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Insight into industrial symbiosis and carbon metabolism from the evolution of iron and steel industrial network

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ABSTRACT

Industrial Symbiosis (IS) as an effective way to promote the sustainable development of industrial network has attracted extensive attention. Exploring the evolution of IS is crucial to present a dynamic perspective of IS. This paper highlights the drivers and the mechanism of policies on the evolution of IS as well as the environmental benefits of IS. A backward approach that provides comprehending on how industrial network emerged over time was used to analyze the sequences of IS in a typical case study of an iron and steel industrial network from 1958 to 2012. Results show that symbiotic links increased from 2 to 75 over time, with the average number of symbiotic links per entities from 1 to 3.26. The main guiding factors in the evolution of industrial symbiosis are not only the interests of enterprises and knowledge of industrial symbiosis, but also related policies and regulations. Industrial symbiosis can improve carbon metabolism efficiency and avoid pollutants emissions. Exchange-based IS can avoid more carbon dioxide emission (CO_2) than the other pollutants, and energy exchanges had a greater contribution to pollutants emission reduction than the solid waste/byproduct exchanges. The network structure and the evolution of IS can be understood better through considering not only the inter-firm level and the regional or global level but also the intra-firm level.

1. Introduction

Industries and organizations that engaged in the production, transportation, transaction and utilization of goods and services form an industrial network where they interact with each other (Axelsson and Easton, 1992; Melo Brito, 2001). An industrial network includes not only selling products and raw materials through supply chain, but also selling wastes for reuse and sharing utilities (Ashton and Bain, 2012). While industrial symbiosis network focuses on the cooperative management of resource flows, it tends to emerge in places where natural resources are limited, or the cost of disposal is expensive (Chertow et al., 2008). Industrial symbiosis network promotes the sustainable development of industrial network and seeks to reach zero waste by reusing and recycling waste (Karn and Bauer, 2001; Lecanda et al., 1998). The most frequently cited definition of industrial symbiosis (IS) is proposed by Chertow (2000)— "traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity". The definition reflects the state of research and practices at that time. As the evolution of IS, there are some arguments about it, especially the entity boundary (Lombardi and Laybourn, 2012) or "traditionally separate" (van Berkel, 2009), which refers to different organisms: generally referred to firms or companies (Chertow, 2000; Ehrenfeld and Gertler, 1997; Frosch and Gallopoulos, 1989; Jelinski et al., 1992), also are facilities (Graedel, 1996; Jacobsen, 2006) and processes (Côté and Reid, 1997; Frosch, 1992). In addition, the entities should not only contain "industries", but also "other organizations", such as researches and government organizations. For example, the United Kingdom government introduced the National Industrial Symbiosis Programme (NISP) that is the first national-level IS programme; Chinese Research Academy of Environmental Sciences and the Eco-Industrial Research Center of Tsinghua University provided technical support for the planning of National Eco-Industrial Park.

Recently, Lombardi and Laybourn (2012) proposed an updated definition —"IS engages diverse organizations in a network to foster eco-innovation and long-term culture change. Creating and

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Abbreviation list

IS	industrial symbiosis
JISCO	Jiuquan Iron & Steel Co., Ltd.
SFA	substance flow analysis
EIP	eco-industrial park
HTPC	Hongsheng thermal power company
JRRDC	Jirui Renewable resources development company
HBMC	Hongda Building materials company
DYC	Da You company
LDG	Linz—Donawitz Process Gas
BF	blast furnace
GHG	greenhouse gas
BOF	basic oxygen furnace
FGD	Flue Gas Desulfurization
BFG	blast furnace gas
COG	coke oven gas
TRT	top gas pressure recovery
CDQ	Coke Dry Quenching
PCWTS	phenol cyanogen wastewater treatment station
CCWTS	cold rolling wastewater treatment station
IOP	iron oxide powder
GGBS	ground granulated blast furnace slag

sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs and value-added destinations for non-product outputs, as well as improved business and technical processes". They pointed out that although geographic proximity is important to IS, it is not the only condition on resource exchange. Geographic proximity is a factor impacting transport that directly related to distance, and the "short mental distance" of the participants to communicate with each other. The economy and resource's transport management regulations determined the relative importance of proximity (Côté and Cohen-Rosenthal, 1998; Lyons, 2007). However, recent work has shown that transport cost is less than the economic benefit of synergies (Jensen et al., 2011). The redefinition emphasizes that eco-innovation can be promoted by creating and sharing knowledge through the network, which focuses more on Collaborative research and development (R&D) that is important to industrial network (Coombs and Georghiou, 2002).

The lack of a unified definition of IS leads to some confusion about IS. Although the Lombardi and Laybourn's definition includes a wider range of organizations and network, there is still a challenge to IS researches: Spatial boundary—whether the exchange of waste/byproduct between facilities or processes occurring in one organization should be considered as IS? Should the facilities or processes be the basic units of IS (or nodes in the IS network)? Is counting facilities or processes as nodes in the IS network helpful to study industrial symbiosis?

There are many motivations for pursuing industrial symbiosis, but the most common reasons are profit and competitiveness in the beginning (Chertow, 2007). Pursuing IS will result in economic and environmental benefits (Berkel et al., 2009; Chertow and Lombardi, 2005; Eckelman and Chertow, 2009; Jacobsen, 2006; Jung et al., 2013). Industrial symbiosis can reduce raw material consumption and waste discharge, and improve resource productivity of system (Wen and Meng, 2015). Industrial sector is the major discharger of greenhouse gas (GHG) (Moomaw, 1996), and its emission have become the focus of reducing GHG emissions (Lee et al., 2008). Industrial symbiosis is an effective way to reduce carbon emission (Hashimoto et al., 2010; Tian et al., 2012; Yu et al., 2015a). However, the researches on environmental performance tended to calculate air pollution, such as sulfur dioxide (SO_2) and nitrogen oxides (NOx), or GHG, ignoring the carbon metabolism which is closely related with emission of GHG. The carbon metabolism depicts how carbon is supplied, consumed, and discharged in ecosystem (Lu et al., 2015; Smart, 1992). In addition, previous studies failed to consider the dynamic process of IS, most of them tended to choose a reference year. The static studies could not illustrate changes in environmental benefits during the evolution of IS.

Policies and regulations are also important motivations for IS development (Jiao and Boons, 2014). Industrial symbiosis have been more successful as a result of related policies and regulations (Deutz and Gibbs, 2008), such as cleaner production and Circular Economy in China (Yu et al., 2015b). Although the way that policies promote IS is not "one-size-fit-all" and the impact of policies in different regions is different (van Beers et al., 2009), the question that how policies facilitate the evolution of industrial symbiosis is still not clear.

This study aims to present insight into the evolution of industrial symbiosis from 1958 to 2012 through typical case study of an iron and steel industrial network in China. Along with the analysis of the evolution of IS, it also discussed the drivers and the mechanism of policies on the evolution of IS. In addition, the environmental benefits of IS including carbon metabolism, pollutants emission reductions and emissions intensity also were quantitatively analyzed.

2. Materials, methods and data

2.1. Development of Jiuquan Iron & Steel Co., Ltd.

Iron and steel industry as one of the pillar industries in China has unique advantage in the industrial network formation. Jiayuguan city is located in the western of China, which is a modern city that developed on the basis of Jiuquan Iron & Steel Co., Ltd. (JISCO) in 1965. JISCO, one of the national key construction projects in the First Five-Year Plan of China, was founded in 1958, which was chosen for a case study. As a pillar of the Jiayuguan city's economy, JISCO has made an active contribution to Jiayuguan city's rapid rate of growth. Its total production of crude steel overtook 10 million tons, ranking the 30th in the world in 2013. It has typical long process of iron and steel-making from mining, mineral processing and sintering, coking to the iron, steel, hot-rolled, cold-rolled. At the same time, relevant industries like ferroalloy, lime, building materials, electric power have been promoted in local area through purchasing raw materials and selling products and byproducts.

In the context of Chinese policies, JISCO's development deeply influenced by government policies, which went through four stages. The stages and experience of JISCO are introduced in Table 1. The first stage was from 1958 to 1972. JISCO was in a situation of extensive development, ignoring environmental problem. The second stage was from 1973 to 1993. The environmental management strategy in the stage was mainly end-of-pipe control. Toward the third stage, from 1994 to 2006, environmental management strategy shifted from end-of-pipe control to cleaner production. In the fourth stage, from 2007 to 2012, JISCO was in a state of further implementation of cleaner production and circular economy. Its main products and average production capacities in each stage are shown in Fig. 1. Due to obsolete techniques and insufficient funds, JISCO manufactured pig iron for the first time in 1970. The total