Resources, Conservation & Recycling 136 (2018) 345–354

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Structure of international iron flow: Based on substance flow analysis and complex network

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ARTICLE INFO

Keywords:
Iron
International trade
Substance flow analysis
Complex network

ABSTRACT

Iron is a basic substance in the manufacturing industry of a country. The industry chain of iron and steel is an integrated and complicated system with substance exchange through import and export. Features and structure of this system can reveal the global pattern of the iron and steel industry chain. This study aims to quantitatively analyze the evolution of features and structure of international iron flow by combining the theory of Substance Flow Analysis and Complex Network. The network model was constructed based on the iron substance flow embodied in the trade among all the countries in the world. Trade density, concentration of trade activities, concentration of trade volumes, and hierarchy structure of the network were studied. Results show that the trade density of iron-contained commodities can act as the "barometer" of world economy; the concentration of trade activities shows a reverse relationship with the world economic prosperity; the trade volumes are highly concentrated in a small number of countries; and the hierarchy structure of the network of international iron flow is becoming more obvious. Some policy implications according to the results were provided.

1. Introduction

Iron is a basic substance in all walks of life and is an important material in manufacturing industry. In the background of globalization, manufacturing industry of a country is not a closed system; every phase in the industry has substance exchange with foreign countries through import and export of raw materials and products, thus, forming an integrated and complicated system. A better understanding of this system can help us look further into the global pattern of the industry chain of iron and steel. This study aims to analyze the features and structure of international iron flow by modelling the iron substance flow embodied in the trade of commodities containing iron material among all the countries in the world. It provides a quantitative study of the global pattern of the iron flow combining Substance Flow Analysis and Complex Network Theory.

Substance Flow Analysis provides theoretical and methodological basis for the life cycle research of the industry chain. For example, Xu et al. modeled and analyzed the overall substance flow in China's economic system (Xu and Zhang, 2007); Chen et al. conducted a dynamic analysis of the flow of aluminum in the United States and China (Chen and Graedel, 2012; Chen and Shi, 2012); Gao et al. studied the flow of cement in China (Gao et al., 2016). On iron substance flow analysis, Wang et al. (2014) and Yan and Wang (2014) studied the substance flow at different stages of the life cycle of China's iron elements, but did not consider the import and export of iron resources; and Guo et al. considered the iron resources inventory, import and export, and loss, to analyze China's iron material life cycle characteristics (Guo and Zhang, 2016). These results provided good references for the study of the whole life cycle flow and stock framework for the construction of the iron substance flow. However, their main concerns are the characteristics of the flow of iron within a country, not at the global level.

To extend the system boundary of the study, Tendall et al. studied the uranium flow between European countries (Tendall and Binder, 2011); Dong et al. looked into material flows and resource productivity in China, South Korea and Japan from 1970 to 2008 (Dong et al., 2017); Munoz et al. studied the material flow embodied in the bilateral trade between Latin American countries and the USA (Munoz et al., 2011). At the global level, Tong et al. constructed global copper resource (Tong

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https://doi.org/10.1016/j.resconrec.2018.05.006
Received 20 October 2017; Received in revised form 2 March 2018; Accepted 3 May 2018
0921-3449/

and Lifset, 2007); Liu et al. studied global aluminum resource (Liu and Mueller, 2013); Dittrich et al. studied global iron and coal resources (Dittrich et al., 2012); and Nakajima et al. studied the embodied iron substance in the bilateral trade between countries (Nakajima et al., 2014). These studies can help us understand the substance flow at the global level. However, the previous results did not reveal the global pattern systematically and dynamically.

Complex network analysis can reveal many new features and topology dynamics of the international trade entirely and partially (Serrano and Boguna, 2003; Garlaschelli and Loffredo, 2005; Fagiolo et al., 2010). For example, Qi et al. studied the structural characteristics and evolution of the international trade network of ferrous metals (Qi et al., 2014). Hao et al. studied the pattern evolution and influencing factors of fossil energy international trade network (Hao et al., 2016). Zhong et al. studies analyzed the structural characteristics and pattern evolution of the international network of fossil fuels and puts forward policy suggestions for the network roles and status of major countries (Zhong et al., 2016; Zhong et al., 2017). On the complex network of iron substance, Wang et al. analyzed the structure and status of the international trade network of iron ore, and obtained many new characteristics and pattern of iron ore international trade network based on complex network analysis indicators (Wang, 2011). However, this study only studied the global trade flows of one commodity iron ore, and ignored other commodities in the industry chain such as pig iron, crude steel, steel products, and other products that containing iron substance.

Combining complex network model and substance flow analysis can look further into the global pattern of substance flow. By this approach, Tokito et al. studied the international trade network complexity of platinum (Tokito et al., 2016); Tong et al. constructed global copper substance flow network (Tong and Lifset, 2007); and Liu et al. constructed global aluminum substance flow network (Liu and Mueller, 2013). These are good attempt on constructing global substance flow network models. However, these studies mainly focused on the analysis of substance flow and stock, and the application of complex network indexes was limited.

This study goes further in the life circle analysis on iron substance flow embodied in the international trade by constructing complex network model and applying network analysis. Section 2 is the introduction of the data and modelling. In Section 3, the complex network indexes and analysis such as trade density, concentration of trade activities, concentration of trade volumes, and hierarchy structure of the network are applied to reveal the global pattern of iron flow. Section 4 is the discussion and conclusion.

2. Data and modelling

This study constructed framework of iron substance flow analysis according to the whole life cycle of iron-contained commodities (please see Fig. 1). The whole life cycle of a steel product is the whole industry chain of raw material extraction, manufacturing, consumption, disposal, and recycling. According to the whole industry chain, this study divided the life cycle into six phases: iron ore, pig iron, crude steel, rolled steel, steel product, and scrap. The iron ore is smelted into pig iron, the pig iron is smelted into crude steel, the crude steel is rolled, and then steel product is manufactured. In this study, the steel product not only contains the steel as material, but also contains all the commodities made from iron or steel, such as machine, car, ship, etc. The scrap phase includes scrap from the processes of crude steel, rolled steel and steel product. In the background of globalization, the industry chain of iron and steel is not a closed system. There are export and import of commodities containing iron substance in every phase of the industry chain.

2.1. Data

The data of international trade of all the commodities of the six phases is from the website of *UN Comtrade*[1] which contains all the export and import flows among countries and regions (hereinafter referred to as countries) all over the world. The trade volumes are measured by kilogram. The data selected in this study is the trade volume of the commodities that contain iron material in it (hereinafter referred to as iron-contained commodities). There are six categories of products: iron ore, pig iron, crude steel, rolled steel, steel product, and scrap. The iron contents of the six categories and the HS code of the commodities are shown in Table 1. The annual data of all the eligible commodities from 2000 to 2015 is selected in this study.

2.2. Network model

The complex network model G = (V, E) contains the nodes V and the edges E, where V = $\{v_i: i = 1,2,\ldots,n\}$, n is the number of nodes, E = $\{e_i: i = 1,2,\ldots,m\}$, and m is the number of edges. The matrix of the complex network model is

$$G = (V, E) = \begin{bmatrix} 0 & w_{1,2} & \cdots & w_{1,n} \\ w_{2,1} & 0 & \cdots & w_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ w_{n,1} & w_{n,2} & \cdots & 0 \end{bmatrix} \tag{1}$$

In the network model of international iron flow, the nodes are the countries, the edges are the trade relationships, the directions of the edges are the directions of the iron flows, and the weights of the edges are the total iron content of all the iron-contained commodities in the trade between the countries.

An example of the international iron flow network in 2015 is shown in Fig. 2. We filtered the network with the iron content of the edges in order to make it more readable, thus there shows the top 32 countries in the total weights of the edges. The larger size of the node indicates the higher iron content in the sum of the import and export of the country. The wider edge indicates the higher iron content of this trade link.

3. Results and analysis

3.1. Trade density

The scale of the network is shown by the total number of countries and the total number of trade relationships (please see Fig. 3). The total number of countries was remaining at around 245 during the whole period. The total number of trade relationships was increasing from around 16,000 in 2000 to more than 21,000 in 2008, it was fluctuating a little after 2008, and it was decreasing in recent years.

Based on the total number of countries and the total number of trade relationships, the network density can be calculated to reflect the prosperity of the international trade. Network density measures the thickness of the trade relationships among the countries in the network. The higher network density indicates that the international market of iron is more prosperous. If the number of total relationship is m, the number of countries is n, then the network density is (Geng et al., 2014):

$$\Delta = \frac{2m}{n(n-1)} \tag{2}$$

The evolution of network density is shown in Fig. 4. The network density increased rapidly from 2000 to 2008, fluctuated between the year 2008 and 2010, and then slightly decreased after 2010.

3.2. Concentration of trade activities

The range of a country's direct impact in the network can be

[1] https://comtrade.un.org/.