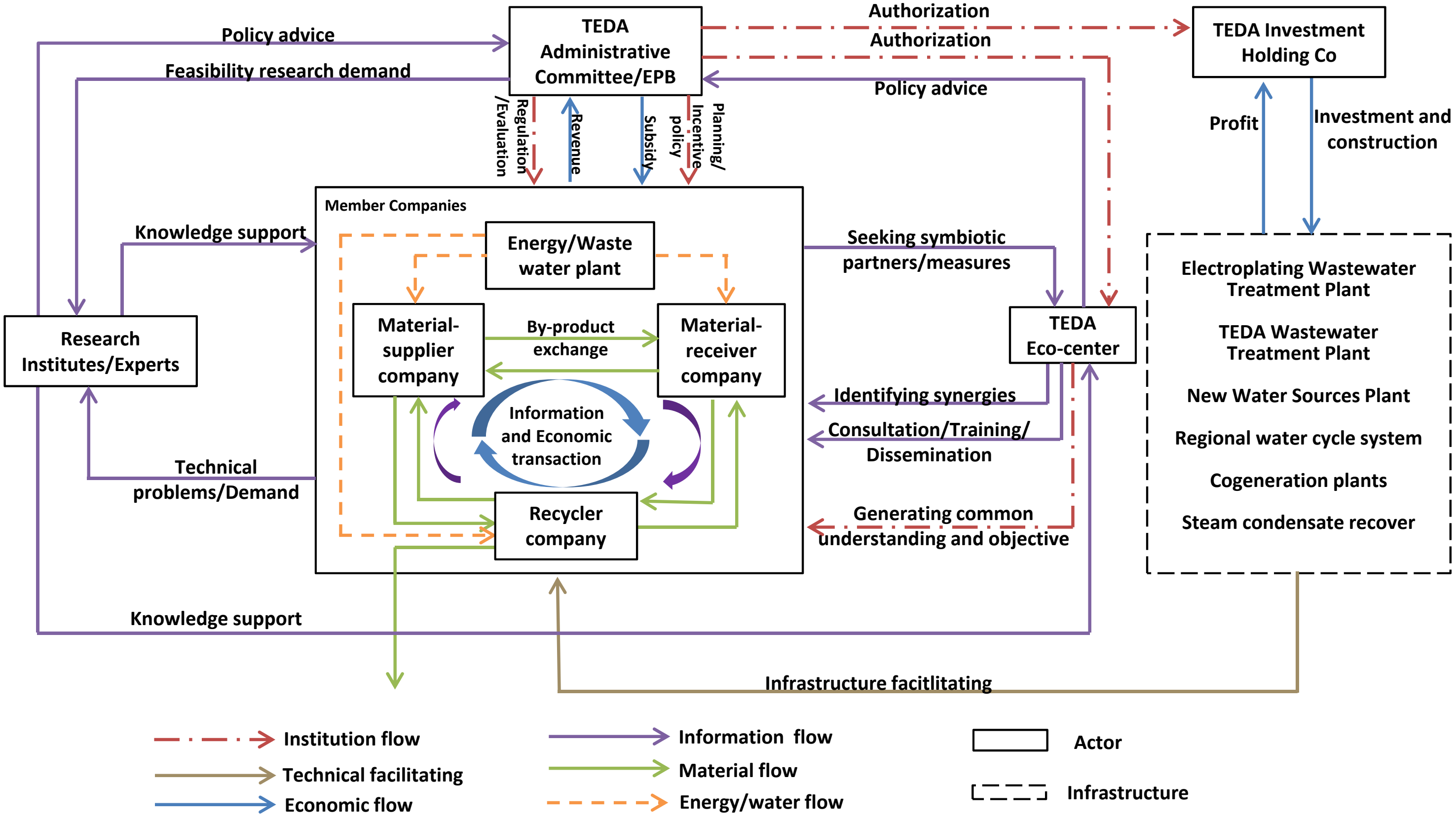

Figure 4.7 – TEDA's system structure in the emerging era

4.4.2 Scope and applicability

The scope of this research has limitations. Our focus is on a regional industrial park, hence the technical facilitation focuses on public utility projects for co-siting. For cross-regional programs, such as NISP, technical facilitation may involve the use of ICT tools. Moreover, the TEDA case shows that company activity does not have as much influence at the system level as the other key activities. It seems that company activity is an outcome that is co-shaped by the other four. This explains that the developed framework is suitable for analyzing both planned and facilitated EIPs. In more self-organizing environments, however, such as Kalundborg, company activity does play a vital role in driving the whole system and it changes the causal relationships between the key activities. Therefore, a next step should be to further validate and adjust the framework through applying it to other EIP cases in China and in other institutional and physical contexts.

TEDA's trajectory has shown a transition from "a planned EIP" to "a planned plus facilitated EIP". Government planning came first, and it soon was accompanied by supporting policies. In the initial era, networking utilities were provided for water and energy utilization. Several goals were set to guide the EIP's continuous development, such as closed-loop chains and industrial symbiosis. Moreover, the coordinating body created by the local authority strengthened the common understanding of IS business and promoted the spontaneous collaborative behavior among firms. Such an actor can integrate the information streams of local waste, water, energy and by-products. The coordinator can offer technical and consultancy services to uncover and foster synergy possibilities. It also provided decision-making advice to the national government to adjust the wider institutional framework in desirable ways. This strengthens the argument made by Chertow and Ehrenfeld (2012) that the top-down planned EIP model which stresses matching flows alone is less successful. The key is to stimulate firms to join and accept shared behavioral norms and a common understanding, which facilitates continuous inter-firm exchanges and resource conservation.

TEDA's approach is driven by public policy in the sense that it reveals the primary focus on institutional activity and the relative weakness of company activity. TEDA reflects a wider Chinese tendency that lets public authorities take a leading role in EIP development. However, it would be premature to assume that the same tendency exists or even should exist in other national and regional contexts. In terms of the systems approach laid out in this article, one could argue that the set of five activities to analyze EIPs around the world are likely to remain the same (therefore more or less "universal"), but their relative importance in general and the developmental phases can be different from that of TEDA. Subtle differences may already exist among various cases in China, where the national institutional framework is largely the same. Different contexts such as those in Denmark or the US are likely to show different interrelations and importance of the activities throughout development stages. Consequently, drawing policy lessons (Rose, 1993) regarding the successful intervention in eco-transformation from Denmark to China and transplanting institutions from Kalundborg to TEDA or vice versa cannot be underpinned by scientific evidence yet in this research. In other words, before policy recommendations can be formulated for a given case based on the lessons from another one, more research and analysis is needed on how institutional specificities, local preferences and the physical context (de Jong et al., 2002) affect the five key activities and what the implications are for policy transferability.

4.5 Conclusion

We have adapted the methodology of process analysis to deconstruct the mechanisms of eco-transformation and how the changes of an EIP unfold over time. An approach has been developed rooting in process analysis, industrial symbiosis and socio-technical systems to trace the five key activities that drive the evolution of an EIP. The structured process analysis approach directs one to bring together qualitative information about the events in an EIP system and their sequence over time. The database thus built allows one to quantify trends of the key activities.

The approach was applied to the TEDA case in order to analyze TEDA's eco-transformation between 2000 and 2011. The application of the analytical approach was examined through the case study. Overall, the five key activities sufficiently cover the main determining factors during an EIP's development. Thus we conclude that the process analysis approach led to a structured and documented analysis that is open to adjustment, expansion and critique. These characteristics make the approach amenable for an institutional environment that differs from the Chinese context, as the relative importance of the five key activities and the recommended policies can be different. Through developing a systemic analytical framework, a major step has been taken to deconstruct EIP development and to enrich our understanding about the underlying mechanisms and drivers of eco-transformation. Further work is required to flesh out how this framework is to be deployed or adjusted in different institutional contexts. Comparative analysis may provide clues on the possibilities, limitations and pre-conditions for transferring policy recommendations across borders.

5

What makes eco-transformation of industrial parks take off in China?

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5.1 Introduction

Industrial symbiosis (IS) is based on realizing mutually profitable transactions, which may inspire a network of businesses to seek novel sourcing of required inputs and value-added destinations for non-product outputs, and improved business and technical processes (Lombardi and Laybourn, 2012). The concept of IS initially revolved around physical exchange of materials and by-products, shared management of common utilities and infrastructures (Chertow, 2000). Gradually, it has been enlarged to involve knowledge sharing and long-term cultural change (Lombardi and Laybourn, 2012). After reflecting on planned and unplanned IS projects, scholars appear to have reached a consensus that the key to IS lies in self-organizing activities embedded in a context that is shaped by policy requirements, economic incentives, common understanding and social norms (Chertow and Ehrenfeld, 2012; Mirata and Emtairah, 2005; Boons and Howard-Grenville, 2009; Ashton, 2008). Among the success factors, the role of governments may exert strong and wide influence through using policy instruments such as economic incentives, regulatory and voluntary instruments. Indeed, a suitable institutional setting (a set of rules and norms) can influence actor behavior and steer the development of the system to a desired direction (Ostrom, 2005), which in this case is a shared belief that the efficient utilization of energy and materials is a necessary condition for a prosperous regional industrial system. Scholars in IS have suggested that governments should stimulate collaborative networking of firms and work together with business associations and universities, aiming to create a continuous self-organizing process where governmental scaffolding is no longer required (Costa et al., 2010; Domnech and Davies, 2011). The eco-transformation of an industrial park then requires integrated institutional arrangements to direct companies' business routines and gradually shift from command-and-control measures to performance-oriented incentives that foster self-organization.

In 2001, the Ministry of Environmental Protection (MEP) of China launched the program of National Demonstration Eco-industrial Parks to balance environmental impact and industrial activities (Shi et al., 2012a; Zhang et al., 2010). According to the national standards issued in 2009, an Eco-industrial Park (EIP) aims to establish the model of industrial producer, consumer and decomposer through resource-service sharing and by-product exchange. This implies the pursuit of closed-loop recycling of materials, energy cascading and information feedback. Moreover, EIP's development requires innovation of institutions (MEP, 2009). In China, EIPs incorporate the principles of IS, such as utility sharing and waste exchange. Meanwhile, Chinese EIPs also adopt various environmental management tools (for example, cleaner production, green supply chain and energy audit) to handle the different environmental issues at intra-firm, inter-firm and at regional levels (Shi et al., 2012b; Tian et al., 2013). This has been beyond the concept of IS that focuses on the synergies between companies. Therefore, how to use integrated policy packages to effectively implement the diverse tools is vital to favor EIP development in China.

The progress to-date of China's national EIP program has been reviewed, such as management procedures, features of the national EIPs, and the applicability of national EIP standards (Geng, Zhang, Côté and Fujita, 2009; Zhang et al., 2010; Tian et al., 2013; Shi et al., 2012a). Most of the Chinese EIPs are planned as transformation of existing industrial parks and improve their environmental performance (Shi et al., 2012b). Local authorities usually play multiple roles: administrator, investor, planner and facilitator. This explains the progress of China's EIP initiatives that have been achieved in a relatively short time, as these authorities had public utilities built to mitigate end-of-pipe pollution and enforced EIP planning. However, the risk associated with such a top-down retrofitted EIP is that overemphasizing matching flows limits market demand and the embeddedness of institutions (Chertow and Ehrenfeld, 2012). To transform the existing industrial parks, another key is to leverage markets and foster norms for local companies that enable them to capture and continue synergies. This requires appropriate policy instruments to materialize. Relying on command-and-control and mandatory environmental standards can only solve specific pollution problems, because it does not improve companies' attitude towards environmental responsibility (Geng and Zhao, 2009). Indeed, local companies often show a limited interest in EIP projects and believe these are mostly government-led initiatives (Shi et al., 2012b). Some would even prefer to pay levies or fines rather than to reduce their waste or pollution. To resolve this issue, a facilitated EIP model has been proposed to engage bottom-up company participation through appropriate intervention (Paquin and Howard-Grenville, 2012; Hewes and Lyons, 2008). In China, the facilitated model has been explored through the coordinating roles of local authorities or other third-party organizations (Chertow and Ehrenfeld, 2012; Shi et al., 2012a). Nevertheless, the debate on tailored EIP models in China requires thorough analysis underpinned with empirical evidence. Comprehensive case studies appear to be useful to increase our understanding of eco-transformation, while lessons learned can help authorities to foster industrial park eco-transformation.

In this chapter, the focus of our research is on "the effects of policy instruments that could develop viable eco-industrial parks in China". Our objective is to provide empirical grounding for assessing and improving EIP management at the park level in China through reviewing the EIP development process since 2000 and analyzing the performance of two cases. The structure of the chapter is as follows. Section 5.2 presents the available policy instruments at the park level that shape and promote eco-industrial development. Section 5.3 introduces our research methods for the comparative case study, and details the criteria for case selection, research approach and data collection. In section 5.4, we present empirical evidence and analyze the EIP development of Tianjin Economic-technological Development Area (TEDA) and Dalian Development Area (DDA). Finally, we draw the lessons learned from the comparative case study for other policy-driven EIPs.

5.2 EIP management in China

For most national level industrial parks, an Administrative Committee (AC) has been set up and accredited by the municipal government to take charge of the park's development and management[1]. On behalf of local authorities, the Environmental Protection Bureau (EPB) in the industrial park supervises companies' environmental management and compliance with laws on environmental protection and commitment to pollution prevention. Although an AC cannot issue provisions with legislative power like municipal and provincial governments, the guidelines and policies adopted by the AC at the park level can influence companies' decisions and shape the context for EIP development. Especially as a mature national environmental legislation has not yet developed in China, the instruments of the AC at the park level can remedy the institutional barriers to advance environmental performance.

The participants of the national EIP program have explored various measures to implement EIP principles and to overcome barriers, for example, the conflicts between EIP construction and existing environmental policies (Zhang et al., 2010). Thus, National Demonstration EIPs provide an experimental field for testing the effect of policy packages for environment management and eco-transformation. When preparing for the EIP program, the ACs are required to submit their EIP planning reports that detail how to retrofit the existing sites. These reports include how to match the flows among tenants, address the capacity of environmental infrastructures, and list the complementary projects that would be recruited in order to optimize the industrial structure (Geng et al., 2008). Additionally, in these reports, the quantitative targets for EIP performance had to be specifically formulated, such as the reduction rate of energy intensity and chemical oxygen demand (COD) (Zhang et al., 2010). As the planning of EIP development is approved by the central government, the eco-transformation mainly starts from six aspects (see Table 5.1): (1) administrative organization that leads the eco-industrial development; (2) industrial structure adjustment; (3) environmental infrastructures; (4) economic instruments; (5) regulatory instruments and (6) voluntary instruments.

5.3 Research methods and data collection

We have selected Tianjin Economic-technological Development Area (TEDA) and Dalian Development Area (DDA)[2] as our case studies. Several criteria lead us to choose these two cases. TEDA and DDA have common basic

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[1] In some industrial parks in Shanghai, the management is under the charge of a development corporation. The ACs in these Shanghai industrial parks are the liaison between the corporation and local government.

[2] DDA has combined the neighbor residential area since 2010 at the administrative level and is currently named Jinzhou New District. This article keeps focusing on DDA because it is still the major industrial area in this new district.

Instruments	Concrete implementation
Administrative organization	• Set up leading office for promoting eco-industrial development or circular economy. • Apply for regional ISO14000 certification.
Industrial structure adjustment	• Recruit anchor tenants and the related supporting industries. • Recruit complementary projects to connect and extend the existing industrial networks. • Recruit waste scavenger companies.
Building/retrofitting environmental infrastructures	• Centralized wastewater treatment and recycling: Wastewater treatment plants; Rain water collection; Seawater desalination; Water pipelines. • Energy system: Cogeneration plants; Flue gas desulphurization of coal-fired boiler; Solar power and wind power for electricity and lighting; Waste-to-energy.
Economic instruments	• Subsidize companies using reclaimed water. • Fund firms to qualify and apply for ISO14001 certification. • Fund, reward, give priority of land supply and discount loans, provide tax exemption/deduction for energy-saving and environmental protection projects.
Regulatory instruments	• Mandatory cleaner production and energy auditing for energy-intensive consumers or polluters. • One ballot veto for intensive energy/material/emission-intensive projects. • Examine and issue pollution discharge permits, waste treatment permits. • Carry out administrative and economic penalties to firms that fail environmental assessments.
Voluntary instruments	• Disseminate the knowledge of industrial symbiosis, circular economy and cleaner production. • Encourage environmental information disclosure. • Voluntary agreement on energy-saving signed between AC and energy intensive companies. • Set up a coordinating organization to organize inter-firm networking, uncover existing synergies, and foster the potential synergies. • Ranking environmental performance of companies. • Training about ISO14001, cleaner production, industrial symbiosis and circular economy.

Table 5.1 – General instruments of AC to promote EIP development at the park level in China. Source: (Geng and Zhao, 2009; Zhang et al., 2010; Su et al., 2013; Tian et al., 2013; MEP, 2009)

features like twin industrial parks (see Table 5.2). Also, they develop in the same context that is shaped by Chinese economic and environmental policies. Both as sector-integrated EIPs, TEDA and DDA were among the earliest ones endeavoring eco-transformation in 2000 and both became pilot national EIPs in 2004. Therefore, the national EIP standard can be used to analyze their performance.

A number of authors have studied on TEDA and DDA. Shi et al. (2010) investigated the evolution of TEDA's environmental institution and synergies, while its planning and optimization of water management and waste management were addressed by Geng and colleagues (Geng et al., 2007; Geng

Features	TEDA	DDA
Location	Tianjin City, China Connected with Tianjin Port, 38 km away from airport and 1 hour to Beijing by car.	Dalian City, China. Nearby Dalian Port, 27 km away from Dalian City center and 25 km away from airport.
Established time	1984	1984 
Developed area (km²)	98	90
Population (thousand)	536	650
Companies	28464	24727
Main industries	Electronics and telecommunications, automobile manufacturing, equipment manufacturing, petro-chemistry, food and beverage, biomedicine, aerospace industry, new energy and new materials.	Petro-chemistry, electronic telecommunications, equipment manufacturing, automobile parts and shipbuilding.
Start time of eco-transformation	2000	2000
Status	Brownfield industrial cluster with multi-industrial sectors	Brownfield industrial cluster with multi-industrial sectors
Initiator of eco-transformation	TEDA Administrative Committee	DDA Administrative Committee
Main steps of eco-transformation (Year)	ISO14000 National Demonstration Park (2000). Environmental Management Pilot Park (2001) Plan of National Demonstration EIP approved by MEP (2004). Circular Economy Pilot Park (2005). Passed the evaluation and accredited the label of National Demonstration EIP (2008).	ISO14000 National Demonstration Park (2000). Environmental Management Pilot Park (2001) Plan of National Demonstration EIP approved by MEP (2004). Circular Economy Pilot Park (2005).

Table 5.2 – General features of TEDA and DDA. Data sources:(TEDA, 2010a; DDA, 2011b)

and Yi, 2006). The practice of the environmental management system between 2000 and 2002 was introduced by Geng and Côté (2003) in DDA, and DDA's eco-efficiency of 2006 was analyzed by the method of emergy (Geng et al., 2010). When evaluating the Chinese EIP standard, Geng et al. (2008) used TEDA and DDA, respectively, to test the standard's applicability. In the literature, the EIP activities in the two sites have been analyzed from various angels. It provides much information and a starting-point for our analysis. However, what is lacking is a structured analysis of policy instruments at the park level that influence eco-transformation. Besides, for both sites, the EIP performance has not yet been assessed based on a continuous dataset to reveal the effectiveness of policies.

We conjecture that such a comparison between TEDA and DDA resting on thorough empirical evidence would be insightful to elucidate their commonalities and differences and to unravel possible causes thereof. Lessons can be drawn for policy making to foster eco-transformation in an industrial park. We anticipate that the pattern of the development and performance in TEDA and DDA can demonstrate a profile of China's EIP development.

The case study will concentrate on how the EIP program is promoted in the two sites according to the policy instruments in Table 5.1. It will unfold in four sub-sections: 1) general context of the two cases, 2) institutional activities, 3) environmental infrastructures, and 4) the results of eco-transformation. A qualitative analysis is conducted to determine what instruments were used by AC and how to stimulate companies' participation in EIP projects. Quantitative assessment is used to investigate the economic and environmental outcome of the policy instruments and environmental infrastructures.

To assess the environmental performance, we used the National Standard for Sector-integrated Eco-industrial Parks (MEP, 2009) as a benchmark. This standard has four categories: 1) economic growth, 2) material reduction and recycling, 3) pollution control, and 4) administration and management. Our selection of indicators covered only the second and third catalogues with respect to energy, water and waste. The reasons are that the last amendment of the standard in 2012 has proposed that the economic growth rate is no longer compulsory (Tian et al., 2013); and the data for the fourth category are not suitable to determine as these indicators are hard to quantify.

We first assess the performance in TEDA and DDA with respect to each indicator. Subsequently, the indicators are aligned to allow for a holistic evaluation and elucidate overall EIP performance in TEDA and DDA. The analysis is framed as a Multi-Criteria Decision Analysis (MCDA). The methods of MCDA have been widely used in environmental science, such as AHP (Analytic Hierarchy Process), TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and MAUT (Multi-Attribute Utility Theory) (Pohekar and Ramachandran, 2004; Kiker et al., 2005; Huang et al., 2011). We have selected TOPSIS, because this method can select the best alternative by using a simple mathematical algorithm. Moreover, it is suitable when the sample and the number of indicators is small (Wang and Lee, 2009; Yoon and Hwang, 1995; Wu et al., 2008). In the classic TOPSIS method, the weights of the indicators are determined from expert opinions. To avoid this subjectivity, we employ an advanced TOPSIS that uses information entropy to obtain the weights (Huang, 2008; Wu et al., 2008). The procedure for calculation is given in the Appendix E.

The indicators in the national standard only view the industrial park as a whole, which cannot reveal the performance of company participation. This presents a problem, as company activity is a key indicator to reveal the effects of the policy instrument. To overcome this problem, we have established a database for TEDA and DDA that consists of the events that characterize their eco-industrial development. A process analysis approach (Boons and Spekkink, 2012; Yu et al., 2014) has been adapted to track the events related to company activity on promoting eco-industrial development. We focus on the changes of three indicators: 1) ISO14001 and environmental/energy projects (that is the project can reduce pollution or improve energy efficiency, such as desulphurization, cleaner production audit and energy audit), 2) companies joining IS projects, 3) environmental information disclosure and information exchange for potential synergies. The indicators are used to code the events in the databases about the EIP-related activities in TEDA and DDA from 2000 to 2011. Each detected event of company activity is given a value of “1”. Eventually, after compilation of the empirical data, trends of company activities can be plotted. Thus the changes of company activities can be detected as policy instruments are adapted over time.

Regarding the data collection, the data sources include the government documents, annual reports and statistical yearbooks from the ACs and the EPBs. Additionally, our field research in the two sites also enriched our information. When using national EIP standard as benchmark, we collect the data of EIP performance from TEDA’s Yearbooks and DDA’s EPB offices. Due to the discontinuous data before 2008, we assess and compare the data from 2008 to 2011.

5.4 Case studies

5.4.1 General context of two cases

TEDA and DDA both were established in 1984 and have become local economic pillars. Their GDP was 154 billion and 120 billion RMB respectively in 2010, an increase of 80% and 83% compared with 2001. Table 5.2 has provided an overview of their general features.

Like other national industrial parks in China, TEDA and DDA encountered bottlenecks in the 1990s. First, the priority of national industrial parks was to attract foreign investment and to increase export (Shi et al., 2012a). However, the competition among the national industrial parks was so intense that they needed to explore new measures to recruit more international capital (Shi et al., 2010). Second, as the export increased, the environmental standards of the products and production process needed to be improved to enter the international market. Third, the pollution problems in the industrial parks had become severe due to the lack of environmental principles in the planning and industrial production in the 1980s (Geng and Côté, 2003). Additionally, TEDA and DDA both suffered from water scarcity that constrained production and development. Under such conditions, in 2000, the ACs of TEDA and DDA initiated the eco-transformation to retrofit the existing sites, basically following the strategies of ISO14000 certification, national EIP and circular economy. The advanced infrastructures and improved environmental management were deployed to attract more investment and to resolve the pollution issue in the parks. Moreover, the EIP practice has strengthened the completion within industrial chains and the links between industrial sectors, intending to generate increased clustering in the mixed industrial parks.

5.4.2 Institutional activities

When preparing for the EIP pilot programs, both TEDA and DDA established a new office to lead and issue specific planning and guidelines for eco-industrial development. TEDA and DDA obtained the label of ISO14000 National Demonstration Park in 2000. Such certification is given to an AC to indicate that the governmental organization has the capacity to operate environmental management. This is also a major plus in attracting more investment (Geng and Zhao, 2009). The complementary projects have been recruited by ACs to expand the industrial network, which gradually forms the pillar industries mentioned in Table 5.2. Moreover, TEDA and DDA have recruited recycling companies to treat and recycle hazardous waste and other industrial solid waste. In TEDA, HejiaVeolia started its business in 2003 and has a treatment capacity of 57,800 tons/year, 14% of which is recycled. In DDA, Dalian Dongtai was established in 1991 and currently has a treatment capacity of approximately 80,000 tons/year.

Regarding the policy instruments, Table 5.3 presents a collection of policy instruments used in TEDA and DDA since 2000 to carry out the goals of pollution control, material reduction and recycling. The policy instruments are in the categories of economic, regulatory and voluntary instruments. To deal with water scarcity, TEDA proposed price mechanisms in 2000 and 2002 to stimulate companies to retrofit their own wastewater treatment devices and to use reclaimed water. In 2004, the sales amount of reclaimed water increased by 84.1% compared to 2003. In order to reduce sulfur dioxide (SO_2) emissions, TEDA's AC subsidizes companies which would like to equip or

Instruments	Year	TEDA	Year	DDA
Economic instruments	2000	Exemption from sewage disposal fee. A company whose wastewater is reused or reaches the Grade II national standard is exempted from the sewage disposal fee (1 RMB/ton in 2000, currently 1.2 RMB/ton).	2000	Funding of 50% application fee for ISO14001 certification.
			2000	Water quota pricing system.
	2002	Encouraging reclaimed water. The price of the reclaimed water was 3.9 RMB/ton (currently 4.5 RMB/ton), 20% lower than the tap water.	2002	Encouraging reclaimed water. The price of the reclaimed water was 2.3 RMB/ton, 23% lower than the tap water.
	2007	Subsidy for desulphurization facilities to reduce SO_2.	2006	Funding for environmental protection projects. Companies get funding for up to 30% of the total investment.
	2007	Funding for waste reduction and recycling, energy-saving and environmental information disclosure (Budget:100 million RMB/year)		
Regulatory instruments	2007	Mandatory environmental information disclosure for pollution intensive and energy intensive companies.	2001	Expanding district heating and terminating the distributed boilers (capacity ≤ 1 ton/h).
			2009	Mandatory flue gas desulphurization for steam boilers (capacity ≥ 75 tons/h).
	2009	Integrity evaluation for companies' environmental performance.	2011	Cleaner production auditing for pollution intensive companies.
	2010	Measures on energy management for the energy intensive companies (energy consumption ≥ 1 kiloton standard coal equivalent/year).		
Voluntary instruments	2004	Waste minimization club.	2000	Free consulting services and dissemination for ISO 14001 together by the AC and external experts.
			2008	Commitment to environmental self-regulation.
	2005	Eco-labeling management system for industrial solid waste.		
	2007	Guidelines for voluntary environmental information disclosure.		
	2010	Industrial symbiosis coordination program involving dissemination, training and match-making workshops.		
	2010	Negotiated agreement on energy-saving between AC and energy intensive companies.		

Table 5.3 – Major policy instruments to promote EIP in TEDA and DDA. Source:(TEDA, 2004, 2007, 2012; DDA, 2004, 2006, 2011a; Shi et al., 2010; Geng and Côté, 2003).

retrofit desulphurization facilities. Companies that retrofit desulphurization facilities can get the subsidy of 5.28 RMB per ton for steam production as long as the emission meets the national standard. The first four companies whose total SO_2 emissions accounted for 90% of TEDA signed agreements with the AC in 2007 and increased their desulphurization efficiency by more than 98%. Furthermore, TEDA has provided funding since 2007 to stimulate more company participation (Shi et al., 2010). The current catalogue covers energy saving, solid waste utilization, desulphurization, ISO14001 certification, eco-labeling and environmental information disclosure. Funding can be organized as direct subsidy, discounted loan or reward (TEDA, 2011b). By 2011, the total amount of funding reached 160 million RMB for 400 projects. The regulatory instruments in TEDA mainly target environmental information disclosure and energy management. The intensive energy consumers and polluters that refuse to publish environmental information or fail the evaluation will be deprived of preferential policies and cannot apply for the environmental verification for refinancing or being listed via the stock market. Aiming at stimulating company participation, several voluntary approaches have been employed as Table 5.3 shows. TEDA set a coordinating organization (Eco-center) to organize an IS program and provide consultancy on eco-solutions. As a professional organization, Eco-center regularly organizes the training and workshops whose topics are related to the current highlights of environmental policies. So far, the Eco-center has recruited 600 companies and accomplished 40 synergy projects through match-making workshops, training and dissemination. These IS projects have avoided 170 kilotons of solid waste landfill, 700 kilotons of raw materials and 30 kilotons of CO_2 emissions (Eco-center, 2012). Moreover, voluntary agreements on energy saving were signed by 30 companies that reduced a total of 60 kilotons standard coal equivalent in 2010.

DDA's policy instruments mainly focus on economic and regulatory instruments. Between 2000 and 2003, the AC of DDA initiated the program of an environmental management system (EMS). As Table 5.3 shows, measures were issued to implement EMS to improve water management, reduce SO_2 and encourage companies to apply for ISO14001. A water quota pricing system was set to release the pressure of water shortage before the reclaimed water plant was built. The industrial users must pay 20 times the regular rate if the water usage exceeded quotas (Geng and Côté, 2003). The reclaimed water plant in DDA was a BOT (Build-Operate-Transfer) project invested by Hengji Water Company. The AC subsidizes 0.36 RMB/ton to the reclaimed water producer, and made the price of reclaimed water lower than tap water. Thus the use of reclaimed water benefits both producers and consumers (Geng et al., 2008). To encourage companies' environmental management, DDA funds 50% of the application fee for the ISO14001 certification. By 2009, 38 companies had been funded for ISO 14001 certification with a sum of approximately 760 thousand RMB. Moreover, another funding program was issued in 2006 to support projects on wastewater treatment and reclaimed water, desulphurization and solid waste recycling. By 2011, the total amount of funding reached 6 million RMB and 10 companies' projects were supported. The regulatory instruments in DDA focus on district heating. These require heating suppliers to install desulphurization devices in order to reduce SO_2 emissions. In addition, a cleaner production audit was conducted in 16 intensive polluting companies in 2011, and the results were announced to the public. With respect to voluntary instruments, in 2000, DDA's AC provided consulting services for local companies to establish EMS systems and adoption of ISO14001 certification. Additionally, the EPB of DDA and 12 foreign-capital companies (such as Canon and Intel) together initiated an environmental self-regulation activity in 2008. They formulated plans to reduce energy consumption and pollutant generation. This kind of voluntary activity engaged another 28 companies in 2009.

5.4.3 Environmental infrastructures

The water/energy consumption and pollution will be aggravated in an industrial park as new companies settle or tenants expand their production capacity. Improvement of regional environmental infrastructures can release the stress. Sharing infrastructures with high quality and low cost can reduce companies' treatment burden and prevent illegal discharge, which enhances the overall environmental performance of an industrial park (Shi et al., 2010; Yuan et al., 2010). However, such infrastructure projects require large investments or subsidies. Infrastructure investment and construction are usually commissioned to a state-owned development company authorized by the AC. Figure 5.1 and Figure 5.2 present the main centralized water and energy infrastructure system in TEDA and DDA since the eco-transformation. The capacity and environmental outcome are also illustrated in the figures. From 2000 to 2011, the investment in the infrastructures in Figure 5.1 was approximately 880 million RMB. Their development was financially supported by TEDA Investment Holding Co., except for the BOT project of the wastewater plant in the west zone. In DDA, Dalian Detai Investment Holding Co. invested 456 million RMB in wastewater treatment utilities as shown in Figure 5.2. The reclaimed water plant was a BOT project and the DDA local authority invested in a 30 km long pipeline as an auxiliary project.

Due to water scarcity, TEDA and DDA have intended to build a centralized wastewater treatment and reclaimed water system since 2000. Through the building and retrofitting of wastewater treatment plants, the domestic and industrial sewage can be completely treated to meet the national standard for wastewater discharge. The TEDA New Water Source Plant started to produce reclaimed water in 2002 by using the sewage from the No.1

Wastewater Plant whose standard of effluent meets Grade I-B[3]. Meanwhile, the New Water Source Plant supplies approximately 1000 tons of reclaimed water per day to Binhai Energy Cogeneration Power Plant for cooling and production, which has resulted in a cost saving of approximately 0.53 million RMB/year. Currently, the pipelines for reclaimed water cover the entire TEDA area. Aided by the price mechanism, the consumption of reclaimed water has gradually increased. In 2011, sales of reclaimed water amounted to almost 3 million tons (TEDA, 2011a), mainly for industrial users. The profit of reclaimed water production was about 1.8 million RMB. In TEDA, the price of reclaimed water is 1.45 RMB/ton lower than that for tap water, which means that the industrial users of reclaimed water together saved 4.3 million RMB in 2011. In DDA, since 2003, the Hengji Reclaimed Water Plant started to supply reclaimed water to 17 companies. The usage of reclaimed water resulted in a cost saving of 0.9 RMB/ton compared with using tap water in DDA.

Besides the economic benefits, the environmental outcome in Figure 5.1 and 5.2 also show that the environmental infrastructures contribute to the reduction of COD and SO_2 emissions, tap water consumption and fly ash generation. Together, these infrastructures assisted TEDA and DDA to meet the national EIP standard. Especially in DDA, the centralized wastewater treatment plants have all reached Grade I-A of the national standard for wastewater and achieved a 90% reduction rate with respect to COD (DDA, 2006). Additionally, the No.2 Cogeneration Plant equipped with an SO_2 scrubber has replaced 66 self-serviced coal-fired boilers in DDA, which has significantly reduced the SO_2 emissions.

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[3] As Chinese Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB18918-2002) requires, Grade I-A effluent has COD no more than 50 mg/L. And Grade I-B effluent has COD no more than 60 mg/L.

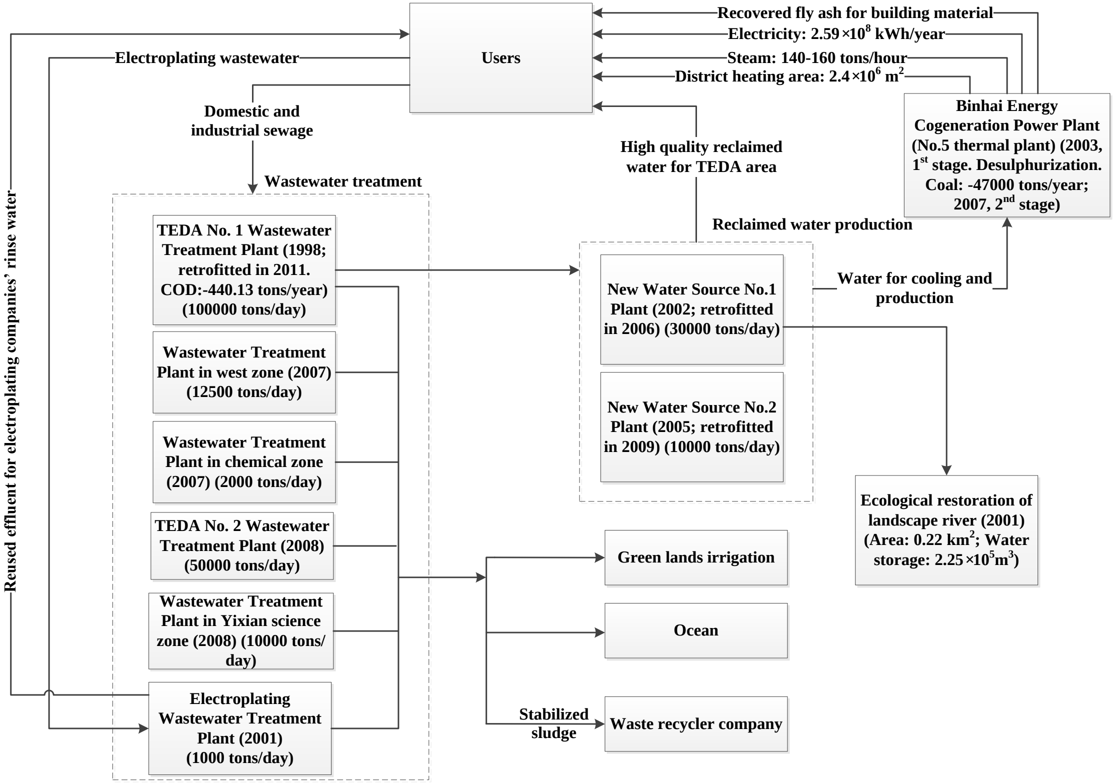

Figure 5.1 – The centralized water and energy system in TEDA. The year was the time when the utility started to operate. The capacity is the designed capacity. Data sources:(TEDA, 2004, 2007, 2012) and the field research in TEDA. kWh refers to kilowatt hour.

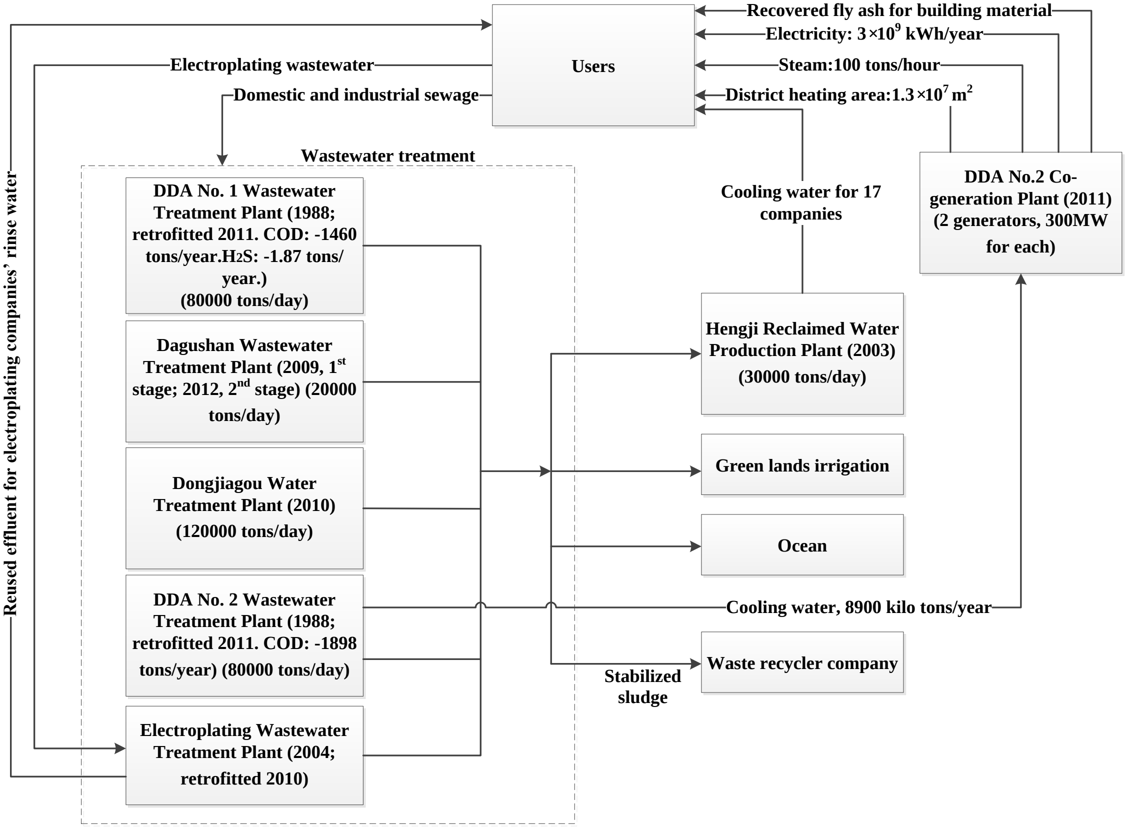

Figure 5.2 – The centralized water and energy system in DDA. The year was the time when the utility started to operate. The capacity is the designed capacity. Data sources:(DDA, 2004, 2006; DLHKY, 2009) and the field research in DDA. kWh refers to kilowatt hour. MW refers to megawatt.

5.4.4 Results of eco-transformation

Progress according to the national EIP standard

Table 5.4 shows the performance of the main indicators and the growth rate in 2011 (base year: 2008). The indicators, criteria and calculation are in accordance with the national EIP standard (MEP, 2009).

The energy consumption per IAV had steadily been reduced by 11% in 2011 from 2008. Its four-year average value was 0.144 tce/10^4 RMB, 71% lower than 0.5 tce/10^4 RMB (the threshold outlined in the standard), which shows that TEDA has made good progress on increasing energy efficiency. The policy instruments on water management result in the effects on reducing and reclaiming wastewater. The four-year average value of the indicators on water (freshwater consumption, wastewater discharge and COD discharge) were 51.8%, 69.4% and 68.8% lower than the national standard, respectively. The freshwater consumption and the wastewater discharge were reduced by 29.2% and 40.1%, which is evidence of improved water utilization. The reuse rate of industrial water on average was 17% higher than the national standard. For waste management, a 35% decrease of solid waste generation was realized, and a 4.6% growth of the comprehensive use rate. The subsidy for desulphurization facilities led to a 48.7% reduction of SO_2 emissions.

In DDA, the energy consumption and SO_2 discharge did not meet the national standard in 2008. Efforts have been made to reduce energy consumption and SO_2 emissions: a 18.9% and 33.2% reduction was realized in 2011, respectively. However, the SO_2 emissions still failed the national standard and thus requires attention from policy makers. The four-year average value of freshwater consumption, wastewater discharge and COD discharge were 24.9%, 39.3% and 67% better than the national standard. The high quality of the wastewater treatment utilities that were built or retrofitted after 2008 contributed to the 28% reduction of COD discharge. The reuse rate of reclaimed water grew by 9.5%, which indicates an ongoing improvement on sewage recycling, but the average value still lagged behind the national standard by 43.8%. The two indicators on solid waste management had met the standards, however, the reduction of solid waste discharge did not change much in the four years. The comprehensive use rate of industrial solid wastes even fell by 0.8%. Thus DDA should be alert on solid waste management.

		Indictor (criterion)	**Unit**	**TEDA**					**DDA**				
				2008	**2009**	**2010**	**2011**	**Growth rate**	**2008**	**2009**	**2010**	**2011**	**Growth rate**
Material reduction and recycling	I_1	Energy consumption per IAV (≤0.5)	tce/10^4 RMB	0.154	0.143	0.142	0.137	-11%	0.53	0.45	0.4	0.43	-18.9%
	I_2	Freshwater consumption per IAV (≤9)	$m^3/10^4$ RMB	5.34	4.19	4.05	3.78	-29.2%	8.8	4.9	6.66	6.68	-24.1%
	I_3	Wastewater discharge per IAV (≤8)	ton/10^4 RMB	3.07	2.58	2.31	1.84	-40.1%	6.3	4.06	4.52	4.55	-27.8%
	I_*	Reuse rate of industrial water (≥75) of TEDA; Reuse rate of recycled water of DDA (≥40)	%	88.03	87.4	87.5	87.74	-0.33%	21	27	19	23	9.5%
	I_4	Solid waste generation per IAV (≤0.1)	ton/10^4 RMB	0.04	0.028	0.029	0.026	-35%	0.05	0.034	0.05	0.05	0
	I_5	Comprehensive use rate of industrial solid wastes (≥85)	%	90.71	90.77	90.86	94.92	4.6%	87	92	86.1	86.3	-0.8%
Pollution control	I_6	COD discharge per IAV (≤1)	kg/10^4 RMB	0.34	0.25	0.36	0.3	-11.8%	0.4	0.35	0.27	0.29	-27.5%
	I_7	SO_2 discharge per IAV (≤1)	kg/10^4 RMB	0.39	0.31	0.26	0.2	-48.7%	2.5	2.15	1.65	1.67	-33.2%

Table 5.4 – Performance of material reduction and recycling, and pollution control in TEDA and DDA. Note: IAV is industrial added value. tce is ton of coal equivalent. As regards I*: Although the data are insufficient for both cases, we have kept it to show the performance of water reclaiming in TEDA and DDA, respectively. Data sources: (TEDA, 2008, 2009, 2010a, 2011a) and DDA's EPB office.

Analysis results from using TOPSIS

The analysis above reflects the performance with respect to each indicator in accordance with national standard. We also would like to see the overall EIP performance and the progress of the two categories: material reduction and recycling, and pollution control. This comprehensive analysis can extract the effects from a portfolio of policy instruments. To this end, TOPSIS is used to analyze the performance of the two EIPs in the four years. The 8 alternatives are the four-year performance of TEDA and DDA, with respect to the indicators I_1 to I_7 as listed in Table 5.4. The indicator of I* is eliminated because of insufficient data. Thus a matrix matrix $(x_{ij})_{m\times n}$ consisting of 8 alternatives and 7 indicators is generated. First, we use TOPSIS to evaluate the comprehensive environmental performance based on all 7 indicators. Second, the 7 indicators are divided into two sub-groups according the national standard as Table 5.4 shows. The performance of material reduction and recycling (I_1 to I_5), and pollution control (I_6 to I_7) can also be evaluated and compared, following the same TOPSIS procedure.

Details of the calculation procedure are given in the Appendix E. The relative closeness c_i^+ from each alternative to the positive ideal solution is calculated. The rank of the alternatives is eventually based on the descending order of c_i^+. Table 5.5 shows the results of the comprehensive evaluation and the sub-groups' evaluation.

The rank based on the entire set of 7 indicators in Table 5.5 shows that TEDA 2011 ranks first, while DDA 2008 is last. The comprehensive environmental performance of TEDA was better than DDA in each year. TEDA's rank shows an upward trend, while DDA progressed in 2009 but fell afterwards. We also inspected the rank per sub-group. Regarding the material reduction and recycling, TEDA was better than DDA in every year and kept improving over the four years. In this regard, DDA made improvement in 2009 because of the enhanced water and solid waste management. However, the progress was not sustained and its rank fell in 2010 and 2011. The pollution control of TEDA was better than that of DDA in 2008 and 2009, while DDA surpassed TEDA in 2010 and 2011, which was due to the large improvement in COD reduction. To some extent, the results per sub-group reflect the different strategies and instruments of TEDA and DDA when carrying out EIP projects. It implies that the instruments at TEDA were effective both in material reduction and recycling, and also pollution control. In DDA, the effects of the measures on pollution control was more obvious.

Relative closeness	TEDA 2008	TEDA 2009	TEDA 2010	TEDA 2011	DDA 2008	DDA 2009	DDA 2010	DDA 2011
Results of the comprehensive evaluation of the entire 7 indicators								
c_i^+ of comprehensive evaluation	0.66	0.89	0.79	0.91	0.01	0.52	0.40	0.37
Rank	4	2	3	1	8	5	6	7
Results of the evaluation of sub-groups								
c_i^+ of material reduction and recycling	0.69	0.88	0.91	1	0.01	0.54	0.35	0.33
Rank	4	3	2	1	8	5	6	7
c_i^+ of pollution control	0.41	0.99	0.29	0.67	0	0.33	0.84	0.72
Rank	5	1	7	4	8	6	2	3

Table 5.5 – Results of the relative closeness c_i^+ of the comprehensive evaluation and the sub-groups' evaluation.

Progress with respect to company activities

To illustrate company participation, we trace the changes of the three indicators related to company activities in TEDA and DDA: 1) ISO14001 and environment/energy projects, 2) companies joining IS projects, 3) environmental information disclosure and information exchange for potential synergies. The trends of these indicators may reveal the performance of company participation in the EIP development, as a supplement of the national EIP standard.

Overall, company participation in TEDA shows a remarkable growth after 2008 (see Figure 5.3 (a)). The IS projects before 2009 mainly included utility synergies (e.g., wastewater recycling and cogeneration) and waste recycling. With the coordination work of TEDA's Eco-center, the number of IS projects gradually increased and the portfolio also expanded to by-product exchange. The indicator for the number of ISO14001 and environment/energy projects was steady before 2007 and started to grow in 2008, which appears to have been triggered by the funding for environmental protection and energy conservation. Moreover, the events labeled "environmental information exchange and disclosure" appeared on the scene as of 2004 when the waste minimization club was organized by the AC and ten companies. Following the issuance of the mandatory measure on information disclosure in 2007, companies indeed started to publish annual reports of their environmental performance, which evidently led to a higher score on this sub-indicator. The value of the sub-indicator on information opening surged in 2010, apparently benefiting from TEDA Eco-center's activities, in particular the regularly organized workshops and trainings. These activities also serve as platforms for knowledge sharing and dissemination.

The company activities in DDA were relatively steady and at a low level (see Figure 5.3 (b)). The EIP projects were more active before 2006. These mainly involved wastewater recycling, fly ash recovery and solid waste recycling. The number of events on ISO14001 certification and environmental protection and energy efficiency projects was relatively stable between 2000 and 2011, implying that companies in DDA were participating in the EIP-related projects but not to a significant extent. Besides, companies started to publish environmental reports in 2006 in response to the requirements from Dalian City's EPB. Some growth of such events appeared in 2008 and 2009 because of the environmental self-regulation activity that was initiated by the EPB and companies in DDA. As these policies to stimulate company activities were discontinued in 2010, the number of events declined again. In 2011, the number of the company activities slightly increased, which can be attributed to the cleaner production audit.

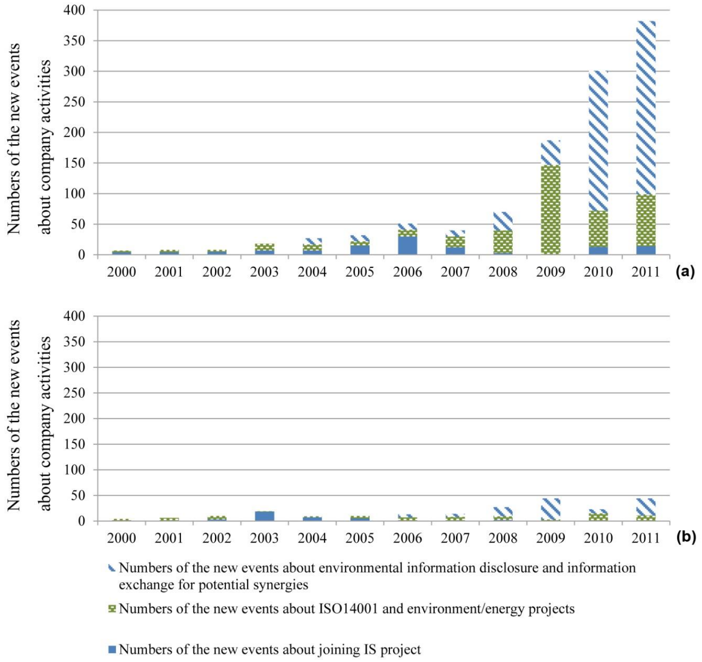

Figure 5.3 – Numbers of the events about company activities in TEDA (a) and in DDA (b).

5.4.5 Discussion

The case studies have revealed the effects of the policy instruments employed for EIP development. TEDA and DDA follow the EIP planning that aims to

Policy instruments	**TEDA**	**DDA**
Price mechanisms for water consumption and reclaimed water usage	+++	+++
Funding for ISO14001, cleaner production audit, energy audit, and environmental technologies	+++	+
Wastewater treatment plant	++	+++
Reclaimed water plant	+++	+++
Co-generation plant equipped with SO_2 scrubber	+++	+++
Mandatory energy audit and cleaner production audit	+++	++
Mandatory environmental information disclosure	+++	+
Training and dissemination for eco-solutions	+++	+
Networking activities to engage company participation	+++	+

Table 5.6 – The effectiveness of the policy instruments found in TEDA and DDA. The scale is from partly, largely to mostly.

retrofit the existing industrial parks, in terms of infrastructures, industrial structure and obligatory tasks for reducing energy and pollution. To carry out the goals assigned by the planning, the ACs in both industrial parks have tested policy instruments that range from economic incentives, regulatory measures and voluntary participation. As Table 5.6 summarizes, our comparative study has revealed similarities and differences between TEDA and DDA. The analysis shows that the effectiveness of the facilitated model are more notable in TEDA than that in DDA.

In both sites, the price mechanism for water usage has been employed to solve the problem of water scarcity. The centralized water treatment plants, reclaimed water plants, and energy infrastructures have been supported since the beginning of eco-transformation, which proves to be useful for regional pollution control (Geng et al. 2008). To propel the obligatory tasks, the intensive polluters and energy users are targeted through mandatory regulations. Meanwhile, financial incentives have been provided for other regular companies to improve energy efficiency and reduce pollution. In TEDA, the amount of funding for EIP-related projects is large and the coverage is wide, which is useful to enhance material reduction from the sources in the entire industrial park (Geng et al., 2007). In DDA, the funding for environmental projects has been issued to guide companies (for example, ISO14001 certification), but the scale is relatively small. The involved companies are either the leading companies who already have good environmental performance, or the intensive polluters who need mandatory environmental assessment. Moreover, the voluntary approach in TEDA was deployed more successfully than that in DDA. The diverse voluntary approaches have been introduced in TEDA for energy-saving, environmental information disclosure and by-product exchanges. Training and dissemination organized by TEDA's EPB appear to be useful to improve the environmental awareness, which stimulates companies to use a waste management online system and reduce solid waste (Geng et al., 2007). The coordinating body, TEDA Eco-center, strengthens networking and information exchange among companies, which can facilitate the identification and establishment of synergies among the participating companies. The voluntary approaches can be useful to assist companies to follow up other policy instruments from the AC. With this regard, DDA has not shown much effectiveness. The commitment to environmental self-regulation of some international companies in 2008 was an indication that spontaneous behavior can be encouraged to engage wider participation. Indeed, regarding the stimulus to engage companies in environmental management, several scholars have suggested that strict regulations (for instance, command-and-control approaches) and economic incentives are important drivers, while marketable instruments and knowledge diffusion are also vital (Zhang et al., 2009; Shi et al., 2008; Baas and Boons, 2007). These facilitated approaches allow companies to realize the competitive advantages and improve their social responsibility through environmental management.

TEDA can be characterized as an example of the transition from a planned EIP model towards a facilitated EIP model. It is marked by tailored policy instruments that regulate and trigger companies' environmental performance, meanwhile highlighting voluntary approaches to engage companies in participation. The results of the TOPSIS analysis and the performance of company participation indicate the positive effects of TEDA's strategies. The next step for TEDA is to keep fostering the context of self-organization and to enhance support for the coordinating body to encourage more bottom-up events.

DDA has started its eco-transformation at the same time as TEDA. Its EIP planning and progress in the early 2000s can be gleaned from the literature (e.g., (Geng and Côté, 2003; Geng et al., 2008; Fang et al., 2007; Geng et al., 2010). Our research reveals that the recent EIP performance in DDA has been average. To some extent, DDA's environmental performance mainly relies on the retrofitted environmental infrastructures, which does improve the performance of pollution control. However, the progress of material reduction and recycling is not obvious. The overall company participation in DDA has been steadily inactive, which implies that triggers were absent to continuously stimulate companies to join EIP projects. Thus, more incentives need to be created to engage companies to adopt environmental management tools. The AC may enlarge its funding to support related projects and enhance the enforcement of regulatory instruments, aiming to engage a larger number of companies in the park. The AC or other coordinating body may organize training, workshops and newsletters that are indispensable to increase the environmental awareness of companies and create a consensus regarding EIP's development (Mirata, 2004; Paquin and Howard-Grenville, 2012).

5.5 Conclusions

Given the condition of the government-driven EIP model in China, this study aimed at understanding how policy instruments affect eco-transformation of industrial parks. We characterized and compared the cases of TEDA and DDA, in order to elucidate the effects of EIP management at the park level. We reviewed the background of China's national EIP program which has been in place for more than a decade. An inventory was made of the instruments available to local authorities (ACs) to shape and promote eco-industrial development. Our empirical research in TEDA and DDA revealed that diverse strategies and instruments have been carried out by their ACs to facilitate the EIP development, and these have had different levels of effectiveness. The research findings lead us the following conclusions about what makes viable eco-transformation of Chinese industrial parks.

The planned EIP model is useful in the early stage of EIP development and later it should be combined with a facilitated model to achieve long-term goals for eco-transformation. In retrospect, the absence of planning in the 1980s caused a fragmented industrial structure with companies spread over many sectors in one industrial park and led to pollution due to the low environmental threshold (Shi et al., 2012a). In this respect, eco-transformation requires a planned EIP model that integrates environmental criteria in the retrofitting of sites. Such a top-down retrofit model is effective in the early stage of the eco-transformation, because the environmental performance can then be significantly improved in a short time. However, the planned retrofit EIP model is insufficient to keep EIP projects viable. As Chertow and Ehrenfeld (2012) suggested, the risk of the retrofit EIP model is that local companies do not actively embrace the norms or values that enable inter-firm collaboration. Indeed, as we observed, eco-transformation requires long-term commitment and institutionalization. Wider company participation is indispensable to explore the capacity of energy efficiency and pollution reduction. Therefore, the facilitated model is necessary to engage companies, which requires voluntary instruments and the associated activities to internalize the environmental management in the companies' business routines. Moreover, the facilitated activities can guide companies to follow up other policies in complying with economic and regulatory instruments. Thus, the policy package of economic, regulatory and voluntary instruments should be integrated and tailored by ACs in alignment with the local situation.

In addition, the assessment of EIP performance requires the compilation of multiple criteria. TOPSIS is useful for analyzing and comparing the overall performance over time between sites. We have analyzed EIP development in TEDA and DDA. However, there are some limitations in our research. Due to the difficult data acquisition, the dataset for evaluating the EIP performance was relatively small and the timeline was from 2008 to 2011. Although key indicators have been evaluated, more data over a longer time period would further have strengthened our results. Nonetheless, we have demonstrated the usefulness of the TOPSIS procedure to evaluate EIP's performance. More extensive research can be conducted once a larger dataset can be compiled.

Our study shows that the appropriate policy instruments within a combination of planned and facilitated model can promote the eco-transformation of industrial parks. The lessons learned from the two Chinese cases are potentially useful for other policy-driven EIPs.

6

From an eco-industrial park towards an eco-city: a case study in Suzhou, China

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6.1 Introduction

The national demonstration EIP program has been in force in China for over a decade. The program was launched in 2001 as an approach to remedy the environmental degeneration caused by the unscientific industrialization that occurred in the national industrial zones from the 1980s onwards. So far, eco-transformation of the first-generation industrial parks has led to what could be labeled EIPs in terms of improving energy efficiency and pollution prevention (Geng and Zhao, 2009; Tian et al., 2013; Yu et al., 2014; Zhang et al., 2010).

Then what is the next step for eco-transformation of Chinese EIPs? As scholars have pointed out, Chinese EIPs are not just industrial areas, but they have also become industrialized towns or urban districts (Liu et al., 2012; Shi et al., 2012a; Tian et al., 2013). Unlike the US model, an industrial park in China is often a complex that integrates industrial production and residential functions. When the first batch of national industrial zones was established in the 1980s, many of these development zones were located far away from their mother cities, allowing their development across a large acreage of land. Some residential buildings were built as auxiliary facilities for employees. As more companies started their business in the industrial parks, more employees with their families settled down. This required the provision of medical care, education and commercial centers etcetera (Tian et al., 2012). Furthermore, in these industrial parks, the secondary and tertiary sectors began to dominate the economy, which is a typical feature of urban economics and development (Arnott and McMillen, 2006). Another key indicator of initial urbanization is the share of tertiary industry. Tian et al. (2013) investigated 17 national demonstration EIPs in China and found that the proportion of tertiary industry exhibited notable growth, in some EIPs amounting to nearly 60% : 40% (secondary : tertiary). Thus, these industrial parks have shown clear signs of urbanization. The next logical step for eco-transformation of Chinese EIPs then would be to integrate urban and industrial functions to minimize energy consumption and pollution. As a consequence, the related planning, measures and assessment for environmental management need to simultaneously consider the industrial sites and the residential areas.

With respect to the environmental performance of a city, the concepts of eco-city and low-carbon city have been promoted in China to deal with the environmental consequences and energy consumption caused by rapid urbanization (de Jong et al., 2013; Dong et al., 2013; Joss and Molella, 2013). An eco-city has been defined as a city that can minimize the demands on resources (like energy and water) and reduce waste (Roseland, 1997), in order to provide healthy living conditions. Several principles need to be considered to realize the goals of an eco-city, for instance, resource recycling and conservation, measures in industries to reduce pollution, accessible transportation, affordable and decent housing (Roseland, 1997). The concept of a low-carbon city has substantial overlap with that of an eco-city, as it focuses on the decoupling between urban economic growth and CO_2 emissions (Chen and Zhu, 2012).

In the literature, a few of studies have appeared to date regarding the environmental contributions from industrial sites to cities' eco-development. Urban symbiosis has been elaborated to analyze Japanese eco-towns that use waste from cities as alternative raw materials or energy sources for industrial operations (Geng et al., 2010; van Berkel et al., 2009). Dong et al. (2013) evaluated how industrial symbiosis in the industrial sites of Liuzhou City in China can facilitate low-carbon city construction. Renewable energy and industrial symbiosis were applied to the forestry industry to integrate the eco-development of two Swedish cities, Linköping and Norrköping (Baas, 2010). The progress of circular economy at the regional level in Dalian City was reviewed (Geng, Zhu, Doberstein and Fujita, 2009), which analyzed the policy actions at the city level to encourage industries to reduce energy consumption and recycle wastes. Furthermore, urban metabolism has been employed to analyze the flows of energy and waste generated in the technical and socioeconomic processes that occur in cities (Kennedy et al., 2007; Wolman, 1965). The literature thus provides valuable knowledge about how to utilize resources in the industrial sites to better serve mother cities. However, an industrial park is normally positioned as a component of a city that is developed at a time the city already had been established. As we have outlined above, in China many industrial parks sparked the growth of what today have become small towns and urban districts in some cases. Thanks to the preferential policies, effective administration and infrastructures, these industrial parks develop much faster than other cities. So instead of the city accommodating the EIP, it is the industrial park that drives development to become a flourishing new urban district. When one seeks to implement environmental principles to transform industrial park and city, how can the management of an industrial park incorporate, steer or even leverage the accompanying urbanization? The research to date does not provide answers to this question.

This chapter therefore aims to provide empirical grounding for understanding what conditions that an eco-industrial park may provide for eco-city development. To this end, we report and interpret our findings about Suzhou Industrial Park (SIP). The structure of the article is as follows. We first introduce the research methods and data collection (section 6.2). Subsequently, we present the empirical research of our case study in SIP (section 6.3). Finally, we draw conclusions about the opportunities and necessary conditions of an EIP for an eco-city.

6.2 Research methods and data collection

Established in 1994, Suzhou Industrial Park (SIP) was one of the earliest national demonstration EIPs. Currently, as a “new town” in Suzhou City, its development strategies have shifted from manufacturing to innovation and a service based economy (Shi et al., 2012a; Wang, Lei, Wang, Liu, Yang and Bi, 2013; Wei et al., 2009). It may thus be seen that SIP presents an interesting case to study the eco-transformation of an industrial park towards an eco-city.

After introducing the general context of SIP, we observe the institutional activities to elucidate what policy instruments SIP employs and how these are used to reduce energy consumption and avoid harmful environmental impact. Moreover, synergies among environmental infrastructures are investigated to reveal how the water and energy infrastructures are utilized to connect industrial and residential areas.

To evaluate eco-development in SIP, we would like to integrate environmental performance and economic growth. To this end, the method of *eco-efficiency* is employed, as it is a concept used to simultaneously reflect environment and economy during sustainable development (Ehrenfeld, 2005; Schmidheiny, 1992). Eco-efficiency means “producing more economic value with less resources and less environmental influence” (Huppes and Ishikawa, 2005; Kuosmanen and Kortelainen, 2005). Initially it offered a concept for companies to maintain business profits in an environment-friendly way. Later, eco-efficiency indicators have been used to measure the changes of regional and national environmental pressure (Seppäläa et al., 2005; Wang et al., 2011; Yu et al., 2013). Eco-efficiency indicators appear to be useful in environmental reporting because they can link information of environmental impacts to economic information in a comprehensive and consistent manner over periods of time (van Caneghem et al., 2010). Therefore, we will use a set of eco-efficiency indicators (including energy, water and air) to reflect the regional environmental pressure during SIP’s development.

Eco-efficiency is defined as the ratio between the added economic value and the added environmental influence. This implies, for example, that the efficiency of energy consumption is the ratio between GDP and the total amount of energy consumption. However, fast economic growth can cause the numerical result of eco-efficiency to appear to have improved, while the environmental impact keeps increasing (Wang et al., 2011). To remedy this, we adopt *decoupling* theory which allows one to clearly evaluate the relation between environmental influence and economic growth. As the United Nations Environment Programme (UNEP) defines, decoupling means “reducing the amount of resources used to produce economic growth and delinking economic development from environmental deterioration” (UNEP, 2011). *Relative decoupling* indicates that the environmental influence is increasing, but its rate is lower than the economic growth. *Absolute decoupling* means the growth rate of environmental influence is zero or negative as the economic value increases (Wang, Hashimoto, Yue, Moriguchi and Lu, 2013; Yu et al., 2013). Moreover, *decoupling indicators* of energy and emissions can also be calculated, as a relative form of eco-efficiency, to present the extent of decoupling as follows (Lu et al., 2011; Wang, Hashimoto, Yue, Moriguchi and Lu, 2013):

$$D = \frac{t}{g}(1+g) \tag{6.1}$$

where D is the decoupling indicator; g represents the GDP's growth rate; t represents the decreasing rate of resource use per unit of GDP or waste emission per unit of GDP. For instance, the decoupling indicator of energy, D_{energy}, is calculated as:

$$D_{energy} = \frac{t_{energy}}{g}(1+g) \tag{6.2}$$

where t_{energy} is the decreasing rate of energy consumption per GDP. The same method can also be used to calculate the decoupling indicator of emission, $D_{emission}$. For instance, the decoupling indicator of wastewater, $D_{wastewater}$, is calculated as:

$$D_{wastewater} = \frac{t_{wastewater}}{g}(1+g) \tag{6.3}$$

where $t_{wastewater}$ is the decreasing rate of wastewater emission per GDP. Under the condition of growing GDP, absolute decoupling occurs when $D \geq 1$; relative decoupling occurs when $0 < D < 1$; non-decoupling occurs when $D \leq 0$. The former two are acceptable, while the third one is the alerting situation. In addition, the larger D is, the less environmental influence is generated (Lu et al., 2011).

With these methods, we can evaluate SIP's eco-efficiency. We have selected the indicators that can cover the environmental influence of energy, water and air. The indicators include energy consumption and five major pollutants: wastewater, chemical oxygen demand (COD), ammonia nitrogen (AN), sulfur dioxide (SO_2) and dust. This selection of indicators refers to the requirements stated in the 12^{th} Five Year Plan of Suzhou City and SIP, which pointed out the key pollutants that need to be monitored (SIP, 2011; Suzhou-Municipality, 2012). Meanwhile, we also considered the data acquisition and the continuity of data set. The data were acquired from SIP's departments: Administrative Committee (AC), Environmental Protection Bureau (EPB), Economic, Trade and Development Bureau (ETDB) and China-Singapore SIP Public Utilities Development Group (CSPU). The data on energy consumption and pollution emission cover industrial and residential areas. Thus, the results of eco-efficiency calculated by GDP can show the results of the environmental performance in the entire SIP region.

6.3 Case study

6.3.1 General context of SIP

Suzhou Industrial Park (SIP) was established in 1994 as a project of government-to-government collaboration between China and Singapore. Located in the eastern part of Suzhou City, SIP occupies a total area of 288 km^2, of which the China-Singapore Cooperative Zone (the main industrial site in SIP) covers 80 km^2. The total population had reached over 700 thousand in 2012, including residents and nonresidents. Currently, approximately 25% of the land is industrial land, and 30% is residential and commercial land. The remainder is green space and water. The train from SIP takes 20 minutes to arrive in Shanghai and 1 hour to Nanjing. With a convenient transportation network (see Figure 6.1), it is well connected with the nearby seaports.

Figure 6.1 – Geographic location and transportation network of SIP.

Due to the collaboration between China and Singapore, the management in SIP has a special structure and authority as Figure 6.2 shows. At the top level there is a China-Singapore Joint Steering Council (JSC) chaired by the vice premiers of the two countries. JSC provides substantial political support for SIP from the vice premiers, central ministries to local authorities. A Joint Working Committee (JWC) reviews the operational issues reported by the SIP Administrative Committee (SIPAC) and China-Singapore SIP Development Corporation (CSSD), a joint venture company. SIPAC is in charge of park management, in a similar fashion as the ACs in most of the Chinese industrial parks. In addition, CSSD is responsible for urban development and infrastructure operation. When CSSD was established in 1994, the shares were divided between Chinese and Singaporean players in a ratio of 35% to 65%. After several adjustments, the Singaporean consortium currently holds 28%.

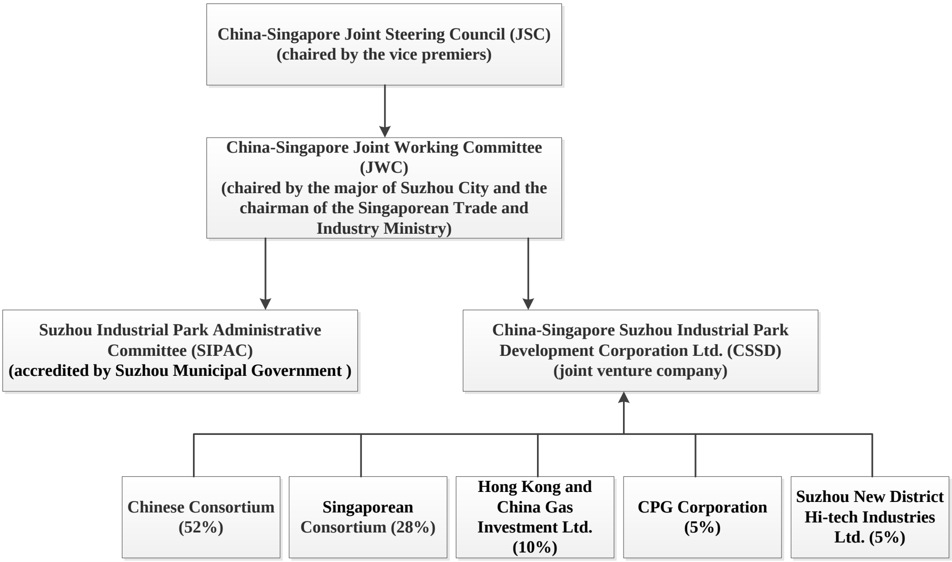


Figure 6.2 – Organizational structure of jointly management in SIP in 2012. Source: (de Jong et al., 2013) and field research in SIP.

Benefiting from the collaboration model, SIP adopted knowledge from Singapore regarding urban planning, market economy, social service and management (Wei et al., 2009). The land use and industrial layout strictly followed the original planning that integrated short-term and long-term goals. Thus, SIP's development avoided the confusion caused by revised planning and demolition. The knowledge from Singapore on planning and management ensured the enforcement of environmental quality since its establishment. SIP's GDP in 2012 reached RMB 173.8 billion, representing 15% of Suzhou City's GDP. The two pillar industries (i.e., electronics and telecommunications, and precision machines) accounted for 47% and 20% of this GDP in 2012, respectively (see Figure 6.3). With respect to EIP development, in 2001, SIP obtained the label of ISO14000 National Demonstration Park. As the national EIP program was launched, SIP was approved as a pilot in 2004 and started to implement EIP planning in accordance with the National EIP standard. In 2008, SIP passed the evaluation and obtained the label as one of the first three National Demonstration EIPs (MEP, 2008). Currently, the energy consumption per GDP is 61% lower than the national level. The discharge amount of COD and SO_2 are only one-eighteenth and one-fortieth of the national average, respectively.

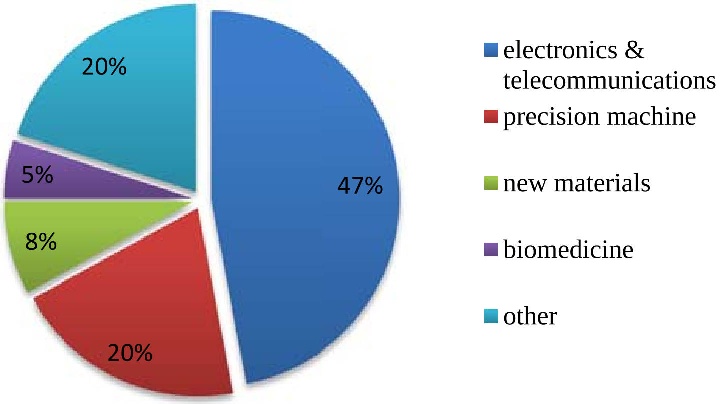


Figure 6.3 – The proportion of the industries in SIP by 2012.

Signs of urbanization can be revealed by the ratio of tertiary industry and residential population (Arnott and McMillen, 2006). Figure 6.4 indicates the proportion of three sectors in the annual GDP and the number of registered population. In 1994, the shares of primary, secondary and tertiary industry were 25.9%, 53.5% and 20.6%, respectively. As the development of industrialization and urbanization proceeded, the shares had changed to 0.1%, 62.2% and 37.7% in 2012. It shows that tertiary industry has substantially increased. In 2015, the goal of tertiary industry is to increase to 44% of GDP (SIP, 2008c). The amount of population of SIP was steady in the first 8 years, but since 2001 it started a continuous growth. In 2012, the registered population reached 392 thousand, more than twice the number of inhabitants in 1994. The growth of tertiary industry and population implies that the demand for social services is rising. Indeed, SIP has incorporated urban functions for commercial and residential areas, which today make it resemble a small city and this gets beyond industrial production only. In 2008, SIP specifically proposed that the industrial park would commit itself to become

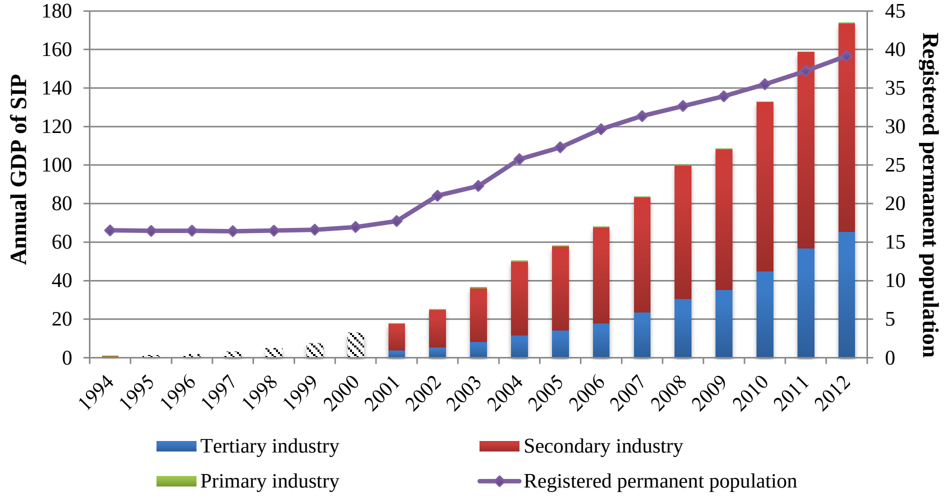


Figure 6.4 – Annual GDP of three industrial sectors and the registered permanent population in SIP. Unit of GDP: billion RMB. Unit of population: 10000 people. Note: The data of 1995-2000 is total GDP, because the data of three industrial sectors is not available. Data source: SIP's ETDB.

a new city center of Suzhou City and accommodate comprehensive urban services such as financial and commercial centers, cultural tourism and exhibitions (SIP, 2008c). Since 2010, the Planning of Ecological Optimization of SIP was launched with 76 eco-oriented projects involving industrial efficiency, innovation economy, optimization of urban layout and urban functions.

6.3.2 Institutional activities

The principles of environmental protection have been considered in planning and policy making since SIP was established. Table 6.1 structures the policy instruments for environmental issues. The first regulatory action in SIP's history was the Measures on Environmental Protection for Construction Project in 1995 (SIP, 2001). After that, the regulations on hazardous waste and wastewater were issued in the late 1990s. These measures guided and supervised environmental performance during construction and industrial production in the early stage of SIP. Moreover, when the new companies or projects are recruited, the environmental impact and energy consumption are assessed by SIP's EPB to decide the project can be approved. SIP strictly enforces the rule of one-vote veto in accordance with the environmental and energy inspection. This implies that potential companies or projects shall be rejected as long as their environmental performance does not meet the requirement, no matter how much economic profits the project can generate. Without the approved environmental assessment, the business license will not be issued. From 1995 to 2012, around 400 projects were rejected due to the environmental entry rule, involving the investment of 3 billion US dollars. If the project is approved, as Figure 6.5 shows, the construction of facilities is required to follow the principles of "three synchronization" for pollution prevention. After the environmental examination, EPB will approve the operation and install real-time system to monitor the pollution and emission.

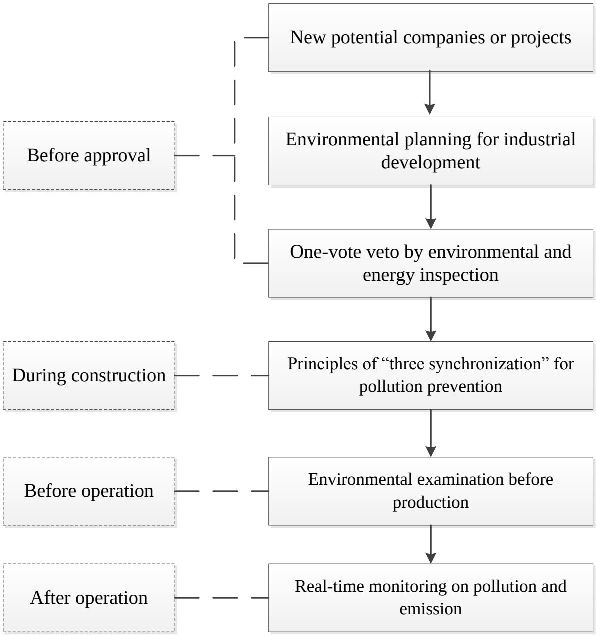


Figure 6.5 – Environmental inspection from project recruiting to project operation. Source: SIP's EPB.

The regulatory instruments in Table 6.1 show that the requirements have become more stringent for both new and existing projects. Since 2007, the requirements of freshwater consumption and wastewater discharge for new projects have been required to conform to the national EIP standard. Meanwhile, some measures have clearly focused on eliminating the companies or industries that have intensive energy consumption or cause excessive pollution. For the existing companies in SIP, energy audits are mandatory and coal-fired boilers are forbidden except for the co-generation plant. Additionally, in 2010, the range of mandatory energy audits has been enlarged to the companies whose energy consumption is larger than 3000 tce/year. These

Economic instruments	2007	Water quota pricing system.
	2008	Annual funding for environmental protection (Budget: 50 million RMB/year). Improvement of intensive pollutant companies; Regional ecological restoration; Technologies for pollution prevention and reclaimed water; ISO14001; Cleaner production audit; Monitoring and emergency response.
	2008	Annual funding for energy saving (Budget: 15 million RMB/year). Technology improvement; New products for saving energy; Applying clean or renewable energy (e.g., natural gas, solar energy, ground/water source heat pump); Elimination of the backward production capacity; Energy audit.
	2012	Annual funding for green building. Green building certificate; Applying renewable energy to buildings; Installing monitoring system for energy audit; Label of energy efficiency for buildings; Retrofitting existing buildings.
Regulatory instruments	1995	Measures on Environmental Protection for Construction Projects (on trial).
	1995	One-vote veto rule by environmental and energy inspection.
	1997	Prevention measures on hazardous waste (on trial).
	1997	Measures on supervision and management for wastewater plant on environmental issues.
	1999	Measures on wastewater discharge management.
	2007	Eliminate all coal-fired boilers except for the cogeneration plant.
	2007	Enhance the environmental access conditions for new projects. • Freshwater consumption per IAV ≤ 9 tons/10^4 RMB; Wastewater discharge per IAV ≤ 8 tons/10^4 RMB; • Stop recruiting electroplating projects and other environmentally risky projects.
	2009	Mandatory energy audit for energy intensive consumers (energy consumption ≥ 5 kilo tce/year).
	2010	Stop recruiting chemical projects and eliminate backward chemical companies.
	2010	Mandatory energy audit for energy intensive consumers (energy consumption ≥ 3 kilo tce/year).
Voluntary instruments	2005	Label of circular economy demonstration organizations and individuals.
	2009	EHS (Environment, Health and Security) association.
	2009	Training and workshops for cleaner production audit and energy audit.
	2010	Low carbon business association.
	2012	Voluntary environmental information disclosure.

Table 6.1 – Policy instruments to promote EIP development in SIP. Sources: (SIP, 2001, 2005, 2007, 2008b,a). Note: tce is tons standard coal equivalent.

regulations especially target the industries of paper making, electroplating and the production of printed circuit boards.

To reduce water consumption, a water quota pricing system has been used since 2007. A company whose freshwater consumption exceeds the national EIP standard has to pay a rate that is 50% higher than the regular water rate. As of which economic instruments for environmental protection in SIP, mainly funding is used as a reward after examining the performance rather than direct subsidies. A maximum of 10% of the actual cost can be rewarded depending on the environmental assessment by SIP's EPB and Financial Bureau. The funding for energy saving can subsidize at most 20% of the investment in equipment or technology. Energy audit fees can be reimbursed for up to 50%. As the details of economic instruments show in Table 6.1, this funding gives clear directions to support the projects that can contribute to the goals of EIP development regarding pollution prevention and energy efficiency. Every year, the funding for environment and energy can support approximately 60 projects that involve 100 companies.

Besides regulatory and economic instruments, voluntary approaches have been used in SIP. Since 2005, the labels of circular economy and environmental protection have been granted to organizations and individuals that made progress on reclaiming water, waste recycling and environmental awareness. The organizations do not only include companies, but also schools and residential neighborhoods, in order to enhance the dissemination of eco-solutions. By the year 2012, around 200 organizations had obtained such labels. Moreover, two non-government business associations are active with respect to environmental issues. Environment, Health and Security (EHS) Association, has been active since 2005 as an informal networking event organized by SIP's companies. In 2009, EHS Association was registered as a non-profit organization that provides training and networking to follow up environmental regulations and assessment, as well as giving feedback to SIP's EPB. So far, EHS Association has attracted more than 200 companies from SIP. Another spontaneous one is the low carbon business association that was initiated in 2010 by 36 companies from the energy sector. Besides training and workshops, this association also provides consulting services for policies and technologies regarding new energy. In addition, in 2012, the first term of environmental information disclosure was launched by SIP's EPB in 20 volunteering companies to publish the information on resource consumption, types and amount of pollutants, waste disposal and treatment equipment.

6.3.3 Environmental infrastructure

All the public utilities in SIP are operated by CSPU whose business segments include water, sewage, natural gas, steam supply, power generation, environmental technology and energy services. Figure 6.6 shows the centralized utilities of water, energy and waste that supply both SIP's industrial and residential areas. Two major groups of synergies are demonstrated in Figure 6.6. One is the symbiosis among the plants of wastewater, sludge and cogeneration. The other one is the regional energy cascading of heating, cooling and electricity.

The centralized wastewater plants treat the industrial and domestic sewage. The maximum capacity of the wastewater plants is 350000 tons/day. To reduce fresh water use, reclaimed water systems were launched in the No.1 and No.2 wastewater plants. The two reclaimed water systems have a total capacity of 30000 tons/day. The reclaimed water is mainly used as cooling water for the Dongwu Cogeneration Plant. However, the larger volume of treated wastewater implies that more sludge will be generated. Usually, the sludge is landfilled or dumped, which is a practice permitted in the absence of regulation on sludge treatment and disposal fees in China. As sludge is known to eventually contaminate groundwater, to avoid unsafe disposal, a sludge drying plant was built in 2011, right next to No.2 Wastewater Plant and Dongwu Cogeneration Plant. The capacity of 300 tons/day in the first stage can completely treat all the sludge in SIP. As Figure 6.6 illustrates, the wet sludge is processed to dried sludge that is mixed as fuel in Dongwu plant to generate electricity, which saves an energy equivalent of 12 thousand tce/year. The ash from the incineration of sludge is used for construction material. The production of the construction material is around 10 thousand tons/year. During the drying process, 90 thousand tons/year of condensed steam water is collected and sent back to the cogeneration plant, which saves water and heating costs amounting to 1 million RMB/year.

The cogeneration plants can supply steam to 90% of the SIP area. The two gas-fired cogeneration plants have a generating capacity of 360 MW and capacity for heating 560 tons/hour steam. Compared with the coal-fired plants, these two gas-fired ones can reduce 1500 tons/year of SO_2 and 300 thousand tons/year of ash. The let-down steam from Dongwu plant is used to produce chilled water for district cooling. This non-electric air-conditioning project can decrease 1 to 2 degrees of the ambient temperature for the Moon Bay Business District (gross floor area of 1.1 hectare). Every year, the cooling center can save 3390 tce of energy, 8000 tons of CO_2, 70 tons of SO_2 and 70 tons of NO_x. In addition, through replacing the distributed air-conditioners, the district cooling can save the cost of 5×10^7 RMB/year maintenance cost.

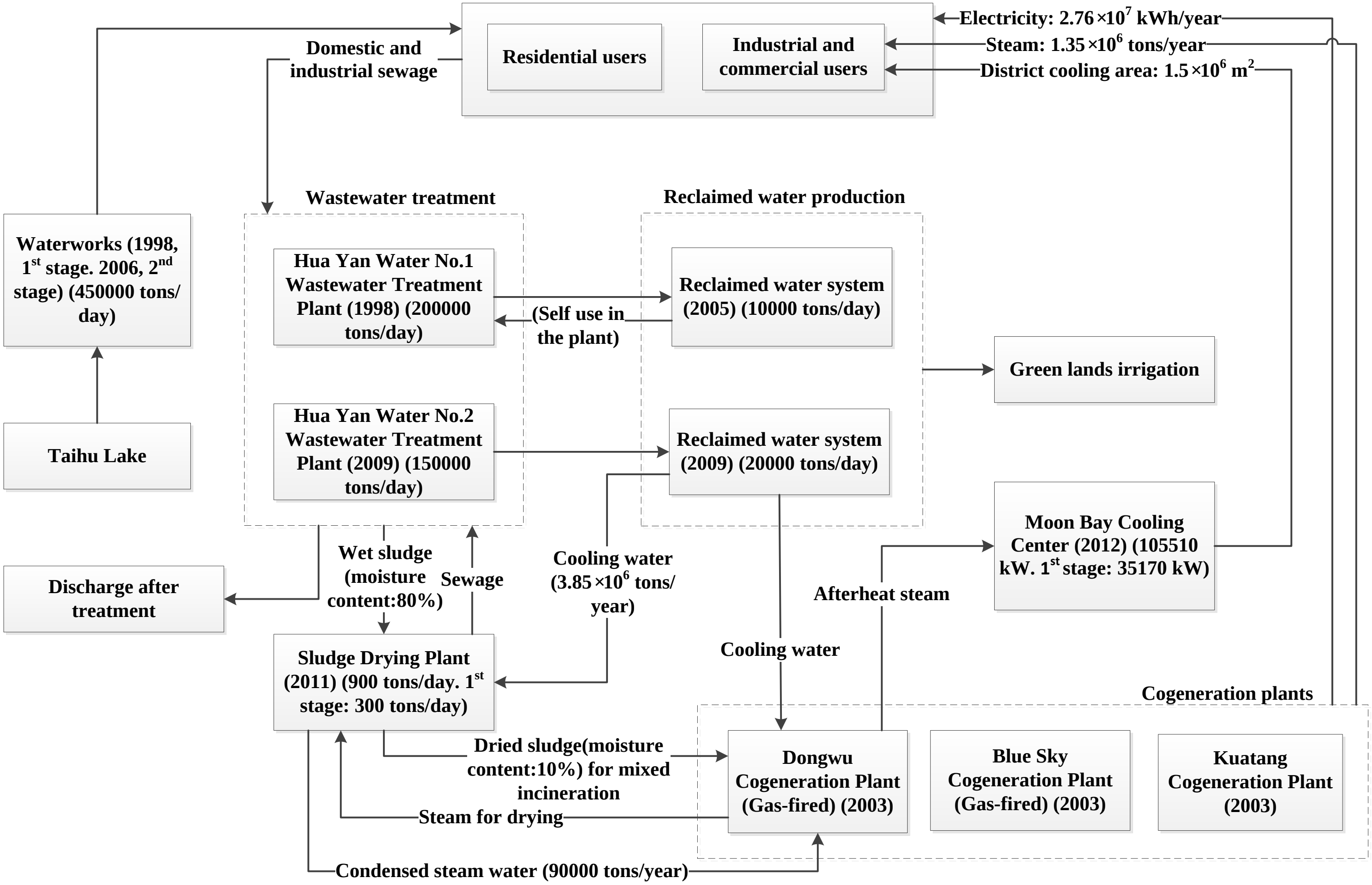


Figure 6.6 – The centralized public utilities in SIP, mapped in the year when the utility began its operations. Data source: (CSPU, 2011) and our own field research.

6.3.4 Results of environmental performance in SIP

Energy consumption and energy efficiency

As Figure 6.7 shows, the total energy consumption had kept growing to 4.45×10^6 tce in 2012, with an average annual growth rate of 10.3%. The amount of 2012 was almost twice as much as the energy consumption of 2005. Regarding the energy consumption by sector, the manufacture industry accounted for the largest share (see Figure 6.8), while its relative share had progressively decreased to 75.8% in 2010, 9% lower than in 2005. The energy consumption of the service industry had a notable increase and became the second largest share. From 2005 to 2010, its proportion rose from 7.9% to 11.53%, with an average annual growth rate of 25.75%. The changes in the proportion of manufacturing and the service industries indicate that the industrial structure in SIP has gradually changed. Moreover, another trend of growing energy consumption happened in the residential areas. In 2010, the residential energy consumption (mainly from buildings) took up by 7.1%. The total amount in 2010 was 2.66×10^5 tce, twice as much as in 2005. The average annual growth rate of residential energy consumption was 19.5% from 2005 to 2010, which implies that energy consumption per unit of floor space has grown considerably.

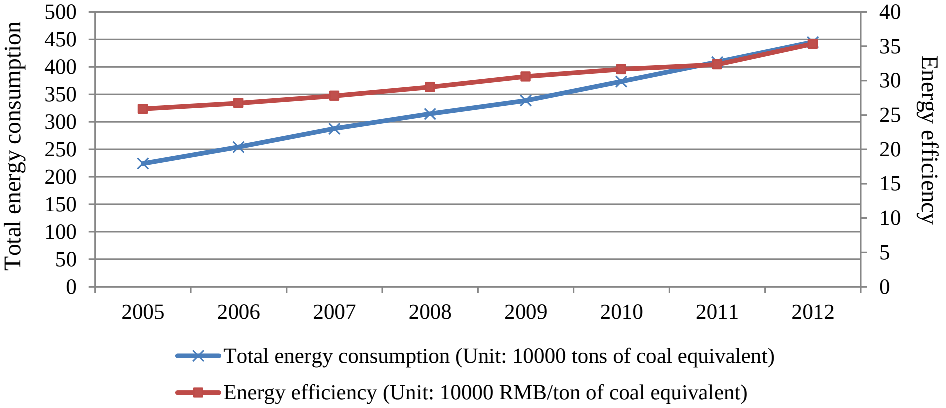


Figure 6.7 – Total energy consumption and energy efficiency of SIP from 2005 to 2012.

Energy efficiency continued to improve (see Figure 6.7) between 2005 and 2011, with an obvious growth in 2012. Compared with 2005, an increase of 36.6% was realized in 2012 and the annual growth rate was 4.55%. The decoupling indicator of energy consumption (D_{energy}) is calculated by Equation 6.2. The results of D_{energy} (see Table 6.2) are all between 0 and 1. It

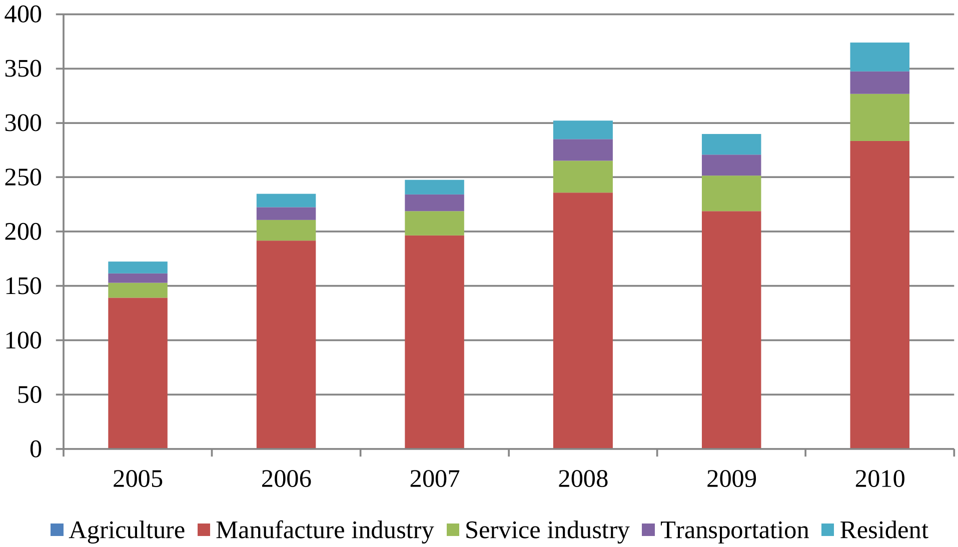


Figure 6.8 – Energy consumption of different sectors in SIP. Unit: 10^4 tons standard coal. Data source: (SIP, 2012).

indicates that SIP's energy consumption had sustained relative decoupling from 2005 to 2012. In this period, the energy consumption increased but the growth rate was smaller than that of GDP. During 2006 to 2009, D_{energy} had kept increasing, implying that the growth rate of energy consumption was decreasing. Then the value dropped to 0.29 and 0.2 in 2010 and 2011. In 2012, D_{energy} rose to 0.53 and that was the highest in the seven years.

	GDP (10^8 RMB)	g (%)	Total energy consumption (10^4 tce)	Energy efficiency (10^4 RMB/ tce	t_{energy} (%)	D_{energy}
2005	580	-	224.15	25.88	-	-
2006	679	17.1	254.14	26.72	3.1	0.21
2007	799	17.7	287.64	27.78	3.7	0.25
2008	914	14.4	314.42	29.07	4.4	0.35
2009	1036	11.8	338.77	30.58	4.9	0.46
2010	1182	13.3	373.51	31.65	3.4	0.29
2011	1322	11.8	408.67	32.35	2.2	0.21
2012	1573	19	445.05	35.34	8.4	0.53

Table 6.2 – Decoupling indicator of energy consumption of SIP from 2005 to 2012. Note: GDP of 2006-2012 is in constant price of 2005. Data source: SIP's ETDB.

Environmental efficiency of water and air

In this section, we calculate the eco-efficiency of water and air, aligning the performance of five major pollutants (i.e., wastewater, COD, AN, SO_2 and dust). In order to plot the trends of total emission and eco-efficiency, we have normalized the data, as Figure 6.9 illustrates.

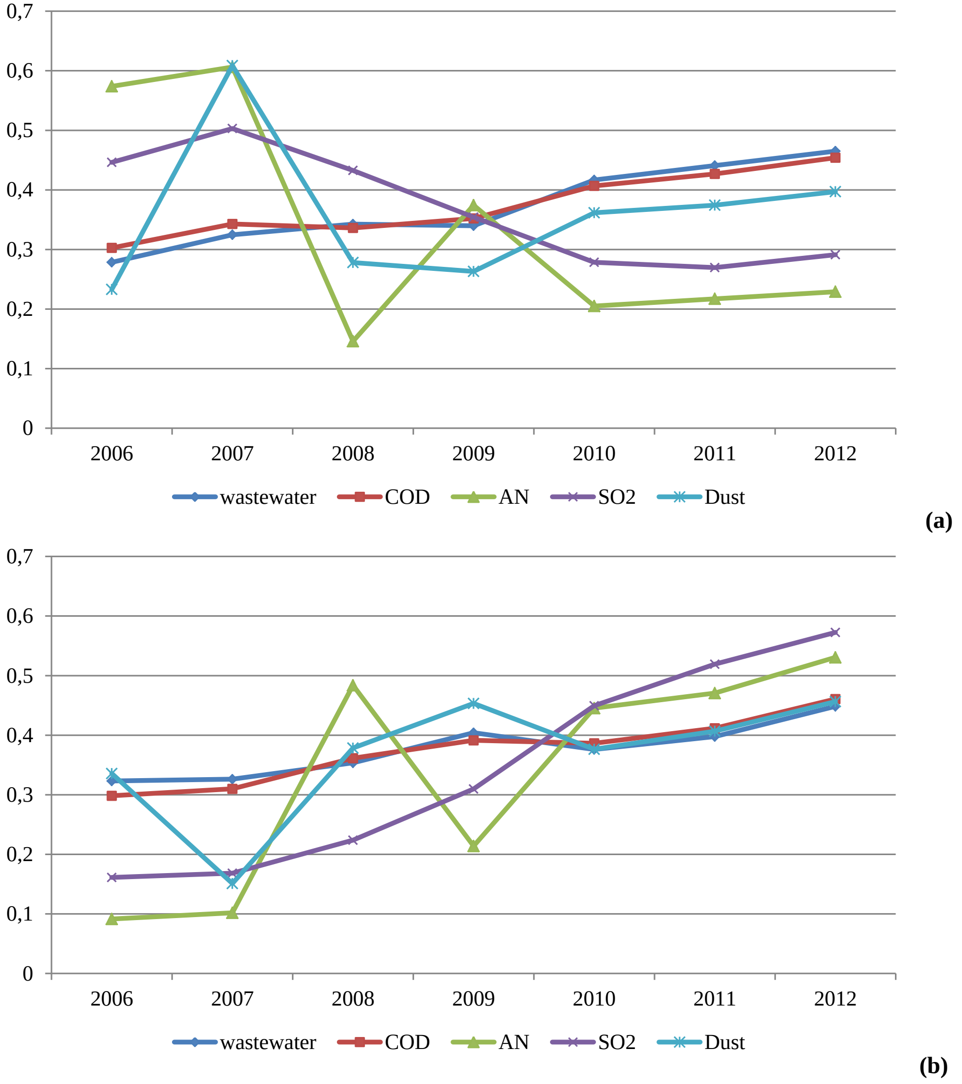


Figure 6.9 – Total emission (a) and eco-efficiency (b) of the main pollutants in SIP from 2006 to 2012. Note: The results have been normalized. Data source: SIP's ETDB.

The trends of total volume are shown in Figure 6.9(a). The total volume of wastewater and COD show increasing trends during the seven years, growing by 67% and 50% in 2012 (compared with 2006). AN had a significant decrease of 60% after several fluctuations. The total volume of SO_2 had a relatively steady decrease from 2127 tons to 1387 tons between 2006 and 2012. The annual decrease rate of SO_2 was 6.9%, while the emission of dust shows an upward trend.

The eco-efficiency of the five pollutants has been calculated by Equation 6.1. Overall, the eco-efficiency of all the pollutants had increased in the seven years. As Figure 6.9(b) shows, the most notable improvement is SO_2. The efficiency of SO_2 constantly increased and the amount of 2012 was over twice as large as in 2006. The efficiency of AN rose to a peak in 2008, and after a drop in 2009 it increased again. Wastewater and COD improved steadily with a slight decline in 2010. The efficiency of dust fell to the bottom in 2007 and then started to increase since 2008. The decoupling indicators of emissions ($D_{emission}$) are also calculated by equation (2) (see Table 6.3). Among all the indicators, SO_2 had sustained decoupling from 2007 to 2012, as the $D_{emission}$ of SO_2 had been larger than 0 all the time. Moreover, SO_2 had an absolute decoupling for four years since 2008 and the value of $D_{emission}$ increased to 2.52 in 2010. The $D_{emission}$ of wastewater increased from 0.06 in 2007 to 0.71 in 2012, indicating the overall improvement, although it had once non-decoupling status in 2010. The environmental influence of COD and AN were generally acceptable. COD had once non-decoupling and the rest status were either relative decoupling or absolute decoupling. The $D_{emission}$ of AN significantly increased to 6.27 in 2008, then it dropped to -10.71, which shows its unstable environmental performance. Dust had a non-decoupling in 2007 with the lowest indicator of -8.12, then it enhanced above 1. After another non-decoupling in 2010, the indicator stayed at relative decoupling.

	Wastewater		COD		AN		SO_2		Dust	
	D_{emission}	Evaluation	D_{emission}	Evaluation	D_{emission}	Evaluation	D_{emission}	Evaluation	D_{emission}	Evaluation
2007	0.06	RD	0.25	RD	0.68	RD	0.28	RD	-8.12	ND
2008	0.61	RD	1.13	AD	6.27	AD	1.97	AD	4.77	AD
2009	1.06	AD	0.65	RD	-10.71	ND	2.36	AD	1.40	AD
2010	-0.60	ND	-0.10	ND	4.21	AD	2.52	AD	-1.65	ND
2011	0.51	RD	0.58	RD	0.51	RD	1.27	AD	0.70	RD
2012	0.71	RD	0.67	RD	0.71	RD	0.58	RD	0.68	RD

Table 6.3 – De-coupling of the main pollutants in SIP. Note: RD stands for relative decoupling. AD stands for absolute decoupling. ND stands for non-decoupling.

6.3.5 Discussion

The case study has revealed how SIP improves its regional energy consumption and environmental management. Overall, the energy efficiency of SIP has improved as the GDP and total energy consumption rise. This can be attributed to three main factors. First, the industrial structure has been adjusted. The manufacturing industry has gradually given way to service industry that has a much lower energy consumption while creating high added value. This is a natural result of post-industrialization, which is meanwhile steered by SIP's strategies on increasing service industry and expanding urbanization. Second, stricter policy instruments regarding energy efficiency have been implemented to strengthen the energy audits. Some existing companies in the chemical and electroplating industries have been moved out from SIP. Due to the mandatory energy audits, 50 companies whose energy consumption is larger than 3 kilo tce/year had implemented energy audits by 2011. As a result of these audits, 225 projects were carried out that reduced energy of total 80 thousand tce (SIP, 2012). Third, the promotion of clean and renewable energy has been supported by funding and subsidies in industrial production and public and residential buildings. These technologies are effective in improving energy efficiency, such as the Moon Bay district cooling center and the gas-fired cogeneration plants. In 2010, the share of clean energy increased to 78.6% (SIP, 2012). The installation of water/ground source heat pumps and solar water heaters is encouraged in the public and residential buildings. 80% of the new buildings will be green buildings by 2015 (Wang, Lei, Wang, Liu, Yang and Bi, 2013). Currently, the added installation area of this clean energy in buildings can reach 0.45 million m^2 every year (Wang, Lei, Wang, Liu, Yang and Bi, 2013). All these factors contribute to the improvement of energy efficiency and the decoupling between energy consumption and GDP growth.

The progress of eco-efficiency of water and air is made through the following aspects. First, the end-of-pipe treatment infrastructures dramatically reduce the pollutants of COD, AN and dust. Second, the symbiosis through infrastructures integrates the water and energy between industrial and residential areas. Moreover, the synergies among water plants, sludge dried plant and cogeneration plants prevent the pollution from sludge and also reduce wastewater emission. Third, the regulatory and economic instruments have stimulated companies to improve their environmental performance. As we introduced, the stricter regulations target the intensive energy and polluting companies especially in the industries of paper manufacturing and printed circuit boards. Meanwhile, funding has been provided to support companies to improve their environmental performance. For instance, Gold Huasheng

Paper, one of the largest paper manufacturers in China, has invested 34 million RMB in building a water reclaiming system inside the company. Its system has a capacity of 7000 tons/day and COD treatment facilities. This was a key project funded by SIP in 2010. Since the facilities were launched, Gold Huasheng Paper can reduce 2.6 million tons/year of wastewater discharge and 214 tons/year of COD. Through using the reclaimed water, this paper company can also save the 25 million RMB/year of water and pollution fees. Among the performance of the five pollutants, the reduction of SO_2 emission was the most significant and it realized continuous decoupling from 2007 to 2012. This was achieved by the regulation of forbidding coal-fired boilers and the support for using natural gas and other clean energy sources. Moreover, cleaner production audits have been launched in 26 companies since 2011, which has resulted in the reduction of 1.6 million tons water consumption. Furthermore, 227 companies have obtained ISO14001 certifications by 2012. So far, SIP is the industrial park that has the highest density of ISO14001-certified companies among all the national industrial parks. Therefore, eco-efficiency of water and air in SIP is improved by the centralized infrastructures as well as the policy instruments aiming to stimulate companies' environmental performance.

The environmental performance in SIP has revealed that the portfolio of economic, regulatory and voluntary instruments is effective to detach the environmental pressure from the economic growth. Like many national industrial parks in China, the eco-transformation is driven by the AC who gives top-down planning and a set of policy instruments to facilitate company participation (Yu et al., 2014). The policy instruments incorporated the guideline of National EIP standards to assess the new projects and the existing companies, in order to improve the industrial environmental performance. Due to the enhanced environmental requirements, several manufacturing companies have been eliminated from SIP, leading to an industrial transformation. Meanwhile, service industries with high added value have been promoted, such as finance, outsourcing, research and innovation. In this process, the sufficient employment opportunities attract more employees especially the high-educated talents. More residents and commercial businesses have emerged, giving SIP more urban functions. Furthermore, the centralized energy and water infrastructures have been built according to EIP's principles. SIP has expanded these infrastructures to simultaneously serve the residential areas, which provides physical conditions for eco-city development. In addition, green buildings and clean technologies have been encouraged by economic instruments to improve the energy efficiency of residential and commercial areas.

All in all, the efforts made for EIP have facilitated eco-city development in SIP, in terms of the exploration of environmental and industrial policies and urban construction. We have observed that the eco-transformation in SIP has revealed the transition of an industrial park towards an eco-city. The measures issued by SIP's AC for environmental performance primarily concerned industrial pollution since SIP focused on manufacturing. As the urbanization proceeds in SIP, the pollution (e.g., water and air) from industrial sites has drawn more concerns since these pollutants may influence the residential areas. In addition, the energy consumption of buildings in the residential and commercial areas has become notable. Thus, the policy implementations have integrated industrial sites and residential areas. Urbanization in an industrialized town may be a result of post-industrialization, but the resource conservation and pollution prevention need to be steered through policy instruments initiated by local authorities.

6.4 Conclusions

Our empirical research in SIP revealed how an industrial park has been transformed following EIP's principles and integrating urban functions. The eco-efficiency analysis indicates that economic growth can be decoupled from environmental impacts through appropriate policy interventions. This benefits the process of eco-city development with respect to the win-win situation of economy and environment during urbanization in an industrialized town like SIP.

We hereby answer the research question: what conditions that an eco-industrial park may provide for eco-city development. First, mandatory and strict regulations for energy saving and emission reduction can significantly improve the environmental performance in the whole region. Second, the adjustment of industrial structure reduces the presence of intensive energy consumers and polluters and stimulates the service industry with high added value. It is effective to keep the economic growth accompanied by small environmental impacts and to benefit the transition towards urban economy. Third, an EIP has high quality infrastructures that can be utilized by residential areas, which is useful to improve the efficiency of regional energy and water use. Fourth, the urban functions in an industrial park are initially driven by the industrialization that provides sufficient employment opportunities and economic growth. Therefore, such an industrialized town has substantial economic drivers, which avoids the shortcomings of "an empty city" in some brand new eco-cities that lack of industrial activities (Caprotti, 2014).

EIPs and eco-cities have considerable overlap in terms of their concepts and environmental indicators. They both emphasize resource conservation, pollution prevention, efficient waste treatment and recycling. EIPs target the environmental impacts from industrial production, while eco-cities incorporate more goals to provide healthy living conditions and good social welfare to citizens. As more Chinese EIPs have become complexes of industrial production and residential areas, the development of an industrial park requires consideration how industrialization and urbanization can be integrated. The urban functions should not be treated as the auxiliary facilities of industrial sites. Furthermore, industrial parks can also improve their endogenous capacity through such urbanization by reducing their dependency on external capital and technology. Thus, the goal of urbanization in the industrial parks should aim at the agglomeration of capital, talents and innovation to enhance the comprehensive development, in order to impel the industries. This transformation is based on the advantages of an EIP, which paves the way for an eco-city.

7

Discussion and conclusions

In China, the severe pollution and deteriorating environment have triggered people to reflect on the cost of rapid economic growth. Many industrial regions are confronting the consequences caused by the absence of environmental management during industrialization and urbanization. How to implement eco-transformation has been concerned by policy makers, industries and the public. The practice of China's EIP program in the last decade has revealed diverse performance of policy instruments and policy enforcement. Apart from afterthought remedy, we also need to draw lessons from the past and seek cause-and-effect mechanisms. This is crucial for more recently established industrial parks to deploy environmental management. In our theoretical research, we first unveiled the knowledge map of EIP's research field. Then an analytical framework was developed to bring the knowledge together to frame the analysis of EIPs' development. Through empirical research, we acquired a deep understanding about eco-transformation in three Chinese industrial parks.

In this chapter, section 7.1 will first discuss what lessons can be drawn from the EIP development in TEDA, DDA and SIP. Based on the insights from our theoretical and empirical work, we will give recommendations in section 7.2 for making policies of eco-transformation. In section 7.3, we will answer each sub research question posed in chapter 1 and give conclusions to answer the central question. Finally, this chapter will end with reflections and an outlook for future work.

7.1 Insights from empirical research

The empirical research in the previous three chapters shows that TEDA, DDA and SIP have implemented various strategies and policy instruments to promote their eco-transformation. In the latest appraisal (see Table 7.1) by the Ministry of Commerce (MC), TEDA topped the comprehensive index list among 90 national economic and technological development zones; SIP and DDA ranked 2^{nd} and 9^{th}, respectively. With respect to the environmental index (energy efficiency and pollution reduction), SIP was on the top and TEDA was No.3; DDA ranked 19^{th}. The results issued by the MC indicate that TEDA and SIP have achieved balanced growth which integrates economy, environment and social development. DDA still has considerable space to improve. The three cases have several features in common. As national economic and technological development zones, they are obligated to create regional economic growth, attract foreign investment and increase export. With respect to their geographical location, they are all located in the eastern coastal area and have convenient transportation by sea, rail and air, which favors their import and export business. In terms of EIP-related policies, they are in the same national EIP program and the same context of Chinese environmental policies. To some extent, all three cases started from the model of planned EIPs that is driven by government. During the eco-transformation, however, the three industrial parks have revealed different trajectories and performance.

	TEDA	DDA	SIP
Comprehensive index	1	9	2
Economic development	1	6	3
Environment	3	19	1
Technology innovation	5	19	2
Social development	3	4	1
Institutional innovation	1	32	1

Table 7.1 – Rank of TEDA, DDA and SIP in the appraisal of 90 National Economic and Technological Development Zones by the Ministry of Commerce. Source: (MC, 2012).

Our research results reveal three different trajectories of EIP development. TEDA and DDA had similar starting conditions in the first stage when the environmental principles were absent in the policy design and infrastructure design. The EIP program was carried out to retrofit the industrial sites through deploying command-and-control measures and building centralized treatment plants. Later, TEDA transited from a planned EIP model to a planned plus facilitated model. It focuses on how to stimulate company participation and intends to explore voluntary approaches. The events of the key activities and the environmental performance show that TEDA's model is effective. DDA still relies on treatment plants, while the incentives to stimulate companies are relatively weak. Consequently, DDA's recent EIP performance is average. To overcome this bottleneck and drive the EIP's development forward, DDA needs to further enforce the regulations and incentives on pollution and energy consumption. Meanwhile it also needs to guide the companies through voluntary approaches to accept the principles of environmental protection.

SIP is different from TEDA and DDA regarding the starting conditions of eco-transformation. Since its establishment, SIP has enforced environmental principles when recruiting new tenants and building environmental infrastructures. Thus, SIP skipped the stages of pollution and demolition. The requirements for existing member companies have been tightened in terms of energy consumption and environmental performance. SIP has been intending to eliminate the intensive energy consumers and polluters, in order to further improve the environmental performance as well as adjust the industrial structure. Furthermore, the policy instruments for energy consumption and pollution reduction have started to include the urbanization associated with the industrialization. Eco-transformation towards an eco-city seems to be unfolding, which is the result of policy interventions that aim to increase the service industry with high added value and low environmental impact. This complies with the patterns of industrial upgrading and population increase during the post-industrialization stage. In this respect, SIP's trajectory towards an eco-city may also be the next move for TEDA and DDA.

7.2 Recommendations for making policies of eco-transformation

The determining factors that cause the different trajectories of these industrial parks are manifold. Lessons learned are useful for policy makers to steer eco-transformation in other industrial parks. With reference to our theoretical research, both institutions and actors may influence the effectiveness of EIP-related policies. Actors such as policy makers and companies follow the institutions and also create new institutions to adapt to changes. As we observed in the empirical research, the determining factors for effective eco-transformation mainly include: 1) tailored environmental policy instruments for the different development stages, 2) a feedback loop for adjusting policies according to the outcome of EIP projects, 3) actors' enforcement of EIP projects, 4) coordination of actors and resources.

From an evolutionary perspective, we have argued that an EIP's development has stages that need different steering strategies. In China, many industrial parks (especially those established in the 1980s) do not have the physical or institutional conditions to spontaneously evolve towards an EIP, due to the absence of environmental principles in the original planning. In the initial stage, the planned EIP model driven by government is useful to build the physical infrastructures (e.g., retrofitting end-of-pipe treatment plants) and recruit particular companies to connect industrial chains. Command-and-control and mandatory instruments are frequently used to require companies to reduce pollution and emission. This top-down planned model is effective to initiate the EIP program and solve urgent pollution problems. As an EIP's development continues, the policy objectives need to shift to leverage market rules and foster norms for local companies, which enable and encourage them to capture and continue environmental protection in their business models. The portfolio of economic, regulatory and voluntary instruments should be integrated to influence companies to change their routines and stimulate company participation. Thus, the facilitated model needs to be combined with the planned model to achieve long-term goals for eco-transformation. In addition, as more urban functions emerge, the policy objectives and instruments of an EIP need to incorporate the integration between industrial and urban areas, in order to appropriately guide the industrial development and social service.

Furthermore, it is indispensable to have a feedback loop from planning, implementation, monitoring to evaluation during eco-transformation. In the empirical research, we observed that some industrial parks had good EIP planning but the projects ended in failure due to a lack of enforcement and supervision. The policy instruments were deployed, but the projects either deviated from the goals or were restrained by insufficient economic and technological support. Without a feedback loop, problems cannot be reported or solved, which caused the failure of projects.

Actors' enforcement also determines whether the policy instruments can be effective. In the Chinese industrial parks that are obligated to economic growth, sometimes the environmental performance still gives in to profit seeking. On the one hand, for policy makers, this weakens the impact of EPB in the local authority, which makes it hard to compete with other departments for funding and resources. In some industrial parks, the veto of EPB for energy intensive and pollutant projects is almost an empty shell in the company recruitment. The access criteria regarding environment have not been substantially implemented, which leads industrial parks to repeat the pattern of "treatment after pollution". In some pioneering industrial parks, environmental regulations are enforced well due to the institutional capacity of policy makers who know to use environmental performance as a leverage to stimulate the economy. On the other hand, for local companies, the awareness to incorporate environmental performance into their business models needs to be established through market signals and knowledge input. Strict regulations and economic incentives will trigger companies to consider how to reduce the cost burden caused by pollution. Meanwhile, knowledge and training are also indispensable to strengthen companies' capabilities regarding the enforcement of EIP principles.

Coordination is critical to achieve consensus about eco-transformation in an industrial park. EIP's development is a comprehensive task that involves multiple actors, such as the EPB, the investment department, anchor tenants, small and medium enterprises, and research institutes. Individual actors do not have sufficient information to understand the overall benefits of the whole network. The various demands of companies for improving environmental management need to be organized and reported to policy makers. Thus, a coordinating organization is necessary to engage actors and mobilize the resources of information, funding and knowledge. Additionally, coordinators can monitor the projects and strengthen the communication between companies, government and research institutes.

7.3 Conclusions

This thesis was built around the central research question: **how can industrial parks be eco-transformed in China?** A set of sub-questions structured our research and led us towards an answer to the central question. Following each sub-question, we summarize the research findings and conclusions as follows.

Sub-question 1: How has the research on EIP evolved?

Eco-industrial park (EIP) is in the research field of industrial symbiosis (IS). They are key concepts in the research area of Industrial Ecology (IE). We did a bibliometric and network analysis of EIP and IS to investigate a total of 1339 source articles and the corresponding 39122 references for the period from 1997 to 2012.

In the first period (1997-2005), IS research held a minority share in the IE literature. The cluster of IS is relatively scattered and close to Waste Minimization and Recycling and Industrial Ecosystem. The early research of IS incorporated ideas from waste treatment and recycling which can be traced back to the 1860s. Theories about industrial ecosystems were adopted to define an EIP system. The research revolved around the concept of IS, the assessment of EIP projects and the establishment of waste treatment and recycling networks.

In the second period (2006-2012), diverse research approaches and theories enriched the field, which led to maturation in the theoretical development. Apart from LCA, MFA and ecosystem in IE, some new theories were particularly incorporated by IS, such as Regional Economy and Economic Geography, social science and wastewater management.

Our findings clearly illustrated that IS evolved from practice-oriented research towards coherent theory building through a systematic underpinning and linking of diverse topics. As the scientific attention shifted from exploring a phenomenon to elucidating underlying mechanisms, IS knowledge found worldwide practical implementation. The co-authorship network presented a scattered network of the IS domain with eleven groups from nine countries. It showed that the academic communities of IS were distributed worldwide and that international collaboration was widespread.

Sub-question 2: What elements are required to frame the analysis of an EIP?

We proposed an analytical framework for policy analysts to analyze an EIP. This analytical framework in chapter 3 is rooted in the body of knowledge of EIP and IS, a socio-technical perspective and the institutional analysis. It mainly covers four aspects: 1) influencing factors, 2) EIP system description, 3) system performance, and 4) evaluation. Each aspect has particular focal points to sort out. The diagram illustrates the procedure for analysts to decompose an EIP system and structure an EIP case study. First, the influencing factors need to include the attributes of the industrial site (e.g., location and industrial structure), key activities that affect EIP changes, and the portfolio of policy instruments implemented to foster institutions. Second, the step of system description focuses on the reactions of actors and changes in the system structure. The next step is the system performance that reveals the outcomes of policy interventions and actor decisions. It can be portrayed by the indicators that represent the occurrence of the key activities or the technical indicators of economy and environment. Through analyzing the changes in the system structure, we can identify the EIP models and the corresponding performance in the different stages. Moreover, the system performance is evaluated and the results are used to assess whether the policy instruments are effective or whether the system development deviates from the policy objectives. Such analysis can help to adjust policy instruments to better steer the EIP system. Additionally, the time span is taken into account to illustrate the changes across the different stages.

Associated with the analytical framework, we also established a conceptual model of an EIP system to illustrate the actors and the interactions in the perspective of a socio-technical system. The actors of an EIP mainly consist of company, policy maker, coordinating body and research institute. Actors are embedded in the institutional environment that involves formal institutions (e.g., laws, regulations and regime) and informal institutions (e.g., social norms and habits). These institutions, which are the rules of the game, influence actor decisions and shape their interactions. Moreover, an EIP system is also nested in the external natural, economic and social system. It needs to adapt to changes happening in the external world. This conceptual model can be used to sketch out an EIP in order to know how the system is constituted.

The analytical framework was applied to structure our empirical research. The analysis in each chapter had different focal points to answer sub research questions, thus the different components of the framework were emphasized in the different case studies.

Sub-question 3: How can the key activities that effectively shape the evolution of EIP systems be structured? How can the process of system development be tracked over time?

A process analysis was employed to trace and structure the key activities that influence changes in an EIP system. This approach rested on five key activities that affect EIP changes and development: (1) institutional activity (2) technical facilitation (3) economic and financial enablers (4) informational activity and (5) company activity. Applying this lens to TEDA allowed us to build a structured database of activities to analyze its eco-transformation from 2000 to 2011. First, we described the milestone events that had profound impacts in terms of institutional activity, technical facilitation, economic and financial enablers, informational activity and company activity. Second, a system analysis was presented based on the database that had been compiled by collecting historical events from 2000 to 2011. The database was set up in accordance with the indicators of the five key activities. Moreover, the conceptual EIP model was used to decompose TEDA's actors and their relationships and illustrate the changes in the system structure.

In TEDA, institutional activity shaped the institutional arrangements that were pivotal for enabling and shaping the eco-transformation. Company activity had less influence on the system than the other key activities. Informational activity was vital to build trust and relationships. In a long time-span, TEDA transformed from a planned EIP to a planned and facilitated EIP, where the local authority acts as a coordinator and as a facilitator. The process analysis approach is amenable to an institutional environment other than the Chinese context because it results in a structured and documented analysis that is open to adjustment, expansion and critique.

Sub-question 4: What policy instruments can stimulate the emergence of viable EIPs in China? How can the effects of policy instruments be evaluated?

We analyzed the root of China's national EIP program and inventoried the general instruments available to local authorities to shape and promote eco-industrial development. Empirical research in TEDA and DDA led to the activities and actions conducted by local authorities. A quantitative method for comparative analysis, TOPSIS, was adopted to reveal the effects of policy instruments through analyzing the data between 2008 and 2011. Our analysis indicated that the effectiveness differed between TEDA and DDA. The results showed that the policy instruments at TEDA were effective both in material reduction and recycling, and also pollution control. In DDA, the effects of the measures on pollution control was more obvious. Furthermore, the company participation in TEDA was more active.

We conclude that the planned EIP model is useful in the early stage of EIP development and later it should be combined with a facilitated model to achieve long-term goals for eco-transformation. The top-down retrofit model is effective in the early stage of the eco-transformation, because the environmental performance can then be significantly improved in a short time. However, the planned retrofit EIP model is insufficient to keep EIP projects viable. Indeed, as we observed, eco-transformation requires long-term commitment and institutionalization. Wider company participation is indispensable to explore the capacity of energy efficiency and pollution reduction. Therefore, the facilitated model is necessary to engage companies, which requires voluntary instruments and the associated activities to internalize the environmental management in the companies' business routines. To this end, the policy package of economic, regulatory and voluntary instruments should be integrated and tailored in alignment with the local situation.

Sub-question 5: What is the future of mature EIPs?

Some mature EIPs in China tend to acquire more than industrial functions and become eco-cities. We investigated what policy instruments an EIP can deploy to facilitate eco-city development. To this end, empirical research was conducted in SIP, where we analyzed how it had been transformed to an EIP and what effect this had on the accompanying urban functions. The policy instruments and environmental infrastructures were inventoried and analyzed to deduce how SIP improved energy efficiency and reduced pollution. Furthermore, we analyzed the eco-efficiency and used decoupling theory to evaluate the environmental performance relative to economic growth.

The results revealed that relative de-coupling was realized for most eco-efficiency indicators; non-decoupling and absolute decoupling happened incidentally. Deployment of strict regulatory and economic instruments led to this result, combined with more urban service and residential activities. We conclude that an EIP may give impetus for eco-city development because it leads to 1) improvement of environmental performance, 2) increase of tertiary industry, 3) synergies of infrastructures between industrial and residential areas and 4) economic prosperity derived from industrial sites.

Central question: How can industrial parks be eco-transformed in China?

Finally, this research journey comes to answer the central question: how can industrial parks be eco-transformed in China? The theoretical exploration and the lessons learned from three cases have revealed the essential approaches to eco-transform an industrial park in China. We hereby conclude as follows. First, the primary issue is the strict threshold for environmental performance. The environmental requirements must be substantially improved and enforced when industrial parks recruit new companies and evaluate existing companies. If the environmental criteria still give in economic growth, industrial park development will repeat the pattern of "treatment after pollution". Second, the planned EIP model is useful to initiate the EIP program in the starting stage. Such planned model is effective to reduce the urgent pollution through end-of-pipe treatment and mandatory pollution control. Many existing industrial parks do not have physical or institutional conditions to spontaneously evolve towards an EIP, due to the absent environmental principles in the original planning. Thus, the eco-transformation needs to build up the conditions, such as retrofitting environmental infrastructures and institutional innovation. This needs political and financial support from local authority as well as the knowledge input from research expertise. Third, as the EIP development continues, the strategies of policy intervention need to be adjusted to foster the institutions to engage company participation. In this stage, the facilitated model needs to be combined to engage actors to achieve long-term goals for eco-transformation. The portfolio of economic, regulatory and voluntary instruments should be integrated to stimulate company participation. The role of coordinator (either local authority or business association) is important to strengthen the networking among companies and to form the consensus of eco-development. The last but not the least, we need to be aware that new features may emerge as industrialization and urbanization proceed. Industrial activities may change the distribution and structure of population, which further emerges urban functions. Currently, China is promoting sustainable urbanization. Our research findings have revealed that many mature EIPs in China have revealed urban features, which paves the way towards eco-cities. Therefore, policy objectives and instruments of an EIP need to be adjusted to realize the agglomeration of industries, talents and innovation to enhance the comprehensive development of economy, environment and social welfare.

7.4 Reflections and outlook

Several limitations still exist in this research. First, the selected cases are all national demonstration industrial zones. The administrative committees in these industrial parks are dispatched by the municipal government and have a mandate to drive EIP projects via policy instruments. In addition, most of the companies in these industrial parks are foreign companies and export-oriented companies that are motivated to improve environmental performance to enter international markets. Thus, the local authorities and companies in this type of industrial parks are relatively capable and willing to carry out environmental projects. However, severe pollution and energy consumption are also happening in other regular industrial parks. It requires more case studies in the different types of EIPs to validate to what extent the lessons learned in this research can be applied. Second, due to the research scale and time limitation, we could not make a large scale investigation within the companies to gather their reactions to policy interventions and their strategies to accommodate the environmental principles in the business models. Third, some indicators were not aligned in the analysis due to limitations in the data collection. The data of some indicators of the national EIP standard were not recorded when the industrial park just started the EIP program. The data analysis would shed more light if we could have a longer time period of continuous data. In addition, as urbanization within and around many industrial parks proceeds, the indicators for evaluating an EIP should be enriched to incorporate new features in terms of urban economy, environment and society. This requires us to keep tracing EIP's development and update the indicator system.

Nevertheless, these limitations have pointed out the agenda for our future work. One topic is the exploration of different types of industrial parks in terms of scale and composition of companies. In this respect, our analytical framework can be used to structure empirical research and analyze new cases.

Besides, it will further validate our framework. Moreover, as more urban economic activities emerge, the integration between industrial and urban areas brings about new research directions regarding energy efficiency, water treatment and waste treatment. The research will enrich the knowledge of EIPs and provide more solution models for policy makers in different contexts.

Another topic is to compare the design and evolution of EIP policies across countries, especially across Asian countries that have similar cultural backgrounds. Similarly to the national EIP program in China, many Asian countries have implemented government-driven environmental programs at the levels of industrial clusters and regions. In Japan, the Eco-Town program has been initiated since 1997 by national and local governments to maximize the benefits of economy and environment in the industrial and urban areas. Intending to link industrial symbiosis and urban symbiosis, over 26 areas have been approved as eco-town pilots to strive for waste management, environmental technologies and eco-business market. Not far from Japan and China, a large national EIP program is flourishing in South Korea. The program was launched in 2005 and will last for 15 years covering 3 phases (i.e., trial projects, dissemination and expansion, evaluation and reflection). The ultimate goal is to provide solutions and models to transform all Korean industrial parks into EIPs. The initiation of the EIP programs was rooted in these countries' legislation and long-term national strategies. For instance, the Japanese Eco-Town program is a key to realize the Law for Establishing a Recycling-Based Society. In Korea, the EIP program was generated in the background of the sustainable development stimulated together by environmental, industrial and energy policies. These Asian EIP programs have been launched for several years, which provides empirical evidence for research. Thus, the progress of projects can be evaluated to reveal the effectiveness of their policy design and implementation. On the one hand, we wonder what concrete policy instruments are used to implement the goals, corresponding to their different regional conditions, status of the economy and industrialization, and existing institutional setting. On the other hand, it is interesting to discover the behavioral rules among actors (e.g., relationships between companies and government) and actors' reactions to new policies. The similar cultural backgrounds provide comparable positions to examine how to effectively carry out EIP projects in the Asian countries.

Furthermore, knowledge management of IS is also an appealing research direction. In our empirical research, we find a barrier that the data about IS are stored in various databases with different formats. The types of information vary from input-output flows to the texts of policies and regulations. The diverse sources include news, reports, academic literature, etc. These fragmented data would provide more insights if they were structured and interlinked. For the research community, it would be more valuable if the data can be integrated and shared. This barrier of data interpretation and knowledge sharing has been discussed in the field of industrial ecology by Davis, Nikolic and Dijkema (2010) and Davis (2012). These researchers proposed an open data platform based on a semantic wiki that can accommodate both unstructured and structured data provided by individuals through bottom-up networks. However, so far there has not been an integrated knowledge management tool for IS, which is not efficient for researchers to share knowledge and enhance innovation. Thus, it is necessary to build a platform that has a generic structure based on IS theory and allows researchers to easily store and query information. Consequently, some new research questions are raised: How can we structure the knowledge of IS in an open platform, which can be tested and expanded by other researchers? How can such a platform be built based on a generic design? Our theoretical research in this thesis can contribute to the conceptual structure of the platform. Moreover, the tool of semantic wiki may be a feasible approach to materialize the knowledge management of IS, which deserves more attention and research efforts.

Appendices

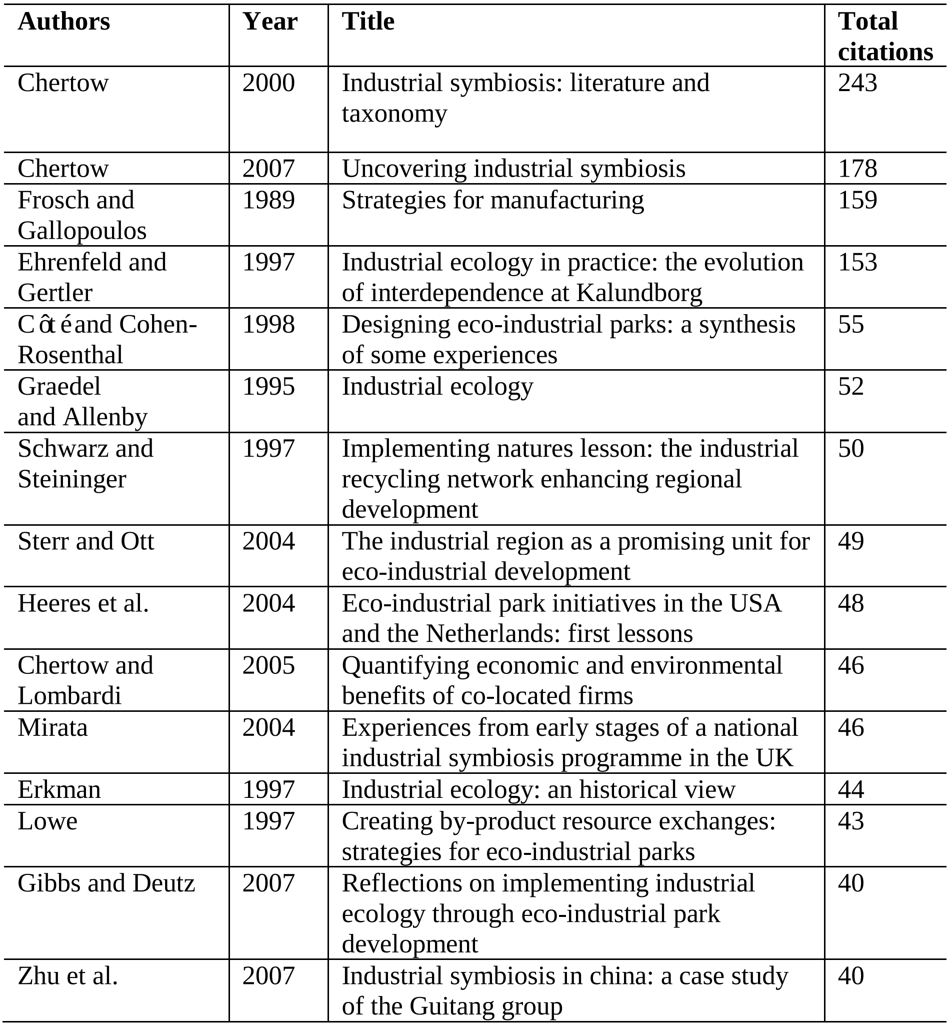
A
China's National EIP Standard

	Indicator		Unit	Criteria
Economic development	IVA per capita		10^4 RMB/per person	≥15
	Annual growth rate of IVA		%	≥15
Material reduction and recycling	IVA of industrial land use		100 million RMB/km^2	≥9
	Energy consumption per IVA		ton of coal equivalent/10^4 RMB	≤0.5
	Energy consumption elastic coefficient		---	<0.6
	Freshwater consumption per IVA		$m^3/10^4$ RMB	≤9
	Freshwater consumption elastic coefficient		---	<0.55
	Wastewater discharge per IVA		ton/10^4 RMB	≤8
	Solid waste discharge per IVA		ton/10^4 RMB	≤0.1
	Reuse rate of industrial water		%	≥75
	Comprehensive use rate of industrial solid wastes		%	≥85
	Reuse rate of reclaimed water	water resources per capita≤1000 m^3	%	≥40
		1000m^3<water resources per capita≤2000 m^3	%	≥25
		water resources per capita>2000 m^3	%	≥12
Pollution control	COD discharge per IVA		kg/10^4 RMB	≤1
	COD discharge elastic coefficient		---	<0.3
	SO_2 discharge per IVA		kg/10^4 RMB	≤1
	SO_2 discharge elastic coefficient		---	<0.2
	Disposal rate of hazardous waste		%	100
	Disposal rate of domestic wastewater		%	≥85
	Disposal rate of domestic waste		%	100
	Capacity of waste collection and treatment		---	Available
Administration and management	Institutional capacity of environmental management		---	Established
	Extent of the establishment of EIP information platform		%	100
	Environmental report		Issue/year	1
	Rate of cleaner production auditing of the major companies		%	100
	Public satisfaction with the environment		%	≥90
	Public awareness degree about eco-industrial development		%	≥90

Table A.1 – National standard of sector-integrate EIP (MEP, 2009). Note: IVA is industrial value added. COD is chemical oxygen demand. According to the latest revision of the standard in 2013, the indicators of "Average annual growth rate of IAV" and "Reuse rate of reclaimed water" have not been mandatory indicators.

B

Top 15 highest cited literatures about industrial symbiosis from 1997 to 2012



Authors	**Year**	**Title**	**Total citations**
Chertow	2000	Industrial symbiosis: literature and taxonomy	243
Chertow	2007	Uncovering industrial symbiosis	178
Frosch and Gallopoulos	1989	Strategies for manufacturing	159
Ehrenfeld and Gertler	1997	Industrial ecology in practice: the evolution of interdependence at Kalundborg	153
Côté and Cohen-Rosenthal	1998	Designing eco-industrial parks: a synthesis of some experiences	55
Graedel and Allenby	1995	Industrial ecology	52
Schwarz and Steininger	1997	Implementing natures lesson: the industrial recycling network enhancing regional development	50
Sterr and Ott	2004	The industrial region as a promising unit for eco-industrial development	49
Heeres et al.	2004	Eco-industrial park initiatives in the USA and the Netherlands: first lessons	48
Chertow and Lombardi	2005	Quantifying economic and environmental benefits of co-located firms	46
Mirata	2004	Experiences from early stages of a national industrial symbiosis programme in the UK	46
Erkman	1997	Industrial ecology: an historical view	44
Lowe	1997	Creating by-product resource exchanges: strategies for eco-industrial parks	43
Gibbs and Deutz	2007	Reflections on implementing industrial ecology through eco-industrial park development	40
Zhu et al.	2007	Industrial symbiosis in china: a case study of the Guitang group	40

Figure B.1 – Top 15 highest cited literatures about industrial symbiosis from 1997 to 2012.

C

Key activities for driving the changes of an EIP system

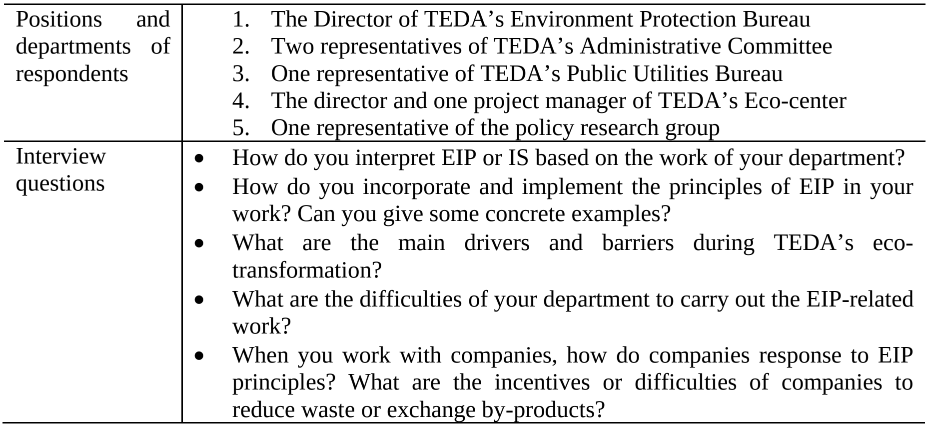
Determining factors	**References**	**Classified as key activities**
• Detailed and flexible planning for medium and long-term goals. • EIP promoters (authority) provide guidance and put frameworks in place to encourage interaction among companies. • Institution set-up encourages green business activities to identify potential synergistic partners. • Voluntary agreements with a group of member companies.	(Chertow, 2007; Chiu and Yong, 2004; Costa et al., 2010; Desrochers, 2001; Ehrenfeld and Gertler, 1997; Fang et al., 2007; Gibbs and Deutz, 2007; Lehtoranta et al., 2011; Mathews and Tan, 2011a; Mirata, 2004; Park et al., 2008; Pellenbarg, 2002; Roberts, 2004; Shi et al., 2010; van Beers et al., 2007; Zhang et al., 2010)	Institutional activity (park-level)
• Evaluation and regular monitoring to ensure ecological and economic goals. • Environmental assessment.	(Côté and Hall, 1995; Geng et al., 2009a; Geng et al., 2008; Mirata, 2004; Zhang et al., 2010)	
• Public policy targets and intervention for IS program. • Policy makers (regional and national governments) provide guidance and put frameworks in place to encourage interaction among companies. • Government provides rewards for the best practice and announces the names of the companies that fail to meet the requirements for IS. • Standards (about EIP, reused and recycled products). • National environmental laws and regulations. • Market-driven actions (e.g. enhancing private property rights; making due allowance).	(Boons, 2008; Chertow, 2007; Chiu and Yong, 2004; Côté and Smolenaars, 1997; Fang et al., 2007; Geng et al., 2009b; Heeres et al., 2004; Lehtoranta et al., 2011; Mathews and Tan, 2011a; Park et al., 2008; Tudor et al., 2007; Yong, 2007; Yuan et al., 2006; Zhang and Wen, 2008)	Institutional activity (regional/national)
• Infrastructures and cost efficient technologies (water, waste disposal, energy cascading and co-generation, ICT tools, service, transport) for enabling industrial symbiosis.	(Chertow, 2007; Chiu and Yong, 2004; Côté and Cohen-Rosenthal, 1998; Grant et al., 2010; Heeres et al., 2004; Mirata, 2004; Park et al., 2008; Shi et al., 2010; Tudor et al., 2007; van Beers et al., 2007; Wang et al., 2006)	Technical facilitation

• Subsidies, special funds and investment. • Profits from symbiotic operation.	(Chiu and Yong, 2004; Côté and Smolenaars, 1997; Ehrenfeld and Gertler, 1997; Jacobsen, 2006; Lehtoranta et al., 2011; Tudor et al., 2007)	Economic and financial enabler
• Preferential tax policies for environmental projects and equipment about energy saving and waste reduction. • Price reforms for resources (e.g. preferential fee for reused water/ increasing charges for disposal of wastes). • Low-cost of waste disposal/low price for utility resources/high landfill tax.	(Costa et al., 2010; Côté and Cohen-Rosenthal, 1998; Geng et al., 2009b; Mathews and Tan, 2011b; Park et al., 2008; van Beers et al., 2007)	
• Inter-firm networking organized by coordination bodies. • Activities for reducing the "mental distance" and cognitive barriers through workshops, training , conferences, dissemination. • Information gathering (basic company information, capacities, resource streams, materials, by-product and etc.). • Reconnaissance teams to identify the kernels of symbiosis. • Collective problem definition and feasibility research for potential synergetic partnership.	(Chertow and Ehrenfeld, 2012; Chertow, 1998; Chiu and Yong, 2004; Côté and Cohen-Rosenthal, 1998; Côté and Smolenaars, 1997; Geng et al., 2009b; Gibbs and Deutz, 2005; Heeres et al., 2004; Lowe, 1997; Mirata, 2004; Mirata and Emtairah, 2005; Park et al., 2008; Roberts, 2004; Sakr et al., 2011; van Beers et al., 2007; Zhang et al., 2010)	Informational activity
• Collaboration on the exchange of energy, raw materials, water and by-products. • Exchange information for potential synergy opportunities. • Reuse and recycle by-products or waste. • Trust and cooperation between companies and between companies and government. • Anchor tenant participation as a "magnet".	(Ashton, 2008; Chertow and Ehrenfeld, 2012; Chertow, 1998, 2007; Côté and Hall, 1995; Côté and Cohen-Rosenthal, 1998; Doménech and Davies, 2011; Gibbs and Deutz, 2005, 2007; Heeres et al., 2004; Jacobsen, 2006; Mathews and Tan, 2011a; Park et al., 2008; Pellenbarg, 2002; Sakr et al., 2011; Tudor et al., 2007)	Company activity

Figure C.1 – Key activities from the literatures for driving the changes of an EIP system.

D

Interviews in the TEDA empirical research



Positions and departments of respondents	1. The Director of TEDA’s Environment Protection Bureau 2. Two representatives of TEDA’s Administrative Committee 3. One representative of TEDA’s Public Utilities Bureau 4. The director and one project manager of TEDA’s Eco-center 5. One representative of the policy research group
Interview questions	• How do you interpret EIP or IS based on the work of your department? • How do you incorporate and implement the principles of EIP in your work? Can you give some concrete examples? • What are the main drivers and barriers during TEDA’s eco-transformation? • What are the difficulties of your department to carry out the EIP-related work? • When you work with companies, how do companies response to EIP principles? What are the incentives or difficulties of companies to reduce waste or exchange by-products?

Figure D.1 – Titles and departments of interviewees and the questions for interviews.

E

Procedure of TOPSIS and the results of calculation

The goal of TOPSIS is to rank the alternatives from matrix $(x_{ij})_{m\times n}$. In this research, i represents indicator (e.g., energy consumption per IAV) and j represents alternative (e.g., TEDA 2008). The standard procedure of TOPSIS is as follows (Yoon and Hwang, 1995; Ostad-Ahmad-Ghorabi and Attari, 2013; Huang, 2008).

Step 1: Normalize the decision matrix and the normalized value n_{ij} is as:

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}; i = 1, \ldots, m; j = 1, \ldots, n \tag{E.1}$$

Step 2: Calculate the weighted normalized matrix. The information entropy method is used to obtain an objective weight of the indicators (Huang, 2008; Wu et al., 2008). The entropy value of each indicator $e_j$is as:

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} n_{ij}\ln n_{ij}; i = 1, \ldots, m; j = 1, \ldots, n \tag{E.2}$$

The weight of each indicator w_j is calculated as:

$$w_j = \frac{1 - e_j}{n - \sum_j^n e_j}; j = 1, \ldots, n \tag{E.3}$$

Therefore the weighted normalized matrix v_{ij} is as:

$$v_{ij} = w_j n_{ij}; i = 1, \ldots, m; j = 1, \ldots, n \tag{E.4}$$

Step 3: Select the positive ideal solution A^+ and the negative ideal solution A^-

$$A^+ = \left\{v_1^+, \ldots, v_n^+\right\} = \left\{ \left(\max_i v_{ij} | \, j \in J_1 \right), \left(\min_i v_{ij} | \, j \in J_2 \right) \middle| \, i = 1, \ldots, m \right\} \tag{E.5}$$

$$A^- = \left\{v_1^-, \ldots, v_n^-\right\} = \left\{ \left(\max_i v_{ij} | \, j \in J_2 \right), \left(\min_i v_{ij} | \, j \in J_1 \right) \middle| \, i = 1, \ldots, m \right\} \tag{E.6}$$

where J_1 is associated with the positive indicator (the larger, the better) and J_2 is associated with the negative indicator (the smaller, the better).

Step 4: Calculate the separation measures by using the Euclidean distance. The separation between each alternative and the positive ideal solution is as:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+ \right)^2}; i = 1, \ldots, m \tag{E.7}$$

And the separation between each alternative and the negative ideal solution is as:

$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^- \right)^2}; i = 1, \ldots, m \tag{E.8}$$

Step 5: Calculate the relative closeness from each alternative to the positive ideal solution

$$c_i^+ = \frac{d_i^-}{d_i^+ + d_i^-}; 0 \leq c_i^+ \leq 1; i = 1, \ldots, m \tag{E.9}$$

Step 6: Rank the alternatives based on the descending order of c_i^+. The better alternative is the one having smaller distance to the positive solution and greater distance to the negative solution.

Following the above steps, we use the data from Table 5.4 except for the I_* and establish the evaluation matrix. I_5 is the positive indicators (the larger, the better) and the rest are the negative indicators (the smaller, the better). Equation (E.4) generates the weighted normalized matrix as Table E.1 shows:

	Indictor	**TEDA 2008**	**TEDA 2009**	**TEDA 2010**	**TEDA 2011**	**DDA 2008**	**DDA 2009**	**DDA 2010**	**DDA 2011**
I_1	Energy consumption of IVA	0.017245	0.016014	0.015902	0.015342	0.059351	0.050392	0.044793	0.048153
I_2	Freshwater consumption of IVA	0.055832	0.043808	0.042345	0.039522	0.092008	0.051232	0.069633	0.069842
I_3	Wastewater discharge of IVA	0.042107	0.035386	0.031683	0.025237	0.086408	0.055685	0.061995	0.062406
I_4	Solid waste discharge of IVA	0.062672	0.043871	0.045437	0.040737	0.07834	0.053271	0.07834	0.07834
I_5	Comprehensive use rate of industrial solid wastes	0.070348	0.070394	0.070464	0.073613	0.06747	0.071348	0.066772	0.066928
I_6	COD discharge of IVA	0.070653	0.051951	0.074809	0.062341	0.083121	0.072731	0.056107	0.060263
I_7	SO_2 discharge of IVA	0.00074	0.000588	0.000493	0.00038	0.004745	0.004081	0.003132	0.00317

Table E.1 – The weighted normalized matrix.

And Equations (E.5) and (E.6) select the positive and negative solutions as:

$$A^{+} = [0.015342, 0.039522, 0.025237, 0.040737, 0.073613, 0.051951, 0.000380]^{T}$$

$$A^{-} = [0.059351, 0.092008, 0.086408, 0.078340, 0.066772, 0.083121, 0.004745]^{T}$$

The separation measures d_i^+ and d_i^- are calculated by Equations (E.7) and (E.8) as:

$$d_i^{+} = [0.037363, 0.011919, 0.024584, 0.010390, 0.104288, 0.053857, 0.067904, 0.070093]$$

$$d_i^{-} = [0.073986, 0.094841, 0.092372, 0.101712, 0.000698, 0.058691, 0.045177, 0.041447]$$

The relative closeness c_i^+ is calculated by Equation (E.8). Finally, the rank is sorted by the descending order of c_i^+ (see Table 5.5).

Following the same steps of TOPSIS, we also calculated the relative closeness c_i^+ of the three sub-groups: economic development, material reduction and recycling, pollution control. The results are also listed in Table 5.5.

Bibliography

Allenby, B. R. and Cooper, W. E. (1994). Understanding industrial ecology from a biological systems perspective, *Environmental Quality Management* **3**(3): 343–354. 22, 29

Arimura, T. H., Hibiki, A. and Katayama, H. (2008). Is a voluntary approach an effective environmental policy instrument?: A case for environmental management systems, *Journal of Environmental Economics and Management* **55**(3): 281–295. 58

Arnott, R. and McMillen, D. (2006). *A Companion to Urban Economics*, Wiley. 118, 124

Asbjornsen, O. A. and Hamann, R. J. (2000). Toward a unified systems engineering education, *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on* **30**(2): 175–182. 43

Asheim, B., M. Bugge, M., Coenen, L. and Herstad, S. (2013). What does evolutionary economic geography bring to the policy table? reconceptualising regional innovation systems, *CIRCLE Electronic Working Papers 2013/5*, Lund University, CIRCLE - Center for Innovation, Research and Competences in the Learning Economy. 51

Ashton, W. (2008). Understanding the organization of industrial ecosystems: A social network approach, *Journal of Industrial Ecology* **12**(1): 34–51. 33, 34, 49, 60, 71, 93

Ashton, W. S. (2009). The structure, function, and evolution of a regional industrial ecosystem, *Journal of Industrial Ecology* **13**(2): 228–246.
URL: *http://dx.doi.org/10.1111/j.1530-9290.2009.00111.x* 41

Aviso, K. B., Tan, R. R., Culaba, A. B. and Cruz Jr, J. B. (2010). Bi-level fuzzy optimization approach for water exchange in eco-industrial parks, *Process Safety and Environmental Protection* **88**(1): 31–40. 34

Baas, L. (2010). stergtland: Towards a sustainable region on the basis of industrial symbiosis and renewable energy. 119

Baas, L. and Boons, F. (2007). The introduction and dissemination of the industrial symbiosis projects in the rotterdam harbour and industry complex, *International Journal of Environmental Technology and Management* **7**: 551–577. 114

Baas, L. W. and Boons, F. A. (2004). An industrial ecology project in practice: exploring the boundaries of decision-making levels in regional industrial systems, *Journal of Cleaner Production* **12**(8-10): 1073–1085. 34

Bastian, M., Heymann, S. and Jacomy, M. (2009). Gephi: An open source software for exploring and manipulating networks, *The Third International AAAI Conference on Weblogs and Social Media*. 26

Binhai-Energy (2005). Product introduction of binhai energy, *Technical report*. 78

Boons, F. (2008). Self-organization and sustainability: The emergence of a regional industrial ecology, *Emergence* **10 (2)**: 41–48. 42

Boons, F. and Howard-Grenville, J. (2009). *The social embeddedness of industrial ecology*, Edward Elgar, Cheltenham, UK. 33, 34, 48, 49, 93

Boons, F. and Spekkink, W. (2012). Levels of institutional capacity and actor expectations about industrial symbiosis, *Journal of Industrial Ecology* **16**(1): 61–69. 68, 100

Boons, F., Spekkink, W. and Mouzakitis, Y. (2011). The dynamics of industrial symbiosis: a proposal for a conceptual framework based upon a comprehensive literature review, *Journal of Cleaner Production* **19**(9-10): 905–911. 69

BP (2013). Bp statistical review of world energy 2013, *Technical report*. 7

Caprotti, F. (2014). Critical research on eco-cities? a walk through the sino-singapore tianjin eco-city, china, *Cities* **36**(0): 10–17. 137

Chai, K.-H. and Xiao, X. (2012). Understanding design research: A bibliometric analysis of design studies (19962010), *Design Studies* **33**(1): 24–43. 24

Chappin, E. (2011). *Simulating Energy Transitions*, PhD thesis. 43

Chen, F. and Zhu, D. (2012). Theoretical research on low-carbon city and empirical study of shanghai, *Habitat International* (0). 118

Chen, X., Fujita, T., Ohnishi, S., Fujii, M. and Geng, Y. (2012). The impact of scale, recycling boundary, and type of waste on symbiosis and recycling, *Journal of Industrial Ecology* **16**(1): 129–141. 34

Chertow, M. and Ehrenfeld, J. (2012). Organizing self-organizing systems, *Journal of Industrial Ecology* **16**(1): 13–27. 15, 22, 34, 41, 42, 43, 45, 48, 49, 67, 90, 93, 95, 115

Chertow, M. R. (2000). Industrial symbiosis: literature and taxonomy, *Annual Review of Energy and the Environment* **25**(1): 313–337. 13, 21, 27, 29, 30, 31, 37, 66, 93, 183

Chertow, M. R. (2007). "uncovering" industrial symbiosis, *Journal of Industrial Ecology* **11**: 11–30. 27, 33, 37, 48, 69, 71

Chertow, M. R., Ashton, W. S. and Espinosa, J. C. (2008). Industrial symbiosis in puerto rico: Environmentally related agglomeration economies, *Regional Studies* **42**(10): 1299–1312. 70, 71

Chew, I. M. L., Tan, R. R., Foo, D. C. Y. and Chiu, A. S. F. (2009). Game theory approach to the analysis of inter-plant water integration in an eco-industrial park, *Journal of Cleaner Production* **17**(18): 1611–1619. 34

Chiu, A. S. F. and Yong, G. (2004). On the industrial ecology potential in asian developing countries, *Journal of Cleaner Production* **12**(8-10): 1037–1045. 71

Costa, I. and Ferrão, P. (2010). A case study of industrial symbiosis development using a middle-out approach, *Journal of Cleaner Production* **18**(1011): 984–992. 34, 44, 45, 46

Costa, I., Massard, G. and Agarwal, A. (2010). Waste management policies for industrial symbiosis development: case studies in european countries, *Journal of Cleaner Production* **18**(8): 815–822. 48, 58, 94

Côté, R. and Hall, J. (1995). Industrial parks as ecosystems, *Journal of Cleaner Production* **3**(12): 41 – 46.
URL: *http://www.sciencedirect.com/science/article/pii/095965269500041C* 22

Côté, R. P. and Cohen-Rosenthal, E. (1998). Designing eco-industrial parks: a synthesis of some experiences, *Journal of Cleaner Production* **6**(3-4): 181–188. 31

CSPU (2011). Introduction of china-singapore suzhou industrial park public utilities development group, *Technical Report 22 August*. 130

Davis, C. (2012). *Making Sense of Open Data: From Raw Data to Actionable Insight*, PhD thesis, Delft University of Technology. 150

Davis, C., Nikolic, I. and Dijkema, G. P. (2010). Industrial ecology 2.0, *Journal of Industrial Ecology* **14**(5): 707–726.
URL: *http://dx.doi.org/10.1111/j.1530-9290.2010.00281.x* 150

DDA (2004). Recycled water plant project in dalian development area. 102, 107

DDA (2006). Implementation plans for circular economy pilot projects. 102, 105, 107

DDA (2011a). Application for circular economy pilot industrial park. 102

DDA (2011b). Dalian statistics yearbook. 98

de Jong, M., Lalenis, K. and Mamadouh, V. (2002). *The Theory and Practice of Institutional Transplantation: Experiences with the Transfer of Policy Institutions*, Springer. 91

de Jong, M., Wang, D. and Yu, C. (2013). Exploring the relevance of the eco-city concept in china: The case of shenzhen sino-dutch low carbon city, *Journal of Urban Technology* **20**(1): 95–113. 118, 123

Desrochers, P. (2001). Cities and industrial symbiosis: Some historical perspectives and policy implications, *Journal of Industrial Ecology* **5**(4): 29–44. 69, 70

Desrochers, P. (2002). Regional development and inter-industry recycling linkages: some historical perspectives, *Entrepreneurship & Regional Development* **14**(1): 49–65. 33

Dijkema, G. P. J. and Basson, L. (2009). Complexity and industrial ecology, *Journal of Industrial Ecology* **13**(2): 157–164. 43, 44, 45, 66

Dijkema, G. P. J., Van Zanten, D. J. and Grievink, J. (2005). Public roles and private interests in petrochemical clusters: Model-based decision support of the regional development board, *Chemical Engineering Research and Design* **83**(6): 739–751. 13

DLHKY (2009). Environmental impact assessment report for retrofitting no.1 wastewater treatment plant of dalian development area. 107

Domnech, T. and Davies, M. (2011). The role of embeddedness in industrial symbiosis networks: Phases in the evolution of industrial symbiosis networks, *Business Strategy and the Environment* **20**(5): 281–296. 67, 94

Dong, L., Fujita, T., Zhang, H., Dai, M., Fujii, M., Ohnishi, S., Geng, Y. and Liu, Z. (2013). Promoting low-carbon city through industrial symbiosis: A case in china by applying hpimo model, *Energy Policy* **61**(0): 864–873. 118

Dosi, G. and Nelson, R. (1994). An introduction to evolutionary theories in economics, *Journal of Evolutionary Economics* **4**(3): 153–172.
URL: *http://dx.doi.org/10.1007/BF01236366* 51

Eco-center (2010). Infrastructures for eco-industrial park. 76

Eco-center (2011). Implementing industrial symbiosis and environmental management system in tianjin binhai new area. 81

Eco-center (2012). Implemening industrial symbiosis energy conservation and emission reduction in tbna. 103

Ehrenfeld, J. and Chertow, M. R. (2002). *A Handbook of Industrial Ecology*, Edward Elgar, chapter Industrial symbiosis: the legacy of Kalundborg. 71

Ehrenfeld, J. and Gertler, N. (1997). Industrial ecology in practice: The evolution of interdependence at kalundborg, *Journal of Industrial Ecology* **1**(1): 67–79. 29, 30, 67, 69, 70

Ehrenfeld, J. R. (2005). Eco-efficiency: Philosophy, theory, and tools, *Journal of Industrial Ecology* **9**(4): 6–8. 120

Engberg, H. (1992). *Industrial Symbiosis in Denmark*, New York University, Leonard N. Stern School of Business, New York, NY, USA. 22

Erkman, S. (1997). Industrial ecology: a historical view, *Journal of Cleaner Production* **5**(2): 1–10. 22, 29, 31, 42

Erkman, S. (2001). Industrial ecology: a new perspective on the future of the industrial system, *Swiss Med Wkly* . 41, 42

Fang, Y., Côté, R., R. P. and Qin, R. (2007). Industrial sustainability in china: Practice and prospects for eco-industrial development, *Journal of Environmental Management* **83**(3): 315–328. 6, 66, 114

Frosch, R. A. and Gallopoulos, N. E. (1989). Strategy for manufacturing, *Scientific American* **261**(3): 9. 27, 37

Garfield, E. (1979). *Citation indexing, its theory and application in science, technology, and humanities*, John Wiley & Sons Inc, Hoboken, NJ, USA. 23

Geng, Y. and Côté, R. (2003). Environmental management systems at the industrial park level in china, *Environmental Management* **31**(6): 784–794. 98, 101, 102, 103, 114

Geng, Y. and Côté, R. P. (2002). Scavengers and decomposers in an eco-industrial park, *International Journal of Sustainable Development & World Ecology* **9**(4): 8. 47

Geng, Y. and Yi, J. (2006). Integrated water resource management at the industrial park level: A case of the tianjin economic development area, *International Journal of Sustainable Development & World Ecology* **13**(1): 37–50. 97

Geng, Y., Zhang, P., Côté, R. P. and Fujita, T. (2009). Assessment of the national eco-industrial park standard for promoting industrial symbiosis in china, *Journal of Industrial Ecology* **13**(1): 15–26. 34, 66, 94

Geng, Y., Zhang, P., Ct, R. P. and Qi, Y. (2008). Evaluating the applicability of the chinese eco-industrial park standard in two industrial zones, *International Journal of Sustainable Development & World Ecology* **15**(6): 543–552. 34, 96, 98, 103, 114

Geng, Y., Zhang, P., Ulgiati, S. and Sarkis, J. (2010). Emergy analysis of an industrial park: The case of dalian, china, *Science of the Total Environment* **408**(22): 5273–5283. 60, 98, 114, 118

Geng, Y. and Zhao, H. (2009). Industrial park management in the chinese environment, *Journal of Cleaner Production* **17**(14): 1289–1294. 13, 15, 34, 95, 97, 101, 117

Geng, Y., Zhu, Q., Doberstein, B. and Fujita, T. (2009). Implementing china's circular economy concept at the regional level: A review of progress in dalian, china, *Waste Management* **29**(2): 996–1002. 70, 119

Geng, Y., Zhu, Q. and Haight, M. (2007). Planning for integrated solid waste management at the industrial park level: A case of tianjin, china, *Waste Management* **27**(1): 141–150. 97, 113, 114

Ghorbani, A. (2013). *Structuring Socio-technical Complexity; Modelling Agent Systems using Institutional Analysis*, PhD thesis. 44, 55

Gibbs, D. (2009). *The Social Embeddedness of Industrial Ecology*, Edward Elgar, chapter Eco-industrial parks and industrial ecology strategic niche or mainstream development. 65

Gibbs, D. and Deutz, P. (2007). Reflections on implementing industrial ecology through eco-industrial park development, *Journal of Cleaner Production* **15**(17): 1683–1695. 34, 66, 71

Gibbs, D., Deutz, P. and Proctor, A. (2005). Industrial ecology and eco-industrial development: A potential paradigm for local and regional development?, *Regional Studies* **39**(2): 171–183. 48, 71

Goulder, L. H. and Parry, I. W. H. (2008). Instrument choice in environmental policy, *Review of Environmental Economics and Policy* **2**(2): 152–174. 48, 58

Graedel, T., Allenby, B., Telephone, A. and Company, T. (1995). *Industrial Ecology*, Prentice Hall, Upper Saddle River, NJ, USA. 29, 49

Halvey, M. J. and Keane, M. T. (2007). An assessment of tag presentation techniques, *WWW '07 Proceedings of the 16th international conference on World Wide Web*, ACM, pp. 1313–1314. 26

Harrison, B. (1992). Industrial districts: Old wine in new bottles?, *Regional Studies* **26**(5): 469–483. 33

Haskins, C. (2006). Multidisciplinary investigation of eco-industrial parks, *Systems Engineering* **9**(4): 313–330.
URL: *http://dx.doi.org/10.1002/sys.20059* 41, 43

Haskins, C. (2007). A systems engineering framework for eco-industrial park formation, *Systems Engineering* **10**(1): 83–97. 43, 53, 54

Heeres, R. R., Vermeulen, W. J. V. and de Walle, F. B. (2004). Eco-industrial park initiatives in the usa and the netherlands: first lessons, *Journal of Cleaner Production* **12**(8-10): 985–995. 34, 66, 70, 71

Hekkert, M. P., Suurs, R. A. A., Negro, S. O., Kuhlmann, S. and Smits, R. E. H. M. (2007). Functions of innovation systems: A new approach for analysing technological change, *Technological Forecasting and Social Change* **74**(4): 413–432. 68, 73

Hewes, A. and Lyons, D. I. (2008). The humanistic side of eco-industrial parks: Champions and the role of trust, *Regional Studies* **42**(10): 1329–1342. 95

Huang, I. B., Keisler, J. and Linkov, I. (2011). Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends, *Science of The Total Environment* **409**(19): 3578–3594. 99

Huang, J. (2008). Combining entropy weight and topsis method for information system selection. 99, 163

Huppes, G. and Ishikawa, M. (2005). A framework for quantified eco-efficiency analysis, *Journal of Industrial Ecology* **9**(4): 25–41. 60, 120

Jacobsen, N. and Anderberg, S. (2004). *Understanding the evolution of industrial symbiotic networks: the case of Kalundborg*, MIT Press, pp. 313–336. 49

Jacobsen, N. B. (2006). Industrial symbiosis in kalundborg, denmark: A quantitative assessment of economic and environmental aspects, *Journal of Industrial Ecology* **10**(1-2): 239–255. 34

Joss, S. and Molella, A. P. (2013). The eco-city as urban technology: Perspectives on caofeidian international eco-city (china), *Journal of Urban Technology* **20**(1): 115–137. 118

Kennedy, C., Cuddihy, J. and Engel-Yan, J. (2007). The changing metabolism of cities, *Journal of Industrial Ecology* **11**(2): 43–59. 119

Kessler, M. M. (1963). Bibliographic coupling between scientific papers, *American Documentation* **14**(1): 10–25. 24

Kiker, G. A., Bridges, T. S., Varghese, A., Seager, T. P. and Linkov, I. (2005). Application of multicriteria decision analysis in environmental decision making, *Integrated Environmental Assessment and Management* **1**(2): 95–108. 61, 99

Koller, T. and Stocks, H. (1918). *The utilization of waste products: a treatise on the rational utilization, recovery, and treatment of waste products of all kinds*, Scott, Greenwood & son, London and New York. 29

Korhonen, J. (2001). Co-production of heat and power: An anchor tenant of a regional industrial ecosystem, *Journal of Cleaner Production* **9**(6): 509–517. 29, 47, 70

Korhonen, J., von Malmborg, F., Strachan, P. A. and Ehrenfeld, J. R. (2004). Management and policy aspects of industrial ecology: an emerging research agenda, *Business Strategy and the Environment* **13**(5): 289–305. 33

Kuosmanen, T. and Kortelainen, M. (2005). Measuring eco-efficiency of production with data envelopment analysis, *Journal of Industrial Ecology* **9**(4): 59–72. 120

Lambooy, J. G. and Boschma, R. A. (2001). Evolutionary economics and regional policy, *The Annals of Regional Science* **35**: 113–131. 10.1007/s001680000033.
URL: *http://dx.doi.org/10.1007/s001680000033* 51

Lehtoranta, S., Nissinen, A., Mattila, T. and Melanen, M. (2011). Industrial symbiosis and the policy instruments of sustainable consumption and production, *Journal of Cleaner Production* **19**(16): 1865–1875. 69, 70

Liang, S., Shi, L. and Zhang, T. (2011). Achieving dewaterization in industrial parks, *Journal of Industrial Ecology* **15**(4): 597–613. 34

Lifset, R. (1997). A metaphor, a field, and a journal, *Journal of Industrial Ecology* **1**(1): 1–3. 22

Liu, L., Zhang, B., Bi, J., Wei, Q. and He, P. (2012). The greenhouse gas mitigation of industrial parks in china: A case study of suzhou industrial park, *Energy Policy* **46**(0): 301–307. 117

Liu, Q., Li, H.-m., Zuo, X.-l., Zhang, F.-f. and Wang, L. (2009). A survey and analysis on public awareness and performance for promoting circular economy in china: A case study from tianjin, *Journal of Cleaner Production* **17**(2): 265–270. 60

Liu, X., Bollen, J., Nelson, M. L. and Sompel, H. V. d. (2005). Co-authorship networks in the digital library research community, *Information Processing & Management* **41**(6): 1462–1480. 24

Liwarska-Bizukojc, E., Bizukojc, M., Marcinkowski, A. and Doniec, A. (2009). The conceptual model of an eco-industrial park based upon ecological relationships, *Journal of Cleaner Production* **17**(8): 732–741. 44, 45, 46, 47

Lombardi, D. R. and Laybourn, P. (2012). Redefining industrial symbiosis, *Journal of Industrial Ecology* **16**(1): 28–37. 21, 22, 93

Lombardi, D. R., Lyons, D., Shi, H. and Agarwal, A. (2012). Industrial symbiosis, *Journal of Industrial Ecology* **16**(1): 2–7. 21, 22, 38

Lowe, E. A. (1997). Creating by-product resource exchanges: Strategies for eco-industrial parks, *Journal of Cleaner Production* **5**(1-2): 57–65. 31, 47

Lowe, E., Moran, S., Holmes, D., Martin, S., Agency, U. S. E. P. and Development, I. (1996). *Fieldbook for the Development of Eco-industrial Parks*, Indigo Development, Oakland, CA, USA. 22, 31

Lu, Z., Wang, H. and Yue, Q. (2011). Decoupling indicators: quantitative relationships between resource use, waste emission and economic growth, *Resources Science* **33**(1): 8. 120, 121

Mathews, J. A. and Tan, H. (2011). Progress toward a circular economy in china: The drivers (and inhibitors) of eco-industrial initiative, *Journal of Industrial Ecology* **15**(3): 435–457. 66, 67, 69, 70

Mattila, T. J., Pakarinen, S. and Sokka, L. (2010). Quantifying the total environmental impacts of an industrial symbiosis-a comparison of process-, hybrid and input-output life cycle assessment, *Environmental Science and Technology* **44**(11): 4309–4314. 34

MC (2012). Appraisal of national economic and technological development zones by the ministry of commerce (mc), *Technical report*, Ministry of Commerce. 140

MEP (2008). Annual progress report of national demonstration eco-industrial park from ministry of environmental protection (mep). http://kjs.mep.gov.cn/stgysfyq/sp/200902/p020090220519033747361.pdf. 124

MEP (2009). Standard for sector-integrate eco-industrial parks (hj274-2009). 13, 94, 97, 99, 108, 154, 183

MEP (2013a). China environment statistical report. 10

MEP (2013b). List of national demonstration eco-industrial parks. 14

Mirata, M. (2004). Experiences from early stages of a national industrial symbiosis programme in the uk: determinants and coordination challenges, *Journal of Cleaner Production* **12**(8-10): 967–983. 34, 65, 69, 70, 71, 115

Mirata, M. and Emtairah, T. (2005). Industrial symbiosis networks and the contribution to environmental innovation: The case of the landskrona industrial symbiosis programme, *Journal of Cleaner Production* **13**(10-11): 993–1002. 93

Nelson, R. and Winter, S. (1982). *An Evolutionary Theory of Economic Change*, Belknap Press Series, Belknap Press of Harvard University Press.
URL: *http://books.google.nl/books?id=6Kx7s_HXxrkC* 51

North, D. (1990). *Institutions, Institutional Change and Economic Performance*, Cambridge University Press. 44

Ohnishi, S., Fujita, T., Chen, X. and Fujii, M. (2012). Econometric analysis of the performance of recycling projects in japanese eco-towns, *Journal of Cleaner Production* **33**(0): 217–225. 34

Ostad-Ahmad-Ghorabi, M. J. and Attari, M. (2013). Advancing environmental evaluation in cement industry in iran, *Journal of Cleaner Production* **41**(0): 23–30. 163

Ostrom, E. (2005). *Understanding institutional diversity*, Princeton University Press. 55, 94

Ostrom, E., Gardner, R. and Walker, J. (1994). *Rules, Games, and Common-pool Resources*, University of Michigan Press. 44, 54, 56

Paquin, R. and Howard-Grenville, J. (2009). *The Social Embeddedness of Industrial Ecology*, Edward Elgar, Cheltenham, UK, chapter Facilitating regional industrial symbiosis: Network growth in the UK's National Industrial Symbiosis Programme. 34, 71

Paquin, R. L. and Howard-Grenville, J. (2012). The evolution of facilitated industrial symbiosis, *Journal of Industrial Ecology* **16**(1): 83–93. 48, 59, 95, 115

Park, H.-S. and Won, J.-Y. (2007). Ulsan eco-industrial park: Challenges and opportunities, *Journal of Industrial Ecology* **11**(3): 11–13. 34

Persson, O., Danell, R. and Wiborg Schneider, J. (2009). *How to use Bibexcel for various types of bibliometric analysis*, ISSI, Copenhagen, Denmark, pp. 9–24. 26

Pilkington, A. and Meredith, J. (2009). The evolution of the intellectual structure of operations management19802006: A citation/co-citation analysis, *Journal of Operations Management* **27**(3): 185–202. 23, 24

Pohekar, S. D. and Ramachandran, M. (2004). Application of multi-criteria decision making to sustainable energy planninga review, *Renewable and Sustainable Energy Reviews* **8**(4): 365–381. 99

Polski, M. M. and Ostrom, E. (1999). An institutional framework for policy analysis and design. 56, 57

Poole, M. S., Ven, A. H. V. d., Dooley, K. and Holmes, M. E. (2000). *Organizational change and innovation processes: theory and methods for research*, Oxford University Press. 61, 67, 68

Porter, M. (1998). *Clusters and the New Economics of Competition*, Harvard Business Review, Boston, MA, USA. 33

Roberts, B. H. (2004). The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks: an australian case study, *Journal of Cleaner Production* **12**(8-10): 997–1010. 70, 71

Romero, E. and Ruiz, M. C. (2013). Framework for applying a complex adaptive system approach to model the operation of eco-industrial parks, *Journal of Industrial Ecology* **17**(5): 731–741. 43, 44, 45, 53, 54

Romero, E. and Ruiz, M. C. (2014). Proposal of an agent-based analytical model to convert industrial areas in industrial eco-systems, *Science of The Total Environment* **468469**(0): 394 – 405.
URL: *http://www.sciencedirect.com/science/article/pii/S0048969713009637* 44, 45

Rose, R. (1993). *Lesson-drawing in public policy: a guide to learning across time and space*, Chatham House Publishers. 91

Roseland, M. (1997). Dimensions of the eco-city, *Cities* **14**(4): 197–202. 118

Sakr, D., Baas, L., El-Haggar, S. and Huisingh, D. (2011). Critical success and limiting factors for eco-industrial parks: Global trends and egyptian context, *Journal of Cleaner Production* **19**(11): 1158–1169. 69

Scharpf, F. (1997). *Games Real Actors Play: Actor-centered Institutionalism In Policy Research*, Theoretical Lenses on Public Policy, Westview Press.
URL: *http://books.google.nl/books?id=2tjZkC5ylmsC* 44, 54, 55

Schmidheiny, S. (1992). *Changing Course: A Global Business Perspective on Development and the Environment*, MIT Press. 120

Sendra, C., Gabarrell, X. and Vicent, T. (2007). Material flow analysis adapted to an industrial area, *Journal of Cleaner Production* **15**(17): 1706–1715. 60

Seppäläa, J., Melanen, M., Menp, I., Koskela, S., Tenhunen, J. and Hiltunen, M.-R. (2005). How can the eco-efficiency of a region be measured and monitored?, *Journal of Industrial Ecology* **9**(4): 117–130. 120

Shi, H., Chertow, M. and Song, Y. (2010). Developing country experience with eco-industrial parks: a case study of the tianjin economic-technological development area in china, *Journal of Cleaner Production* **18**(3): 191–199. 34, 67, 84, 97, 101, 102, 103, 104

Shi, H., Peng, S. Z., Liu, Y. and Zhong, P. (2008). Barriers to the implementation of cleaner production in chinese smes: government, industry and expert stakeholders' perspectives, *Journal of Cleaner Production* **16**(7): 842–852. 114

Shi, H., Tian, J. and Chen, L. (2012a). China's quest for eco-industrial parks, part i, *Journal of Industrial Ecology* **16**(1): 8–10. 94, 95, 100, 115, 117, 119

Shi, H., Tian, J. and Chen, L. (2012b). China's quest for eco-industrial parks, part ii, *Journal of Industrial Ecology* **16**(3): 290–292. 14, 94, 95

Simmonds, P. (1862). *Waste products and undeveloped substances: or, Hints for enterprise in neglected fields*, R. Hardwicke, London, UK. 29

SIP (2001). Regulatory documents in sip. 125, 127

SIP (2005). Promote eip development in sip. 127

SIP (2007). Policy measures to promote circular economy and eco-industrial park. 127

SIP (2008a). Provisional measures on the funding for energy saving in sip. 127

SIP (2008b). Provisional measures on the funding for environmental protection. 127

SIP (2008c). Suzhou industrial park (suzhou eastern new city) planning for subdistrict (2008-2020). 124, 125

SIP (2011). Planning of economic and social development in sip (2011-2015). 121

SIP (2012). The 12th five year plan for energy saving in sip. 132, 135

Small, H. (1973). Co-citation in the scientific literature: A new measure of the relationship between two documents, *Journal of the American Society for Information Science* **24**(4): 5. 24

Sopha, B. M., Fet, A. M., Keitsch, M. M. and Haskins, C. (2010). Using systems engineering to create a framework for evaluating industrial symbiosis options, *Systems Engineering* **13**(2): 149–160. 53, 54

State-Council (2011). Measures of energy conservation and pollution reduction for 12th five-year plan. 10

Sterr, T. and Ott, T. (2004). The industrial region as a promising unit for eco-industrial developmentreflections, practical experience and establishment of innovative instruments to support industrial ecology, *Journal of Cleaner Production* **12**(8-10): 947–965. 71

Storper, M. (1995). Regional technology coalitions an essential dimension of national technology policy, *Research Policy* **24**(6): 895–911.
URL: *http://ideas.repec.org/a/eee/respol/v24y1995i6p895-911.html* 51

Su, B., Heshmati, A., Geng, Y. and Yu, X. (2013). A review of the circular economy in china: moving from rhetoric toimplementation, *Journal of Cleaner Production* **42**(0): 215–227. 6, 97

Sun, Z., Song, Y. and Yu, Y. (2011). A case study about industrial symbiosis: Eu-binhai industrial symbiosis project (in chinese), *Environmental Pollution & Control* **33**(11): 4. 82

Suzhou-Municipality (2012). 12th five year planning of circular economy in suzhou. 121

TEDA (2002). Teda measures for encouraging new water sources. 76

TEDA (2004). Teda national level eip development planning. 77, 102, 106

TEDA (2006). Report of teda circular economy pilot project. 77

TEDA (2007). Annual report of circular economy in teda. 77, 84, 102, 106

TEDA (2008). 2008 annual report of tianjin economic-technological development area. 109

TEDA (2009). 2009 annual report of tianjin economic-technological development area. 109

TEDA (2010a). 2010 annual report of tianjin economic technological development area. 74, 81, 98, 109

TEDA (2010b). Introduction of teda sustainable development. 79, 80, 81

TEDA (2011a). 2011 annual report of tianjin economic technological development area. 105, 109

TEDA (2011b). Catalogue of encouraged projects on energy saving and environmental protection in teda (the fourth batch). 103

TEDA (2011c). Report of teda national level eip development (2008-2010). 81

TEDA (2012). Overview of the eco-industrial development in tianjin economic-technological development area. 102, 106

TEDA-EPB (2012). Company environmental information disclosure in teda. 82

Tian, J., Liu, W., Lai, B., Li, X. and Chen, L. (2013). Study of the performance of eco-industrial park development in china, *Journal of Cleaner Production* **64**: 9. 15, 94, 97, 99, 117, 118

Tian, J., Liu, W., Li, X., Lai, B. and Chen, L. (2012). Study of eco-industrial park development mode in china, *China Popul. Resour. Environ.* **22**(7): 7. 118

Tudor, T., Adam, E. and Bates, M. (2007). Drivers and limitations for the successful development and functioning of eips (eco-industrial parks): A literature review, *Ecological Economics* **61**(2-3): 199–207. 47, 70, 71

UNEP (2011). Decoupling natural resource use and environmental impacts from economic growth. a report of the working group on decoupling to the international resource panel., *Technical report*. 120

van Beers, D., Bossilkov, A., Corder, G. and van Berkel, R. (2007). Industrial symbiosis in the australian minerals industry: The cases of kwinana and gladstone, *Journal of Industrial Ecology* **11**(1): 55–72. 34, 65, 69

van Berkel, R., Fujita, T., Hashimoto, S. and Geng, Y. (2009). Industrial and urban symbiosis in japan: Analysis of the eco-town program 1997-2006, *Journal of Environmental Management* **90**(3): 1544–1556. 66, 118

van Caneghem, J., Block, C., Van Hooste, H. and Vandecasteele, C. (2010). Eco-efficiency trends of the flemish industry: decoupling of environmental impact from economic growth, *Journal of Cleaner Production* **18**(14): 1349–1357. 120

Ven, A. H. v. d. and Poole, M. S. (1995). Explaining development and change in organizations, *The Academy of Management Review* **20**(3): 510–540. 68

Wallner, H. P. (1999). Towards sustainable development of industry: networking, complexity and eco-clusters, *Journal of Cleaner Production* **7**(1): 49 – 58.
URL: *http://www.sciencedirect.com/science/article/pii/S0959652698000365* 42, 43

Wang, H., Hashimoto, S., Yue, Q., Moriguchi, Y. and Lu, Z. (2013). Decoupling analysis of four selected countries, *Journal of Industrial Ecology* **17**(4): 618–629. 120

Wang, H., Lei, Y., Wang, H., Liu, M., Yang, J. and Bi, J. (2013). Carbon reduction potentials of china's industrial parks: A case study of suzhou industry park, *Energy* **55**(0): 668 – 675.
URL: *http://www.sciencedirect.com/science/article/pii/S0360544213000546* 119, 135

Wang, T.-C. and Lee, H.-D. (2009). Developing a fuzzy topsis approach based on subjective weights and objective weights, *Expert Systems with Applications* **36**(5): 8980–8985. 99

Wang, Y., Liu, J., Hansson, L., Zhang, K. and Wang, R. (2011). Implementing stricter environmental regulation to enhance eco-efficiency and sustainability: a case study of shandong provinces pulp and paper industry, china, *Journal of Cleaner Production* **19**(4): 303–310. 120

Wasserman, S. and Faust, K. (1994). *Social Network Analysis: Methods and Applications*, Cambridge University Press, Cambridge, UK. 24

Wei, Y. H. D., Lu, Y. and Chen, W. (2009). Globalizing regional development in sunan, china: Does suzhou industrial park fit a neo-marshallian district model?, *Regional Studies* **43**(3): 409–427. 119, 123

White, H. (1990). *Author cocitation analysis: Overview and defense*, Sage Publications, Newbury Park, CA, pp. 84–106. 24

Williamson, O. E. (1990). *Organization Theory: From Chester Barnard to the Present and Beyond*, Oxford University Press, USA.
URL: *http://books.google.nl/books?id=pDUZD56MdTYC* 54

Williamson, O. E. (1998). Transaction cost economics: How it works; where it is headed, *De Economist* **146**(1): 23–58. 54

Wolman, A. (1965). The metabolism of cities, *Scientific American* **213**(3): 12. 119

Wu, X. Q., Wang, Y., Liu, N., Gao, Q. and Lu, G. F. (2008). Evaluation of circular economy development in industrial park based on eco-efficiency theory and topsis approach, *Chinese Journal of Ecology* **27**(12): 2203–2208. 99, 163

Yong, R. (2007). The circular economy in china, *Journal of Material Cycles and Waste Management* **9**(2): 121–129. 5, 6

Yoon, K. and Hwang, C. (1995). *Multiple Attribute Decision Making: An Introduction*, SAGE Publications. 60, 99, 163

Yu, C., de Jong, M. and Dijkema, G. P. J. (2014). Process analysis of eco-industrial park development–the case of tianjin, china, *Journal of Cleaner Production* **64**(1): 14. 100, 117, 136

Yu, Y., Chen, D., Zhu, B. and Hu, S. (2013). Eco-efficiency trends in china, 19782010: Decoupling environmental pressure from economic growth, *Ecological Indicators* **24**(0): 177–184. 120

Yuan, Z., Bi, J. and Moriguichi, Y. (2006). The circular economy: A new development strategy in china, *Journal of Industrial Ecology* **10**(1-2): 4–8. 6, 34, 65

Yuan, Z., Zhang, L. and Bi, J. (2010). Which is more cost-effective? a comparison of two wastewater treatment models in chinasingapore suzhou industrial park, china, *Journal of Cleaner Production* **18**(13): 1270–1275. 104

Zhang, B., Bi, J. and Liu, B. (2009). Drivers and barriers to engage enterprises in environmental management initiatives in suzhou industrial park, china, *Frontiers of Environmental Science & Engineering in China* **3**(2): 210–220. 60, 114

Zhang, K.-m. and Wen, Z.-g. (2008). Review and challenges of policies of environmental protection and sustainable development in china, *Journal of Environmental Management* **88**(4): 1249–1261. 77

Zhang, L., Yuan, Z., Bi, J., Zhang, B. and Liu, B. (2010). Eco-industrial parks: national pilot practices in china, *Journal of Cleaner Production* **18**(5): 504–509. 15, 50, 94, 96, 97, 117

Zhang, X., Zhang, D., Han, X., Song, Y., Wei, H. and Ma, Y. (2007). Innovative governance of eco-industrial park-case study about waste minimization club in teda (in chinese), *Resources Economization & Environment Protection* **23**(98): 31–33. 80, 81

Zhu, D. (1998). Circular economy and sustainable development in shanghai, *Shanghai Environmental Sciences* **17**(10): 4. 6

Summary

Introduction. During the past three decades, China has achieved impressive economic development. From 1978 until 2012, the growth of its gross domestic product (GDP) averaged no less than 9.9% *per year*. However, the pollution and resource depletion that accompanied China's rapid industrialization have led to severe environmental issues, such as ecosystem degradation, groundwater contamination and smog, which have turned into visible crises.

In China, industrial parks were initiated in the 1980s, aiming to attract foreign investment and to increase export. Most of these were manufacturing bases which lacked environmental planning or management. In these early stages, these parks were mainly dominated by manufacturing companies who process materials into products with low added-value. Local authorities sought sheer GDP growth without considering energy efficiency or environmental cost. While these industrial parks have immensely contributed to China's GDP, the scale, intensity and arrangement of these industrial activities have jeopardized the ecological security and health of local communities. It is therefore imperative to transform China's industrial parks and apply the principles of eco-industrial parks (EIPs).

EIP research lies within the realm of industrial symbiosis (IS), which has been defined as "engaging separate industries in a collective approach involving physical exchange of materials, energy, water and by-products" (Chertow, 2000). In practice, in an EIP one aims for closed-loop material cycles and energy cascading through resource and service-sharing, by-product exchange and environmental management (MEP, 2009), and to improve the environmental performance at the level of the entire industrial park. The realization of an EIP through matching or optimizing flows does not happen overnight. As an economic and industrial site, an EIP involves various actors, their assets and interactions. These are embedded in an institutional and a physical environment. Pollution reduction and resource conservation are achieved by individual tenants, who by cooperating and exchanging materials can improve the EIP-system performance. To steer and transform this system, we need to understand the underlying factors that determine EIP-development, to allow effective, tailored policy interventions. Empirical research resting on case studies would provide us with substantial evidence to understand these underlying mechanisms. An analytical framework would help us discover the required elements to frame the analysis of EIP, aiming at generating useful insights to diagnose current EIP policies or make new ones. Moreover, lessons learned from ongoing EIP practices are crucial for other latecomer industrial parks to deploy environmental management. Thus, in this thesis our central research question has been:

How can industrial parks be eco-transformed in China?

To answer this central research question, we have addressed a set of sub questions that have guided our theoretical and empirical research. These include:

1. How has the research on EIP evolved?
2. What elements are required to frame the analysis of EIP?
3. How can the key activities that influence changes of EIP system be structured? How can the process of the system development be tracked over time?
4. What policy instruments can stimulate the emergence of viable EIPs in China? How can the effects of policy instruments be evaluated?
5. What is the future of mature EIPs?

Understanding the evolution of the research on EIP. The research field of industrial symbiosis (IS) involves EIP research. Thus we analyzed the evolution of both the research on IS and EIP. We elucidate their embeddedness in industrial ecology (IE), trace the development of research themes and reveal the evolution of the research network through analysis of the core literature and journals that appeared from 1997 to 2012 by citation analysis, co-citation analysis and network analysis.

In the first period (1997-2005), IS research held a minority share in the IE literature. The research revolved around the concept of IS, the assessment of EIP projects and the establishment of waste treatment and recycling networks. In the second period (2006-2012), diverse research approaches and theories enriched the field, which led to maturation in theory building. Our findings clearly illustrate that IS evolved from practice-oriented research towards coherent theory building through a systematic underpinning and linking of diverse topics. As the scientific attention shifted from exploring a phenomenon to elucidating underlying mechanisms, IS knowledge found worldwide practical implementation. The co-authorship network shows that the academic communities of IS are distributed worldwide and that international collaboration is widespread.

Through bibliometric and network analysis, we have created a systemic and quantitative image of the evolution of the IS research field and community, which gives researchers an underpinned overview of the research field and may help them to identify new directions and synergy in worldwide research. The first bibliometric analysis within industrial ecology shows that these methods and associated tools are useful to provide an overview of the IS research domain and contribute to our understanding thereof.

An analytical framework for an EIP system. Chapter 3 aims to discover the required elements to frame the analysis of EIP. We develop an analytical framework, aiming to integrate related knowledge from different perspectives to structure the analysis of an EIP's development. This analytical framework is rooted in the body of knowledge of EIP and IS, a socio-technical perspective and institutional analysis. We started using a systems perspective and built a conceptual model to illustrate the actors and their interactions in an EIP (see Figure 1). In general the set of actors of an EIP mainly consist of company, policy maker, coordinating body and research institute. Actors are embedded in the institutional environment that creates incentives for influencing actors' decisions regarding pollution reduction and energy efficiency. Moreover, an EIP system also needs to adapt to the changes happening in the external world (i.e., natural environment, economic environment and social community). Then the long-term process of eco-transformation is portrayed from an evolutionary perspective. This process has relatively identifiable stages that are caused by the patterns of actors' interactions and policy interventions. During the dynamic process, the decisions of actors depend on the preconditions and evolutionary mechanisms when they consider to exchange materials, share knowledge or adopt technologies to reduce pollution.

Moreover, we explored the institutional frameworks for analyzing socio-technical systems to build up the analytical framework for an EIP system. We were inspired by the institutional analysis and development framework (IAD) that can be used as a tool for policy analysts who need to design new policy interventions, evaluate policy effectiveness, or initiate policy reform. Integrating our comprehension about the features of an EIP system, we propose a synthesis framework (see Figure 2) to direct case studies about EIPs, aiming at generating useful insights to analyze EIP policies. It mainly covers four aspects: 1) influencing factors, 2) EIP system description, 3) system performance, and 4) evaluation. Each aspect has particular focal points. The time span is taken into account to illustrate the changes across the different stages. In the end of chapter 3, we also introduce how to use this framework to conduct our empirical case studies in the following chapters.

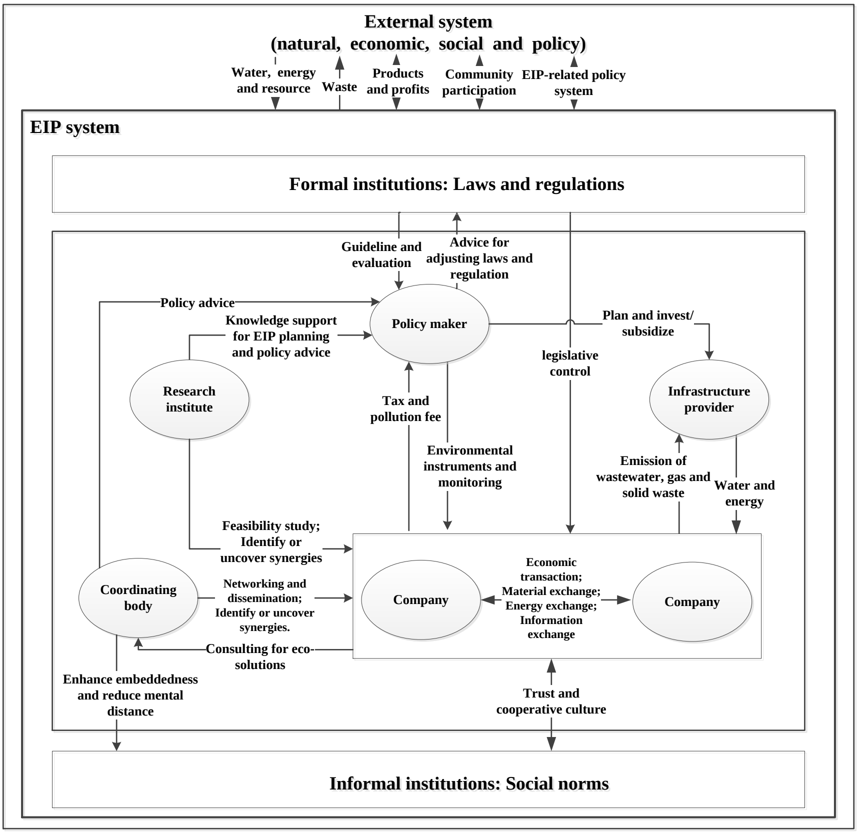


Figure 1. A conceptual model to sketch an EIP system.

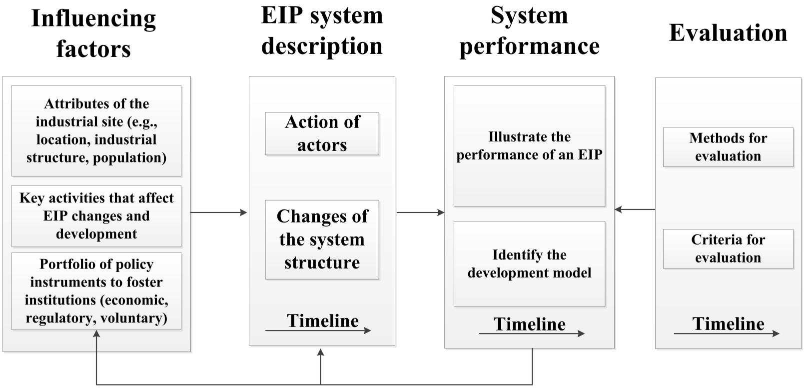


Figure 2. An analytical framework for an EIP system.

Empirical research. In chapters 4, 5 and 6, we follow the framework in Figure 2 to structure our empirical research in three Chinese industrial parks: Tianjin Economic-technological Development Area (TEDA), Dalian Development Area (DDA) and Suzhou Industrial Park (SIP). These three industrial parks are all national development zones that have mixed industrial sectors. They were the earliest pilot industrial parks in the National Demonstration EIP Program. Their experience on EIP development in the last decade provides various empirical materials. We believe that the lessons learned from these cases can demonstrate a profile of China's EIP development. The analysis in each chapter has different focal points to answer sub research questions, thus the different components of the framework in Figure 2 will be emphasized in the different case studies. Nevertheless, the analysis in each chapter links to the central research question from different perspectives: how can industrial parks be eco-transformed in China?

Process analysis of eco-industrial park development. In the study in chapter 4 we present a process analysis approach that enables analysts to trace and structure the key activities that influence changes in an EIP system. This approach rests on five key activities that affect EIP changes and development: (1) institutional activity (2) technical facilitation (3) economic and financial enablers (4) informational activity and (5) company activity. Applying this lens to TEDA allows us to build a structured database of activities to analyze its eco-transformation. In TEDA, institutional activity shapes the institutional arrangements that are pivotal for enabling and shaping the eco-transformation. Company activity has less influence on the system than the other key activities. Informational activity is vital to build trust and relationships. In a long time-span, TEDA transformed from a planned EIP to a planned and facilitated EIP, where the local authority acts as a coordinator and as a facilitator. The process analysis approach is amenable for an institutional environment other than the Chinese context because it results in a structured and documented analysis that is open to adjustment, expansion and critique.

What makes eco-transformation of industrial parks take off in China? In chapter 5, we focus on the effects of policy instruments for developing viable EIPs in China. We analyzed the root of China's national EIP program and inventoried the general instruments available for local authorities to shape and promote eco-industrial development. Empirical research conducted in TEDA and DDA leads to the activities and actions conducted by local authorities. A quantitative method for comparative analysis, TOPSIS, was adopted to reveal the effects of policy instruments. We conclude that the planned EIP model is useful in the early stage of EIP development and later it should be combined with a facilitated model to achieve long-term goals for eco-transformation. To this end, the policy package of economic, regulatory and voluntary instruments should be integrated and tailored in alignment with the local situation.

From an eco-industrial park towards an eco-city: a case study in Suzhou. Chapter 6 raises the question about the future of EIP: what is the next step for eco-transformation of Chinese EIPs? As EIP policies have been in place for over a decade, many mature EIPs tend to acquire more than industrial functions and become eco-cities. It is possible that eco-cities may be the next generation of eco-industrial parks. Thus, we aim at understanding what conditions that an eco-industrial park may provide for eco-city development. To this end, empirical research was conducted in Suzhou Industrial Park (SIP), where we analyzed how it had been transformed to an EIP and what effect this had on the accompanying urban functions. The policy instruments and environmental infrastructures are inventoried and analyzed to deduce how SIP improved energy efficiency and reduced pollution. Furthermore, we analyze the eco-efficiency and used decoupling theory to evaluate the environmental performance relative to economic growth.

The results reveal that relative de-coupling was realized for most eco-efficiency indicators; non-decoupling and absolute decoupling happened incidentally. Deployment of strict regulatory and economic instruments lead to this result, combined with more urban service and residential activities. We conclude that an EIP may give impetus for eco-city development because it leads to 1) improvement of environmental performance, 2) increase of tertiary industry, 3) synergies of infrastructures between industrial and residential areas and 4) economic prosperity derived from industrial sites.

Conclusions. This thesis proposed the central research question: *How industrial parks can be eco-transformed in China?* The process of eco-transformation is influenced by a variety of factors involving actors, technologies and institutions. To unravel this, we built and used an analytical framework to structure and guide our empirical work and allow the systematic, documented and reproducible analysis of an EIP's development. The lessons-learned from three cases have revealed essential approaches to eco-transform an industrial park in China. We hereby conclude as follows.

First, the primary issue is the strict threshold for environmental performance. The environmental requirements must be substantially improved and enforced when industrial parks recruit new companies and evaluate existing companies. If the environmental criteria still give in economic growth, industrial park development will repeat the pattern of "treatment after pollution". Second, the planned EIP model is useful to initiate the EIP program in the starting stage. Such planned model is effective to reduce the urgent pollution through end-of-pipe treatment and mandatory pollution control. Many existing industrial parks do not have physical or institutional conditions to spontaneously evolve towards an EIP, due to the environmental principles being absent in the original planning. Thus, the eco-transformation needs to build up the conditions, such as retrofitting environmental infrastructures and institutional innovation. This needs political and financial support from local authority as well as the knowledge input from research expertise. Third, as the EIP development continues, the strategies of policy intervention need to be adjusted to foster the institutions to engage company participation. In this stage, the facilitated model needs to be combined to engage actors to achieve long-term goals for eco-transformation. The portfolio of economic, regulatory and voluntary instruments should be integrated to stimulate company participation. The role of coordinator (either local authority or business association) is important to strengthen the networking among companies and to form the consensus of eco-development. Last but not least, we need to be aware that new features may emerge as industrialization and urbanization proceed. Industrial activities may change the distribution and structure of population, which lets urban functions emerge. Currently, China is promoting sustainable urbanization. Our research findings have revealed that many mature EIPs in China have revealed urban features, which paves the way towards eco-cities. Therefore, policy objectives and instruments of an EIP need to be adjusted to realize the agglomeration of industries, talents and innovation to enhance the comprehensive development of economy, environment and social welfare.

Publications

1. Yu, C., Davis, C., Dijkema, G.P.J., 2014. Understanding the Evolution of Industrial Symbiosis Research. *Journal of Industrial Ecology*18, 2.

2. Yu, C., de Jong, M., Dijkema, G.P.J., 2014. Process analysis of eco-industrial park development - the case of Tianjin, China. *Journal of Cleaner Production* 64, 14.

3. Yu, C., Dijkema, G.P.J., de Jong, M. 2014. What makes eco-transformation of industrial parks take off in China? *Journal of Industrial Ecology* (Accepted).

4. Yu, C., Dijkema, G.P.J., de Jong, M., Shi, H. 2014. From an eco-industrial park towards an eco-city: a case study in Suzhou, China *Journal of Cleaner Production* (Submitted).

5. de Jong, M., Yu, C., Chen, X., Wang, D., Weijnen, M., 2013. Developing robust organizational frameworks for Sino-foreign eco-cities: comparing Sino-Dutch Shenzhen Low Carbon City with other initiatives. *Journal of Cleaner Production* 57, 209-220.

6. de Jong, M., Wang, D., Yu, C., 2013. Exploring the Relevance of the Eco-City Concept in China: The Case of Shenzhen Sino-Dutch Low Carbon City. *Journal of Urban Technology* 20, 95-113.

7. de Jong, M., Vernay, A. and Yu, C. 2012. Développement d'un laboratoire vivant pour rendre une éco-cité économiquement viables : L'exemple de Shenzhen en Chine. Universités et enjeux territoriaux. 183-196.

Curriculum vitae

Chang Yu was born on 13 May 1985 in Harbin, Heilongjiang Province, China. She obtained her bachelor degree in business management at Heilongjiang University in 2008. In the same year, she was admitted to the master program of policy analysis at Harbin Institute of Technology. In 2010, she graduated with honor and obtained her master degree. Later, she joined in a Sino-Dutch research project of building innovation eco-industrial area in Shenzhen, which enlightened her on environmental policies and approaches of eco-transformation.

In August 2010, Chang started her PhD research at the Energy and Industry Section, Delft University of Technology. Her research focused on eco-transformation of industrial parks in China. Apart from theoretical study, she also conducted substantial field research in several Chinese industrial parks to understand the real challenges in policy implementation. During the research, she attended a plenty of international conferences and received positive feedbacks about her presentations. Chang also published five articles in Journal of Cleaner Production, Journal of Industrial Ecology and Journal of Urban Technology.

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