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Analysis of embodied exergy flow between Chinese industries based on network theory

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ABSTRACT

The transfer of embodied exergy from one industry to another can be modeled using a network to help understand industrial characteristics and resource features of a specific area. In this paper, we build a weighted directed network of embodied exergy flows between Chinese industries based on the 135-sector input–output table from 2007. The density, connectedness and degree distribution are used to describe the overall performance of the network. The results show that the network has a low density and a high connectedness, indicating that the network has little influence on specific industries while individual industries have a strong impact on each other. The degree, weighted degree and betweenness centrality are used to determine the main industries in the network. Key industries are characterized by large degrees that play a key role in the network, of which the mining and washing of coal, the production and supply of electric and heat power, construction, and the rolling of steel have stronger influences on the network. Moreover, the production and supply of electric power and heat power, the manufacture of automobiles and farming are the intermediaries of the network. Finally, we use a block-modeling method to decompose the collection of 135 Chinese industries into seven communities. The community of coal-related industries is the core of the network, which transfers embodied exergy to every other community, whereas the community of steel-related industries is also important, forming the base of the rest of the network.

1. Introduction

Exergy is a good indicator of scarce natural resources. Its relationship with ecology and economics provides new possibilities for understanding nature and society. This paper aims to show how exergy is transferred within an economic system, which is useful for showing the relationship between industries in an economic system from the view of natural resources and in planning and managing activities in a society.

Embodied exergy is used to show the exergy flows behind money flows. The concept of an embodied resource is first proposed as embodied energy, which is the amount of energy used in the production, manufacture, use and disposal of a good or service (Bullard and Herendeen, 1975; Costanza, 1980; Huettner and Costanza, 1982; Jiang et al., 2011; Xu et al., 2009; Monahan and Powell, 2011; Liu et al., 2010). From there, embodied energy is extended to other resources such as embodied water (Chiu et al., 2009; Treloar et al., 2004; Chen et al., 2012), embodied materials, embodied exergy, and so on (Bruckner et al., 2012; Ju and Chen, 2011; Duchin and Levine, 2013; Chen and Chen, 2010; Chen et al., 2009, 2010; Zhou et al., 2010). Using embodied exergy, product and service flows between industries can be measured by corresponding embodied exergy flows.

Natural resource flows between economic sectors have attracted wide-spread attention in recent years. Some researchers focus on the calculation of inter-sector natural resource flows. By applying ecological network analysis, the number of resource flows among sectors and the structure of systems are revealed (Fath et al., 2007; Huang and Ulanowicz, 2014; Dai et al., 2012; Chen and Chen, 2012, 2015; Chen et al., 2014; Zhang et al., 2009–2011). However, in addition to the flow of resources, the relationship structure of the network and the role of each sector within the system are also important for policy making. Therefore, this paper applies complex network theory to analyze the embodied exergy flows between industries. Complex network theory is a useful tool that focuses on the topological structure of networks. It is helpful for showing

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the relationship between each part of a network, providing useful information about the network composition and the power, role and the impact of its underlying components. Complex network theory is not a new topic in the physical and social sciences. However, it has gained popularity in recent years because of the number of new applications that have been found in other fields. Until now, complex network theory has been used to study transportation (Kaluza et al., 2010; Bagler, 2008), relationships between shareholders in listed companies (An et al., 2013, 2014a; Li et al., 2014a,b,c), visualization of geological data (Liu et al., 2011, 2012), international trade (Fagiolo et al., 2008; Baskaran et al., 2011; Serrano and Boguñá, 2003; Hao et al., 2013; Yang et al., 2012; Gao et al., 2014; An et al., 2014b; Zhong et al., 2014), oil price fluctuation (Gao et al., 2011, 2012; An et al., 2014c,d) and inflation (Gao et al., 2014). The embodied exergy flows between industries compose a network that illustrates the paths of exergy use such that it can be analyzed by complex network indicators.

The rest of this paper is organized as follows: Section 2 discusses the data and methodology, where the calculation of embodied exergy flows between industries and the construction of the EEFN are presented. In Section 3, three overall properties of the network (network density, network connectedness and average degree) are selected to show the network complexity, closeness between individuals in the network and how many relationships the individuals have in the network. In Section 4, three centrality properties (degree, weighted degree and betweenness centrality) are used to determine the impact and power of each industry. In Section 5, block modeling is used to decompose the EEFN into several subcategories, showing the internal composition of the network and the role and function of each part. Finally, the findings are discussed in Section 6.

2. Methodology

2.1. Calculation of embodied exergy

Exergy is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes into equilibrium with a reference environment. The exergy contained in a system can be calculated using the following equation:

$$E_x = T_0 \left(S_{\text{eq}}^{\text{tot}} - S^{\text{tot}} \right) \tag{1}$$

where T_0 is the temperature of the environment, $S_{\text{eq}}^{\text{tot}}$ is the entropy of the total system, i.e., the system plus the environment when the system is in equilibrium with the environment, and S^{tot} is the entropy of the total system at a specific appropriate deviation from equilibrium. Exergy is widely used for overall accounting of various resources (Wall, in press; Chen and Chen, 2006, 2007a,b,ca,cb,d,e, 2009; Chen and Qi, 2007; Dai and Chen, 2011; Chen, 2005; Chen, 2006; Ji and Chen, 2006).

The resources considered in this paper as well as their exergy content (Table 1) can be grouped into four categories: fossil fuels, biological resources, minerals, and environmental resources.

Table 1
Resources considered in this article.

Category	Items
Energy	Coal, petroleum, natural gas, hydropower, nuclear power
Agricultural product	Rice, wheat, corn, sugar cane, rapeseed, peanut, fruit, cotton, tubers, beans, sugar beets, tobacco, sesame, tea, hemp
Stock products	Meat, eggs, milk
Fishery products	Aquatic products
Forestry products	Wood
Minerals	Iron ore, copper concentrated, pyrite, bauxite, zinc ore, lead ore, salt

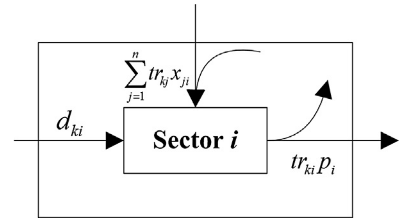

Fig. 1. Input–output direct and indirect resource flows of a typical industrial sector.

Embodied exergy is calculated according to Chen et al. (2010); the flows coming into and out of a specific industry are shown in Fig. 1. In this figure, d_{ki} is the direct resource consumption of sector i, x_{ji} is the monetary flow from sector j to sector i, which can be found in economic input–output tables as intermediate inputs, tr_{ki} is the embodied resource intensities of commodities from sector i, (in other words, the embodiment of resource k per unit of product of sector i), and $\text{tr}_{\text{kj}} \times x_{\text{ji}}$ is the embodiment of resource k from sector j to sector i. P_i is the total output of sector i, and $\text{tr}_{\text{ki}} \times P_i$ is the total output of resource k in sector i. According to physical balance, the total input of resource k into sector i is equal to the total output of resource i. Thus, we have the following equation:

$$d_{\text{ki}} + \sum_{j=1}^{n} \text{tr}_{\text{kj}} x_{\text{ji}} = \text{tr}_{\text{ki}} P_i. \tag{2}$$

Direct input of each type of resource is shown in Table 2. Data in Table 2 are collected from the China Energy Statistical Yearbook (CESY, 2008), China Statistical Yearbook (CSY, 2008), and China Industry Economy Statistical Yearbook (CIESY, 2008). Using direct resource input and the input–output table from China in 2007 (IOTC, 2008), tr_{ki} can be calculated using Eq. (2). The embodied resource flow from sector i to sector j can then be calculated as $\text{tr}_{\text{ik}} \times x_{\text{ij}}$. Detailed algorithms concerning embodied exergy can be found in (Chen and Chen, 2010).

2.2. Network construction

A network is a collection of vertices and edges. We represent each industry as a vertex, the embodied resource flow between two industries as the edge between them, and the exergy content of the resource flow between these two industries is set to be the weight of this edge. There are 135 industries in the input–output table for China in 2007 (IOTC, 2008). First, we built a network by adding all of the industries and their embodied exergy flows into the network. This original network had 135 vertices and 13,863 edges. However, this network had many edges with minimal weights, which can safely be ignored as they do not constitute the main embodied exergy flows. To focus on the key flows, some edges were removed using the following process: we arranged every edge by descending weight and calculated the fraction of each edge relative to the sum of the weights of all edges. The cumulative fraction of embodied exergy flow is shown in Fig. 2, in which we can find a turning point at approximately 80% in the vertical axis. This turning point shows that only a few connections between industries account for most of the embodied exergy flows. Therefore, we chose 80% as our edge weight threshold. Only 540 edges account for 80% of the total embodied exergy flows. We subsequently removed the remaining 13,323 edges from our network. Finally we obtain an embodied exergy flow network with 110 vertices and 540 edges. The final network is shown in Fig. 3.

We used the software *Gephi* to draw Fig. 3. The size of each node indicates the embodied exergy inflow and outflow of each industry. Larger nodes have larger embodied exergy flows. The lines between nodes indicate the directed embodied exergy flows. Wider lines

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