Industrial sustainability in China: Practice and prospects for eco-industrial development

Yiping Fang\textsuperscript{a},*, Raymond P. Côté\textsuperscript{b}, Rong Qin\textsuperscript{c}

\textsuperscript{a}Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China
\textsuperscript{b}School for Resource and Environmental Studies, Dalhousie University, Halifax, Nova Scotia, Canada B3H3J5
\textsuperscript{c}School of Resource and Environmental Science, Chongqing University, Chongqing 400044, China

Received 11 September 2004; received in revised form 2 March 2006; accepted 31 March 2006
Available online 11 July 2006

Abstract

China is a large densely populated country undergoing rapid industrialization and is becoming one of the world’s biggest consumers of natural resources. This circumstance provides a sharp contrast with other countries. As China is so significant in the global economy, studies of its eco-industrial development are very important. In this study we examined the state of eco-industrial development in China and have drawn conclusions from this analysis about some of the future prospects for sustainable development. In the analysis, we investigated the application of industrial ecology concepts by reference to several case studies. We have therefore described the current environmental situation in China, and have provided an overview of eco-industrial development and its implementation. Constraints to industrial sustainability in China have also been examined. We consider that eco-industrial development in China is in its infancy, and that closed loops involving chains and industrial symbiotic webs are the technological key and core of successful initiatives in the application of industrial ecology. In the case studies, we found that each system has different characteristics and management concerns. Our major conclusion is that even though China’s Agenda 21 highlights the principles and sets the directions for eco-industrial development, these have not yet become essential ingredients in the country’s industrial policy and practice for implementing Agenda 21.

Keywords: Industrial sustainability; Eco-industrial development; Closed-loop chain; China

1. Introduction

China is currently in the middle of a period of intense industrialization and ensuring that this development can be sustained is a significant challenge of great importance to the global economy (Ren, 2003). China’s progress has been very rapid. During the two decades that preceded the 1980s, economic institutions were successfully reformed and openness to the outside world was achieved. These social and economic changes paved the way for the recent phase of development which has been extraordinarily rapid. In this paper we examine the opportunities and constraints for China to make further progress in sustainable development by applying concepts in industrial ecology.

It is instructive to compare China’s progress in industrialization with that of other countries. In leading developed countries, such as those in Europe, the process of industrialization has spanned a period of about 200 years, but equivalent progress has been achieved in a few decades in China. The current population of these leading countries is only about 0.7 billion, accounting for 11\% of the total population of the world, while China’s population is 1.3 billion and constitutes 22\% of the total population of the world. Other contrasts of significance are that China’s natural resource base is relatively limited, and economic development is further hampered by many difficult natural conditions (Ren, 2003). China’s rapid industrialization has therefore inevitably resulted in serious conflicts between economic development and environmental performance. The modern economy of China is characterized by high investment, increasing consumption of natural resources, low efficiency in the process of production, very high

---

\*Corresponding author. Tel.: +86 28 85229236; fax: +86 28 85229892.
E-mail address: ypfang@imde.ac.cn (Y. Fang).
emissions to the environment, and an industrial structure that lacks closed loops and other structural efficiencies (Ma, 2004). In essence, China’s mode of economic development has tended to follow a similar industrialization path to that of other countries as they have developed, albeit one that is remarkably rapid.

In the 50 years since the establishment of the People’s Republic of China, GDP has grown 10 times and mineral resource consumption has increased 40 times. During the period of the sixth 5-year plan of national economic development, the rate of investment in fixed assets has grown from 2 yuan for every 1 incremental yuan of GDP to 5 yuan for every 1 incremental yuan (Ma, 2004). The total consumption of all kinds of domestic and imported resources in the most recently reported year was approximately 5 billion tonnes. The amount of oil, coal, iron-ore, steel, alumina and cement account for 7.4%, 30%, 31%, 27%, 25% and 20% of the consumption in the world, respectively, but the corresponding GDP as measured conventionally was just 4% of that of the world as a whole (Ma, 2004).

China’s rapid industrial growth based on extremely high resource consumption has resulted in serious environmental pollution. The output of contaminated water and solid waste per unit of GDP is much higher than in developed countries. Conventional end-of-pipe waste treatment is not attractive to enterprises due to the high investment, long period of return, and consequent low financial benefit.

Of the resources consumed in China annually, 5 million tonnes of waste steel, 200,000 tonnes of non-ferrous metals, 14 million tonnes of waste paper, as well as large amounts of waste plastics and glass never enter the recycling system (Ma, 2004). Unless progress is made towards sustainability, China’s path will be as unsustainable as that of other industrialized countries.

Despite these challenges, China has committed to walking down the path to sustainable development. At the 16th Congress of the Communist Party of China, economic development strategies for a new type of industrialization in the 21st century were adopted. These paths include the following: industrialization pushed forward by information technology; sustainable development created by promoting a circular economy (CE) with optimal utilization of resources and energy; and maximization of integrated community profit. At the macro-level, the development of a CE emphasizes adjusting industrial composition and structure, creating resource recycling systems, and improving these recycling systems. At the meso-level, the CE will be developed by applying industrial ecology concepts. These concepts include: fostering networks among businesses and communities to optimize the use of resources; and planning of eco-efficient energy cascades. At the micro-level, the CE will ensure that by-products are identified in individual enterprises and used effectively either internally through cleaner production (CP) or externally by other industries.

The drive to CP was introduced in China in 1992, after a decade of work involving several main themes: generating suitable laws and regulations, creating demonstration projects in selected enterprises, developing training programs for CP accounting, and various international cooperation projects. As a result of this planned effort, China is recognized as a developing country which has placed particular emphasis on advances in CP (Duan, 2003).

In recent years, there have been several initiatives in China of a local and regional nature that draw upon ideas in industrial ecology and that attempt to implement various forms of eco-industrial development. An initial focus was on the concept of eco-industrial parks (EIPs), and EIPs are currently being promoted as a means of encouraging industrial sustainability (Côté et al., 1994; Ayres, 1996; Lowe, 1997; Indigo Development, 1998).

The EIPs concept was introduced to China in the late 1990s, and research capacity on related topics has been developing quickly, including eco-industrial development theory (Deng and Wu, 2002; Yuan et al., 2004), design (Xue et al., 2003; Wang et al., 2004; Wu et al., 2004) functions (Lu and Zhao, 2001), framework (Fang, 2003), and modes (Liu and Zheng, 2001; Wang et al., 2001). Mathematical modeling of existing EIPs has included models of the input and output of material and energy flows among the industrial units, as well optimization models for the economy and the environment (Chen et al., 2002, 2004; Fang et al., 2002; Liang and Wu, 2002).

It is inevitable that China will explore industrial sustainability in a different manner than western developed countries because the political, economic, environmental and resource contexts are different. To understand the opportunities and constraints that China faces with respect to eco-industrial development, informative case studies that take account of China’s distinct character need to be analyzed.

In this paper, we have reviewed reports on a range of case studies and provide a synthesis of the type and scale of experimental eco-industrial development; supply chains and symbioses in eco-industrial development and the CE; and major constraints to eco-industrial development. Following this synthesis, we present an analysis of the opportunities and constraints with respect to making further progress in eco-industrial development in China.

2. Experimental type and scale of eco-industrial development

To encourage eco-industrial initiatives in China, the State Environmental Protection Administration (SEPA) has supported experiments in eco-industrial development since 1999. By early 2005, SEPA had encouraged 13 demonstration sites of pilot eco-industrial clusters to come into existence (SEPA, 2005). These include several potential EIPs, one demonstration city, and one demonstration province for state-level CE (Table 1).
2.1. Type of eco-industrial development

In Table 1, some basic information is provided on each of the 15 experimental sites. With regard to fundamental organization, the 15 experimental sites fall into two categories: enterprise management and government management. Thus Guigang, Baotou, Lubei, and Fushun experimental sites are managed by enterprise groups while Nanhai, Huangxing, Dalian Economic Development Zone, Tianjin Economic Development Zone, Suzhou Hi-Tech Development Zone, Suzhou Industrial Park, Yantai Economic Development Zone, Guiyang-Kaiyang and Weifang are managed by the Management Commission of the Development Zone, which is the local municipal agency. The Guiyang city and Liaoning province demonstration sites for CE are managed directly by local government. These sites also can be divided into two types of EIPs and CE demonstration sites by their experimental features (see Table 1).

Of these, the Guigang eco-industrial cluster (see Fig. 1) was one of the earliest demonstration sites approved by SEPA in 2001. This cluster has been developed by the

<table>
<thead>
<tr>
<th>Projects</th>
<th>Location</th>
<th>Management organization</th>
<th>Experimental type</th>
<th>Major industries or characteristics</th>
<th>Ratified year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guigang</td>
<td>Guigang, Guangxi zhuang autonomous region</td>
<td>Guitang group</td>
<td>EIP</td>
<td>Sugar industry</td>
<td>2001</td>
</tr>
<tr>
<td>Nanhai</td>
<td>Nanhai, guangdong province</td>
<td>Municipality</td>
<td>EIP</td>
<td>Hi-tech environmentally friendly industry</td>
<td>2001</td>
</tr>
<tr>
<td>Baotou</td>
<td>Baotou, Inner Mongol autonomous region</td>
<td>Baotou aluminum industry group</td>
<td>EIP</td>
<td>Aluminum–electricity industry</td>
<td>2003</td>
</tr>
<tr>
<td>Huangxing</td>
<td>Changsha, Hunan province</td>
<td>Municipality</td>
<td>EIP</td>
<td>Hi-Tech industry (information, new material, biological pharmacy industry)</td>
<td>2003</td>
</tr>
<tr>
<td>Lubei</td>
<td>Wudi County, Shandong province</td>
<td>Lubei group</td>
<td>EIP</td>
<td>Sea water utilization and chemical industry</td>
<td>2003</td>
</tr>
<tr>
<td>Dalian development zone</td>
<td>Dalian, Liaoning province</td>
<td>Municipality</td>
<td>EIP</td>
<td>Wastes (paper, coal ash, domestic refuse) recovery, electroplating industry</td>
<td>2004</td>
</tr>
<tr>
<td>Tianjin development zone</td>
<td>Tianjin</td>
<td>Municipality</td>
<td>EIP</td>
<td>Electronic and telecommunications, medical and pharmaceutical products, machinery manufacturing, food processing</td>
<td>2004</td>
</tr>
<tr>
<td>Fushun</td>
<td>Fushun, liaoning province</td>
<td>Fushun mining industry group</td>
<td>EIP</td>
<td>Coal industry, machinery manufacturing, chemical industry</td>
<td>2004</td>
</tr>
<tr>
<td>Suzhou Hi-Tech development zone</td>
<td>Suzhou, Jiangsu province</td>
<td>Municipality</td>
<td>EIP</td>
<td>Electronic and telecommunications industry</td>
<td>2004</td>
</tr>
<tr>
<td>Suzhou industrial park</td>
<td>Suzhou, Jiangsu province</td>
<td>Municipality</td>
<td>EIP</td>
<td>Electronic information, precise machinery, biological pharmaceutical products, new materials</td>
<td>2004</td>
</tr>
<tr>
<td>Yantai Development Zone</td>
<td>Yantai, Shandong Province</td>
<td>Municipality</td>
<td>EIP</td>
<td>Chemical industry, precise machinery, Phosphate chemical industry, coal chemical industry</td>
<td>2004</td>
</tr>
<tr>
<td>Guiyang-Kaiyang</td>
<td>Guiyang, Guizhou province</td>
<td>Municipality</td>
<td>EIP</td>
<td>Marine chemical industry</td>
<td>2005</td>
</tr>
<tr>
<td>Weifang</td>
<td>Weifang, Shandong province</td>
<td>Municipality</td>
<td>EIP</td>
<td>Chemical industry based on phosphate and coal resources, regeneration of brown field</td>
<td>2002</td>
</tr>
<tr>
<td>Guiyang city</td>
<td>Guiyang, Guizhou province</td>
<td>Municipality</td>
<td>Demonstration city for CE</td>
<td>Metallurgical, coal, chemical, machinery industry based on resource recovery, and regeneration of brown field</td>
<td>2002</td>
</tr>
<tr>
<td>Liaoning province</td>
<td>Liaoning province</td>
<td>Province government</td>
<td>Demonstration province for CE</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Guigang group, the largest state-owned company in the city of Guigang. Today, it operates the largest sugar refinery in China, as well as several other enterprises such as a pulp mill, a paper mill, an alcohol plant, a cement mill and a fertilizer plant. The economy of the group is dominated by the sugar-making industry. Declining economic fortunes of the group from the late 1980s to the early 1990s was due to recession in the sugar industry. This situation resulted in a decrease in economic benefits and an increase in pollution. Thus a major objective for the group as a whole is the creation and revision of its development philosophy from a conventional industrial system to an industrial ecosystem based on sugarcane planting, sugar-making, alcohol production, paper-making, thermo-electricity and integration of the environmental management system. The Guigang group has recognized that their economic gains lie in the reduction of raw material and energy costs, waste management costs, and costs resulting from environmental legislation, as well as the improvement of its “environmental image” to increase its “green market” potential (Burström and Korhonen, 2001; Zhu and Côté, 2004).

The Nanhai site (see Fig. 1) was another type of demonstration site initiated early by SEPA. In contrast with the Guigang site, this kind of park is being funded and managed entirely by the municipality. The idea of eco-industrial development on this previously “green field” site came from a coordinated effort to gain social, economic and ecological benefits through by-product and waste exchanges, multi-dimensional energy and waste-water utilization, as well as sharing infrastructure. At present, industrial ecology efforts at the Nanhai site have focused on the development of the environmental protection science and technology sector, which includes environmental consultative services, manufacturing of environmental protection equipment and development and production of new material, green products, and resource recycling activities. It is hoped that the program will provide the incentive for improved regional environmental performance and economic growth.

Guigang, Nanhai, Baotou, Huangxing, Lubei, Dalian, Tianjin, Fushun, Suzhou Hi-Tech, Suzhou Industrial Park, Yantai, Guiyang-Kaiyang, Weifang (shown in Table 1 and Fig. 1) are 13 sites that are projects at the operational or pre-operational stage at the present time. The economy of these parks is dominated by sugar, paper-making, aluminum-electricity, electroplating, machinery, pharmaceutical, metallurgical, electronic, communication, building material and chemical industries (sea water, coal, phosphate, marine chemical industry, etc.). Two others, Guiyang and Liaoning are municipal and provincial demonstration projects for CE, respectively.

2.2. Scale of eco-industrial development

With regard to the regional scale, the 15 experimental sites (Table 1) fall into three categories: small (13 EICs or EIPs), medium (one demonstration city for CE) and large scale (one demonstration province for CE). Conversely, they can also be categorized as community level (thirteen EIPs), city-level (Guiyang City) and province-level (Liaoning province) initiatives in accordance with administrative responsibilities (see Fig. 2). The latter two projects were ratified by SEPA in 2002. Table 1 and Fig. 2 show that the experimental sites have expanded from the park and
community level to the provincial level, and from single industrial systems to comprehensive economic systems.

The major objective of eco-industrial development lies in offering a holistic conceptual framework for the kind of “significant, systematic industrial change” needed to eliminate environmental damage (Tibbs, 1992). This provides an experimental and popularized basis for thinking about ways to connect different waste-producing processes, plants, or industries as well as consumers into an operating web that minimizes the amounts of industrial materials that go to disposal sinks or are lost in intermediate processes at larger regional scales (Fang, 2003).

Guiyang city is an experimental site for CE at a city scale. It is located in Guizhou Province of southwestern China, with an area of 8034 km² and a population of 3.2 million in 1999. In 2000, the GDP of Guiyang city grew 10.6%, with the growth rates of the agriculture, industry and service sectors being 2.3%, 10.8% and 12%, respectively. The components of the Guiyang economy consist of agriculture (9.1%), manufacturing industry (50.9%), and service sector (40%) in terms of economic value added (Guiyang Statistical Bureau, 2001). The proposed Guiyang demonstration city for CE would represent an important transition from the potential condition of exhausted resources, low rates of resource reuse, and high pollution discharges to a sustainable circular and eco-efficient city (see Fig. 3) (Huang, 2003). It would support several eco-industrial networks (EIN).

Liaoning province in the northeast of China is one of the most important industrial centers of China. In the 1950 and 1960s, after the founding of the People’s Republic of China, there was significant investment in industrial development in Liaoning. In 1957, the value of its gross industrial output was 15% of that of China as a whole (Peng, 2004). During the period between 1953 and 2002, Liaoning produced 1/4 of the steel products, 1/10 of the coal, 1/4 of the crude oil, and more than 1/2 of the machine tools of the whole China, as well as a large amount of machinery (Peng, 2004). These major contributions

---

**Fig. 2. The scale level of eco-industrial development in China.**

**Fig. 3. Conceptual framework for Guiyang demonstration city of CE.**
speeded up the process of industrialization of China, but
the environment was badly damaged by economic de- 
velopment with “high material consumption, high-energy 
consumption and high emission” (Peng, 2004). The original 
resources were being exhausted, and this badly limited the 
revival of the old industrial base in Liaoning.

For the reasons described above, SEPA officially 
approved a CE experimental site for Liaoning province. 
This is the first experimental site for CE at a provincial 
scale, and its structure consists of the following. In each 
enterprise, CP was introduced. Anshan Steel Corporation 
Group was the first to participate. As of 2005, 40 projects 
were undertaken involving recycling and comprehensive 
reuse of steel residue, recovery of mash gas mud, converter 
gas, water and heat, as well as other activities (the Central 

For communities of enterprises, some industrial symbio-
sis networks have been established. The Fushun Mining 
Group has implemented a change in production from its 
traditional program: abandoned resources are being comprehensively reused and new industries have been 
developed. In Shenyang Tiexi New District, nine industrial 
lines and recycling networks were set up among 47 
important enterprises. This was achieved by moving, 
changing and regrouping, as well as adjusting the industrial 
structure and layout of the processes. Material flow, energy 
flow, technology integration, information and infrastruc-
ture were shared among them. In the Dalian economic 
and technology development zone, nine industrial symbiosis 
networks were established by recycling industrial by-
products and comprehensively utilizing discarded home 
electronic equipment (the Central Committee of China Zhi 
Gong Party, 2004). Within Dalian city, efforts have been 
made to establish resource recycling of the city’s own 
wastes, including reusing intermediate water and solid 
wastes (EPI, 2001).

3. Supply chains and symbiosis webs of eco-industrial 
development

There are numerous examples of recycling and symbiosis 
of materials and products that are being re-used through 
remanufacturing activities in China, as well as materials 
that are being recycled. In the following sections, we 
document the symbiotic relationships and integrated supply 
chain initiatives in two eco-industrial clustering cases that demonstrate reuse, remanufacturing and recycl-
ing. We also discuss a CE experimental site. The final 
subsection describes many of the challenges of closing 
loops and fostering industrial symbioses.

3.1. Industrial symbiosis and closed-loop chains of EIP
experimental sites

3.1.1. Sugar-making industry: the case of Guigang

Established in 1954 by the Government of China, the 
Guigang group is now the largest stock company in the city 
of Guigang. The initial purpose of establishing the 
Guigang group was to produce cane sugar. Today it is 
the largest sugar-making industry in China and includes a 
pulp-making plant, a paper-making plant, an alcohol 
plant, a cement mill and a fertilizer plant. The annual 
total production includes sugar (120,000 tonnes), paper 
(85,000 tonnes), alcohol (10,000 tonnes), cement (330,000 
 tonnes), alkali (8000 tonnes), and fertilizer (30,000 tonnes) 
(Zhu and Côté, 2004). All these plants are based on by-
products generated from the sugar-making industry. The web shaped by the Guigang group consists of two main 
chains, namely sugar and paper. The sugar chain consists 
of a sugar-processing plant, an alcohol-processing plant 
and a compound-fertilizer plant. Along this chain each 
down-stream plant uses as its raw material the by-product 
generated by the up-stream plant. The principle of using 
by-products from one plant as raw material for the down-
stream plant has also been adopted in the paper-making 
chain. The paper-making plant uses the sugar slag 
generated from the sugar-making plant, and the down-
stream cement mill uses its by-product, the sludge, as raw 
material for the production of cement (shown in Fig. 4).

3.1.2. Chemical industry: the case of Lubei

The Lubei Group, located in Wudi, Shandong Province, 
near the Bohai Sea, was formed in 1977. It is now a large 
state-owned industrial group covering 12 industrial sectors 
such as building materials, light industry, electricity 
generation and production of machinery.

The industrial ecosystem has 52 member enterprises and 
5300 employees, with total assets of 5 billion yuan. The 
annual production of the Lubei Group includes: ammon-
ium phosphate (300,000 tonnes), sulfuric acid (400,000 
to-ds), cement (600,000 tonnes), sea salt (1,000,000 tonnes), 
sodium hydroxide (60,000 tonnes) and bromine 
(10,000 tonnes). It has been the largest producer of 
phosphate fertilizer in China as well as the largest 
manufacturer of ammonium phosphate, sulfuric acid and 
cement in the world since 2001 (Feng, 2003). There are 
three main industrial chains (illustrated in Figs. 5–7). 
The first chain is the ammonium phosphate–sulfuric acid–ce-
ment integrated industries chain (Fig. 5); the second is a 
chemical industry chain for integrated seawater utilization 
(Fig. 6) and the third is a salt–alkali–electricity manufactur-
ing chain (Fig. 7). The Lubei integrated industrial 
system reveals synergy in the re-use of by-products both 
within and among the three production chains. Sulfuric 
acid and seawater are the basic material flows, steam and 
electricity are the energy flows, and gypsum and furnace 
slag are the main “wastes” flows. (Based on Feng, 2003)

3.2. Industrial symbiosis and closed-loop chains in CE 
experimental sites

Here we analyze the Guiyang demonstration city as a 
case and model for the industrial sustainability system 
known as the “CE”. This system will be required to
Desulphurization, Cement, Compound Fertilizer, Recycle Water

Sugar
Organic Sugar
Fructose

Alcohol
Yeast Cake

Cane Slag Paper CMC

Thermo-Electricity System

Vapor
Electricity

Recycle Water

Alkali Recovering

Sugar Slag

SO2
Ammonia

Phosphate
Rock

Grind
Filter
Condensate
Dry
Ammonium Phosphate

Sulfuric Acid

Charcoal
Clay

Coal Slag

Coal

Compound Materials

Sulfuric Acid Plant

Cement Mill

Cement

Gypsum

Desulphurization, Cement, Compound Fertilizer, Recycle Water

Eco-system Restoration System

Desulphurization, Cement, Compound Fertilizer, Recycle Water

Sugar-Making System
Sugar Slag

Waste Water
Waste Gas
Wastes

Wastes

Recycle Water

Alkali Recovering

Fig. 4. Industrial symbiosis and closed-loop supply chains for sugar-making industry in Guigang Park.

Ammonia
Vapor

Phosphoric Acid

Raw Material

Decomposer

Wastes

Ammonium Phosphate

Sulfuric Acid

Sea Water

Aquaculture
333.3hm2

Bromine
10 thousands t/a

By-products
Gypsum

Salt
1 million t/a

Potassium Sulphate
Magnesium Chloride

Liquefied SO2

Chlorine

Sulfuric Acid
Cement

Halogenated Processing

Fig. 5. Ammonium phosphate, sulfuric acid, cement industrial chains in Lubei Park (1) (based on Feng, 2003).

Fig. 6. Sea water integrated utilization industrial chains in Lubei Park (2) (based on Feng, 2003).
overcome the challenges already outlined. Currently sulfur dioxide (SO\textsubscript{2}) constitutes a pressing problem in Guiyang, where the concentration of SO\textsubscript{2} in the atmosphere is 0.132 mg/m\textsuperscript{3}. This is 1.2 times higher than Grade II of the National Air Quality Standards adopted in 2000. The primary cause of this air pollution is heavy manufacturing and other coal-fueled industries which are using local coal that has a sulfur content of 4%. The Qingzhen Power Plant, the Guiyang Power Plant and Guizhou Crystal Organic Chemical Industry Co. Ltd., for example, discharge more than 77.8% of the total SO\textsubscript{2} emissions in the city (SEPA, 2001). From Table 2, it can be seen that metals, chemical, machinery and equipment, tobacco and electric power generation are the major industries in Guiyang (Guiyang Statistical Bureau, 2000). The Guiyang municipality has adopted a development blueprint with seven elements for eco-industrial innovation. These involve sustainable systems for phosphate manufacturing, clean coal technology and manufacturing, aluminum manufacturing, Chinese herbal medicine, eco-agriculture, construction and other infrastructure industries, and tourism. Process redesign, reorganization and establishment of the components of a circular system are now required (Fang, 2003).

The city of Guiyang has a rich and diverse array of mineral and energy resources. There are more than 20 types of mines including aluminum, phosphorus and iron. Twenty percent of the aluminum of China is processed in Guiyang and one of the three largest phosphorus mines is located within the boundaries of the city (Guiyang Statistical Bureau, 2001). Therefore, aluminum manufacturing and phosphate products manufacturing are important industrial considerations in the implementation of the demonstration city initiatives for CE in Guiyang. Therefore these two industries have been selected as examples for integrated supply chain development in the following analysis. In order to fully understand the nature of closed-loop aluminum and phosphate industrial chains, both forward and reverse flows of materials must be considered. Figs. 8 and 9 show the supply chains for aluminum manufacturing and phosphate manufacturing, respectively (Huang, 2003).

The forward movement of materials consists of the traditional flows from suppliers to manufacturers and end users. In other words, the forward movement of materials consists of the bauxite supplier to the aluminum producer to the aluminum product manufacturer and customers in one example, and the phosphate mineral supplier to phosphate product manufacturer to phosphate customers in the other example. The reverse flows are more complex; manufacturers collect “wastes” or by-products from the processors, manufacturers and end-users or consumers.

Table 2

<table>
<thead>
<tr>
<th>Sector</th>
<th>Output in current year billions Yuan RMB (% of total)</th>
<th>Employment (% of total)</th>
<th>Pre-tax profits (% of total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td>19</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Chemicals</td>
<td>15</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>Tobacco</td>
<td>15</td>
<td>3</td>
<td>49</td>
</tr>
<tr>
<td>Machinery and equipment</td>
<td>10</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Electric power</td>
<td>10</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td>6</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Non-metallic minerals</td>
<td>4</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Food and beverages</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Telecom equipment</td>
<td>4</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Mining</td>
<td>3</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Printing</td>
<td>3</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Electrical equipment</td>
<td>1</td>
<td>2</td>
<td>-2</td>
</tr>
<tr>
<td>Textiles</td>
<td>1</td>
<td>4</td>
<td>-8</td>
</tr>
<tr>
<td>Wood, furniture, paper</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

The re-manufacturer of aluminum does not collect directly from the end-user, but relies on a variety of third-party collectors or scavengers. Fig. 9 illustrates the phosphorus cycle in an industrial system and a natural agricultural system. The phosphate flows shown in Fig. 9 differ from those in the aluminum manufacturing chain shown in Fig. 8. Phosphorus cycles quickly through the living systems and very slowly through the long-term geological process shown on the right of the diagram. The key issue here is therefore preventing phosphate from flowing into water bodies in the physical system where it can act as a deleterious fertilizer and is not readily removed.

3.3. Closing loops in supply chains in eco-industrial development

Based on production flows, the management of the process involves transforming linear chains into cycles connecting raw material purchasing, consuming and recycling. With the extent of economic globalization and the increasing distances between enterprises, the range of the suppliers, manufacturers, distributors, and consumers that are involved becomes large. The supply chains become much longer, and the structures become more complicated. The technological and structural situation is such that the relationship between enterprises must involve both forward and reverse logistic or material cycles (Michael, 2001).

In the simplest terms, closed-loop supply chains have a common set of activities or components. The recovery process consists of several highly interrelated sub-processes: product recovery, reverse logistics, and disposition and distribution of the recovered products or materials (Ayres, 1996; Walton et al., 1998; Jayaraman et al., 1999). However, the previous cases illustrate that, while there are common processes, not all closed-loop supply chains are alike. Each supply chain system has different characteristics and management concerns (Ayres and Ayres, 1996; Walton et al., 1998; Jayaraman et al., 1999).

On the one hand, product recovery is linked to asset management, and is actually a number of related processes, including facility design, product planning, control practices and inventory practices. Reverse logistics activities are
the processes required to move the products from the end-user to the facility where reuse activities will take place (Guide, Jr and Van Wassenhove, 2002). Thus, the characteristics and management effectiveness of different supply chains depend on differences in raw materials, product types, market demands and integrated policies (Guide, Jr and Van Wassenhove, 2002).

On the other hand, the industrial remanufacturing sector is the most difficult to plan, manage and control. Managers of such industries need to have the ability to forecast and control the timing, quantity and quality of product returns, and in addition must be involved in developing technology and processes for reuse. It also requires customer education and new relationships with suppliers (Guide, Jr and Van Wassenhove, 2002).

Due to differences in industrial sectors, the components of the supply chains will also differ (see Table 3). Suppliers of sugarcane, seawater, aluminum ore, phosphorus ore; the manufacturers of cane sugar, paper, sea salt, potassium sulfate, aluminum products, phosphorus products; the distributors and retailers of sugar, paper, refined salt, chemical fertilizer, aluminum materials, and the relevant customers; remanufacturers of cane slag, spent molasses, saturated bittern, gypsum, mine refuse, wasted aluminum, are different in aims, types, structure and functions. Much difference exists in the control objects, methods, techniques and processes.

As to the experimental sites of EIPs and CE, different industrial chains were identified at each site. For instance, the cane sugar industry chain in Guigang, the marine chemical industry chain in Lubei, the aluminum industry chain and phosphorus chemical industry chain in Guiyang, were determined as the dominant industry chains of each site.

The management goal of the supply chains in the three cases of Guigang, Lubei and Guiyang were essentially the same, namely, maximizing the economic benefits, maximizing the resource efficiency and minimizing the environmental pollution. But the resource efficiency is very much related to the significant difference between industry chains. The difference of resource efficiency is very obvious. The utilization level of raw materials such as cane, seawater, aluminum ore, phosphorus ore; the recovery level of cane slag, spent molasses, saturated bittern, gypsum, mine refuse, wasted aluminum, waste gas and the utilization level of energy and water resources were all based on the level of technology and process design of cane manufacturing, the seawater chemical industry, aluminum smelt and processes and the phosphorus chemical industry chains.

In the processes of supply chain management, the sugar-making industry, seawater chemical industry, aluminum smelting and process industry, phosphorus chemical industry, and product purchasing, material selection, technology utilization, environment standard information, etc., are completely different. The collection, analysis, and application of the relevant information must be done on the basis of the industry-specialization database, knowledge base, information system and technology.

Reverse logistics is becoming an increasingly important trend in environmental management of the enterprises of the future. In Europe for example, legislation requires enterprises to recover and dispose of the used products generated after consumption. In a perfect market system, a third-party reverse logistic enterprise will take the initiative to help correlative enterprises complete the loop by recovering products for remanufacturing and recycling. However, in China, with market mechanisms still evolving, more dependence on the law and policy is required to close loops and create a CE. On the one hand, information and education are required to improve the environmental protection awareness of the public and enterprises. On the other hand, laws and regulations can extend manufacturing responsibilities for the enterprises, and this obligation should be imposed as a mandatory provision (Jin and Wang, 2001; Duan, 2001).

If circular industrial systems are to be adopted in China, the prospects and constraints must be explored.

### 4. Prospects and the role of government in eco-industrial development

In this section, we discuss the prospects for eco-industrial development, constraints that limit the potential for such development and the roles of key actors in the transformation of the industrial economy.

#### 4.1. The role of government

By contrast with the historical pattern of laissez-faire industrialization in developed countries, China has formally committed to sustainable development at a relatively...
early stage in the industrial development process. This commitment consists of the adoption of the goals of building the “All-round Better-off Society” (Xiaokang). The Central Government of China is a powerful stakeholder in this commitment and plays key roles in promoting eco-industrial development through such aspects as decision making, creating policies, issuing laws and regulations, organizing pilot activities, providing financial incentives, encouraging innovations in technology and systems, fostering new markets and promoting both education and academic research partnerships.

4.2. Development strategy

The Chinese National Government has been encouraging a new type of industrialization as its main economic development strategy and is adopting strategic policies leading to comprehensive, coordinated and sustainable development. The basic principles and general guidelines of the CE have been established with the following aims by 2010: (1) creating medium and long-term goals for development of the CE; (2) creating a system of policy incentives; (3) establishing the system of law and regulations; (4) encouraging the system of technology innovation; (5) creating mechanisms of motivation and constraint; (6) setting up the indicator system for assessing the CE; (7) promoting CP in the enterprises within key industrial sectors; (8) setting up the system and mechanism of resource recycling within key areas; (9) fostering EIPs and resource-recycling cities which match the mode of the CE and (10) encouraging international cooperation (Ma, 2004). The National Government is paving the way to create a domestic economic system and resource-conserving society based on low resource consumption, minimal environmental contamination and a highly efficient economy.

Since the introduction of CP into China in 1992, after more than 10 years of effort within 26 provinces and autonomous regions, nearly 1000 enterprises had implemented CP demonstration projects. The sectors included mining, metallurgy, electric power, chemicals and petrochemicals, construction materials, general mechanics, electronics, transportation, airplane manufacture, textiles, paper, beer, alcohol and pharmaceuticals. The average reduction of contamination was 20%, with those enterprises implementing CP gaining an average of 1,000,000 yuan per year through savings. In addition, 16,000 people had taken part in a total of 560 training programs on CP practices (Duan, 2003).

4.3. Policy and law

Government policies influence every aspect of industrial activity, from the investment and design stage to the pattern of production and consumption. As part of this policy, the Ministry of Science and Technology has committed US$1.2 billion in science and technology investment for sustainable development (China seeks to develop a “CE”, 2005).

Laws and regulations are also helpful in correcting market conditions, including market failures, and promoting eco-industrial development. In 2002 the Energy Economization Law and the CP Promotion Law were promulgated. Tentative Guidelines on the Planning of Ecological Industry and Demonstration Parks were issued in 2003 (EID_Circular, 2003). The CE law is currently in the process of being passed by the National Government in 2005, at the time this paper was written. From a macro-level point of view, it therefore seems that a consistent framework is emerging for progress in eco-industrial development. Nevertheless, all relevant legislation and policies are not in place and it is insufficient to guide the implementation of the framework for industrial sustainability.

4.4. International cooperation

Openness to the outside is one of the features of the new style of industrialization in China (Ren, 2003). The National Government has encouraged individual and collective attempts to find opportunities to advance the CE by means of cooperation between China and developed countries in the field of eco-industrial development. International development in the developing world is like a game of leapfrog in which successful advances in one country encourage similar developments in another, and so China’s efforts to speed up the introduction of concepts in industrial ecology has effects throughout the community of developing nations.

An initial institutional network has been formed through multilateral and bilateral support programs. The Asian Development Bank provided technical assistance for the Ministry of Science and Technology to set up a Center for Environmentally Sound Technology Transfer, whose mission is to assist China’s industry, particularly small- and medium-sized enterprises in pursuing stronger economic competitiveness and better environmental performance by adopting CP and environmentally sound technologies (ESTs) (Centre for Environmentally Sound Technology Transfer, CESTT, 2004). SEPA has attempted to coordinate its efforts with those of the Asia Development Bank, the European Union, United Nations Development Program (UNDP), United Nations Environment program (UNEP), the World Bank, Australia, Canada, Japan, Germany, the United Kingdom and Norway, among others, that have been promoting CP and pollution prevention (Cleaner Production in China, 2004). In 2000, SEPA collaborated in a project with UNEP to initiate demonstration sites for EIPs. In addition, many multinational corporations have been expanding their manufacturing activities in China since the 1990s. Many of them have adopted preventive environmental management strategies such as recycling or CP programs as well as environmentally sound technologies. Companies such as
Bosch-Siemens have adopted hydrocarbon-based refrigeration technology, Motorola has experimented with Design for Environment in their product development, and Toyota is using hybrid technology in vehicle manufacture in China.

4.5. Academic research and application

In 2005, only three significant national laboratories on eco-industrial development have been established. They are at Northeastern University, Tsinghua University and the Chinese Research Academy of Environmental Science. The Chinese Centre for Material Life-Cycle Assessment has also been established (Shi, 2002). Given the size and diversity of China and its economy, these are insufficient on their own. By consequence, academic research on eco-industrial development is in its infancy and relatively weak compared with the work being conducted on CP by the engineering professions. Research capacity on social science and economic aspects of eco-industrial development is similarly in a weak position relative to the capacity for research on the CE.

Due to the support and promotion of CP by SEPA, as an important tool of environmental management, many research institutions are engaged in CP. By contrast, the unavailability and sparseness of data on product life cycles has led to a bottleneck in implementing life cycle assessment (LCA). The application of the industrial ecology concept of design-for-environment is similarly still in its infancy in the domestic industrial system, with the exception of its application by the subsidiaries of some leading multinational corporations such as Motorola, BASF, Mitsubishi, and Lucent Technologies. Material flow analysis (MFA), another important tool of industrial ecology, is even less developed in China. This approach is becoming increasingly important because of the large flows of materials in the Chinese economy.

4.6. Education

Remarkably, education in China is running behind the actual practice of eco-industrial development. On the one hand, collaboration between Chinese academic institutions and their European, North American, and Japanese counterparts is beginning to play an indispensable role in catalyzing pilot research and nurturing China’s initial expertise in industrial ecology. On the other hand, only a very small proportion of universities in China have offered industrial ecology courses to undergraduate and graduate students. The exceptions include Tsinghua University, Northeastern University, Wuhan University, Beijing Polytechnic University, and Dalian University of Technology. Despite the enthusiasm of those advocating EIPs, particularly government officials, there are few industrial estate managers and practitioners who can effectively apply the theoretical framework for eco-industrial development (Shi, 2003). A wider range of educational institutions with capacity in industrial ecology is therefore of critical importance in providing practical tools for eco-industrial development throughout China.

4.7. Information systems

The new type of industrialization in China has a strong element of information technology in its design and is promoted by means of a new approach to information which is described as “informationization” (Ren, 2003). The strategy for informationization focuses on promoting informationization in concert with industrial policy, pushing informationization in the domestic economy, and encouraging informationization in enterprises. Currently, rapid development in informationization has been achieved. This provides a potentially powerful foundation for eco-industrial development.

Environmental information systems at the municipal level are in the process of construction in some cities led by local environmental protection bureaus. In order to improve environmental protection further, it is imperative that environmental information systems also be established within industrial parks and zones to provide integrated and reliable data. The data would include surveys of the members, detailed information about inputs and outputs of materials, environmental monitoring, and other data. The data would be collected and evaluated locally. By using the data for LCA and MFA, industrial park managers would be better able to guide the eco-industrial development of the industrial park. In this way, symbiotic synergies such as exchange of by-products among companies would be encouraged within EIPs.

4.8. Financial incentives

Many existing economic policies in China create disincentives to CP. For example, the low water price resulting from a government subsidy does not provide the necessary incentive for enterprises to adopt water-saving technologies. Incentives for conserving water are very important in those provinces and municipalities, notably in northern China, where there are serious water shortages. In addition, low effluent and waste discharge fees cause enterprises to simply pay the fee rather than implementing CP options or industrial sustainability measures which appear to cost more money under the current circumstances (Wang and Li, 1995).

There is currently a lack of funding to promote industrial ecology education, academic research, and information dissemination in most parts of China (Chiu and Geng, 2004). Financial incentives to encourage adoption of new eco-industrial concepts and tools are also lacking. For example, at every stage of the layout and construction of an EIP financing is an important factor in ensuring its success. Cooperation is therefore needed among government, enterprises, communities and other non-government organizations. Both the economy and the environment will benefit from eco-industrial development, and through these means the private sector, government, and society as a
whole will benefit. Thought must therefore be given to creating incentives which will maximize benefits and ensure that these are shared by all those involved.

4.9. The role of enterprises

Enterprises in China have been embroiled in a struggle among conflicting objectives: pursuing profit, complying with current regulations, and attending to various legal constraints associated with environmental protection strategies that are rooted in end-of-pipe treatment. As a result of struggles like these, most enterprises have been seeking better ways to balance economic performance with environmental performance. Eco-industrial development clearly has the potential to offer solutions in finding this balance. Not only are there domestic benefits to consider in these business strategies for improving environmental performance, but there are also benefits in international trade. For enterprises aiming at international markets, advantages can be obtained by implementing CP and eco-industrial development so as to fulfill environmental standards set by the developed countries and overcome green-tariff or other non-tariff barriers to trade. Although eco-industrial development has the potential to provide these benefits, there are serious constraints in practice. For example, lack of understanding of the relative costs and benefits of participating in EIPs has led to doubts about feasibility. Therefore enterprises need to be provided with clear statements and examples of the profits that can be gained from eco-industrial development, and these statements need to be juxtaposed with explanations of the environmental and social benefits that are also gained.

5. Conclusions

Eco-industrial development is in its infancy throughout the world. Although China has industrialized relatively recently, the first steps in eco-industrial development have been taken. The National Government of China has begun promoting eco-industrial development with demonstration sites for EIPs, as well as a demonstration city and province for CE. Given that China is at an early stage of eco-industrial development, valuable lessons can be learned from both positive and negative experiences. These lessons will provide the basis for future progress. To achieve progress, information about the successes and shortcomings of eco-industrial development projects must be widely disseminated. The National Government will also have to ensure that solid policies are developed to encourage the implementation of the CE. These policies will have to be supported by both economic reformation and incentives. Success in eco-industrial development in China depends not only on unremitting advocacy on the part of government, but also on revealing the actual profits that enterprises stand to gain from eco-industrial development, and most important that entrepreneurs and the public become better aware of eco-industrial development. Further incentives for eco-industrial development must be developed in the form of policies, laws, regulations, and financing. Of equal importance, China needs to make further progress in academic research and fundamental education in industrial ecology because research and education play critical roles in all forms of development, including eco-industrial development. Incentives that focus on improving and expanding research and education in industrial ecology are therefore needed.

With rapidly growing industrialization and urbanization in China, experiences gained from eco-industrial demonstration projects are of critical importance for industrial sustainability in China. The number of small and medium enterprises (SMEs) in villages and small towns is increasing rapidly throughout the country. At the end of 2001, these enterprises numbered 20,040,000 in many different sectors, employing 125 million people (Lin, 2002). Small and medium-sized enterprises accounted for 30% of GDP in China and as much as 50% of the value of domestic industry production (Lin, 2002). The small- and medium-sized business sector can be expected to grow more quickly than larger enterprises. Many of the smaller enterprises were established as a result of the reformation of the agricultural sector and are spread throughout the countryside. Unfortunately, due to their rapid growth, small scale, lack of capital and technology, these clusters of enterprises are causing serious environmental problems and are negatively affecting the sustainable development of China. In light of this, special attention needs to be paid to the sustainable development of SMEs in villages and towns in China’s strategy for eco-industrial development. It will be important to extend current projects into the countryside and begin to create EINs and clusters of SMEs.

China is a developing country, the current economy of China is not yet sufficiently developed to support the highest standards of eco-industrial development, but regardless of the difficulty of the path, China has no choice but to continue along the path of creating the CE.

Acknowledgments

The research is supported by western talent program of the Chinese Academy of Sciences (CAS) (Project no. L10416004). The authors are grateful to the CAS for the financial support that enabled Fang to be a senior visiting professor at Dalhousie University, and to Chongqing University for providing financial support to Rong Qin while she was a visiting scholar at Dalhousie University, which led to the research reported herein. We would like to thank the anonymous reviewers for constructive comments on an earlier version of the paper, to acknowledge Prof. Martin Willison at Dalhousie University for contributions of language revision.

References


