Energy Economics 68 (2017) 44–52

Contents lists available at ScienceDirect

Energy Economics

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

Finding environmentally critical transmission sectors, transactions, and paths in global supply chain networks

Tesshu Hanaka [a,*], Shigemi Kagawa [b], Hirotaka Ono [c], Keiichiro Kanemoto [d]

[a] *Graduate School of Economics, Kyushu University, Fukuoka, Japan*
[b] *Faculty of Economics, Kyushu University, Fukuoka, Japan*
[c] *Graduate School of Informatics, Nagoya University, Nagoya, Japan*
[d] *Faculty of Economics and Law, Shinshu University, Matsumoto, Japan*

ARTICLE INFO

Article history:
Received 21 March 2017
Received in revised form 19 August 2017
Accepted 18 September 2017
Available online 27 September 2017

JEL classifications:
C02
Q43
Q56
Q57
R15
P18

Keywords:
Network analysis
Edge betweenness centrality
Vertex betweenness centrality
World input-output database
Global supply chain networks
CO_2

ABSTRACT

In this article, we develop an economic network analysis to find environmentally critical transmission sectors, transactions and paths in global supply chain networks. The edge betweenness centrality in the global supply chain networks is newly formulated and a relationship between edge betweenness centrality and vertex betweenness centrality is further provided. The empirical analysis based on the world input-output database covering 35 industrial sectors and 41 countries and regions in 2008 shows that specifically, China's Electrical and Optical Equipment sector, which has a higher edge and vertex betweenness centrality, is the most critical sector in global supply chain networks in terms of spreading CO_2 emissions along its supply chain paths. We suggest greener supply chain engagement centered around the China's Electrical and Optical Equipment sector and other key sectors identified in this study.

1. Introduction

Environmentally extended input-output analysis has been widely used to estimate production- and consumption-based emissions in many countries (Peters, 2008; Hertwich and Peters, 2009; IPCC, 2014), and in Japan a national emission inventory has been provided to the public every five years (NIES, 2016). A major advantage of using environmental energy input-output analysis is that product supply-chain networks can be easily modelled and environmentally and ecologically important sectors and paths can be identified from the network (Lenzen, 2003; Lenzen et al., 2012; Wood and Lenzen, 2009; Oshita, 2012). Clustering analysis has also been applied to environmental energy input-output analysis in order to find environmentally important industry groups (i.e., industry clusters) that induce higher CO_2 emissions along their supply-chains (Kagawa et al., 2013a, 2013b, 2015).

It is important to note that the environmentally critical sectors, transactions, paths, and clusters identified by input-output analysis play important roles in reducing consumption-based emissions through the entire economy. A supply-chain path is composed of transactions between two sectors. An environmentally critical sector as identified by key sector analysis (Rasmussen, 1956; Hirschman, 1958; Hazari, 1970; Lenzen, 2003) is considered to be a sector that contributes to emitting larger environmental emissions (e.g., CO_2 emissions) in the economy through not only purchasing emission- and energy-intensive products from other upstream sectors but producing emission- and energy-intensive products in its own sector. Therefore, an effective emission reduction policy (i.e., technology policy) is to improve the production technology of the critical sector toward a cleaner one that has less energy consumption and environmental emissions along the product supply chain.

Information on environmentally critical paths (Lenzen, 2003) and clusters (Kagawa et al., 2013a, 2013b, 2015; Rifki et al., 2017) can support a technology policy in the sense that policymakers can find high-priority supply-chain paths (i.e., upstream products) and clusters

---

* Corresponding author at: Graduate School of Economics, Kyushu University, 6-19-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan.
E-mail address: 3EC15004S@s.kyushu-u.ac.jp (T. Hanaka).

https://doi.org/10.1016/j.eneco.2017.09.012
0140-9883/

(i.e., upstream product systems). However, it is not an easy task to find high-priority paths and clusters from the supply-chain complexity due to the problem of computation (e.g., Kagawa et al., 2015).

Liang et al. (2016) proposed a useful indicator, vertex betweenness centrality, of a specific sector by combining input-output analysis with social network analysis. More specifically, Liang et al. (2016) formulated the vertex betweenness centrality index by applying the notion of network centrality (Freeman, 1977, 1978; Freeman et al., 1979) to structural path analysis (Lenzen, 2003; Defourny and Thorbecke, 1984). Liang et al. (2016) defined a specific sector with higher vertex betweenness centrality in a supply-chain network as a critical transmission sector in the sense that many sectors supply their products to final consumers by passing through the specific sector, and consequently the transmission sector contributes to emitting a large amount of environmental emissions in the economy. Although key sector analysis (Rasmussen, 1956; Hirschman, 1958; Hazari, 1970; Lenzen, 2003) *implicitly* considers the transmission power of a specific sector, previous analyses failed to define this as vertex betweenness centrality consistent with network theory (Freeman, 1977, 1978; Freeman et al., 1979). A technology policy for reducing environmental emissions should target high-priority sectors with higher vertex betweenness centrality.

In this study, we develop another centrality index, edge betweenness centrality, consistent with environmental energy input-output analysis following Liang et al. (2016) and prove a mathematical relationship between “edge” betweenness centrality and “vertex” betweenness centrality. Edge betweenness centrality indicates how much ‘embodied’ environmental emissions of products flow through the transaction and to what extent sectors are connecting through a specific edge (i.e., a transaction) in terms of supply-chain complexity. It is important to note that the embodied environmental emissions (e.g., embodied CO_2 emissions) in supply-chain networks are caused by embodied energy consumption in the entire economy (Hertwich and Peters, 2009; Peters et al., 2011).

The edge betweenness centrality for a particular transaction developed in this study can be regarded as the sum of environmental emissions associated with ‘infinite’ supply-chain paths that include the specific transaction identified using structural path analysis (SPA) (e.g., Lenzen, 2003; Oshita, 2012; Owen et al., 2016; Nagashima et al., 2017). However, a technical problem of SPA is that it is impossible to identify ‘infinite’ paths that include the particular transaction; therefore, the edge betweenness centrality developed in this study can be a useful indicator to express the importance (or criticality) of a particular transaction in the entire supply-chain network.

Liang et al. (2015) also proposed strongest path betweenness. This index represents the importance of a sector in the supply-chain network as a center transmitting or facilitating the creation of environmental impacts. Roughly speaking, it is defined as the sum of the strengths of all strongest paths in the supply-chain network passing through a sector. The strongest path in Liang et al. (2015) is defined as the environmentally important path that causes the largest CO_2 emissions in sector *i* owing to one unit of value added in sector *j*. It is important to note that the strongest path developed in Liang et al. (2015) is defined for a path, whereas the edge betweenness centrality developed in this study is defined for a transaction. A strongest path from sector *i* to sector *j* represents the most inefficient path among all possible paths from *i* to *j*. The point of difference from vertex and edge betweenness centrality is that strongest path betweenness does not consider ‘infinite’ supply-chain paths.

In this study, we compute the edge and vertex betweenness centrality indices using the environmentally extended multi-regional input-output table covering 35 industrial sectors and 41 countries and regions in 2008 (Dietzenbacher et al., 2013; Timmer et al., 2015) and identify high-priority sectors with higher vertex betweenness centrality and high-priority transactions with higher edge betweenness centrality in global supply-chain networks. Finally, we argue how those high-priority sectors and transactions can contribute to reducing CO_2 emissions as climate mitigation.

It should be noted that although we mainly focus on CO_2 emissions as a case study, the method developed in this paper can be applied to energy consumption and other environmental pollutants such as NO_x and SO_x. In particular, although energy consumption and CO_2 emissions are both typical analysis subjects for these methods, our reason for mainly focusing on CO_2 emissions is interest in the effects on recent global warming. For this purpose, we conducted similar betweenness centrality analyses focused on energy consumption and computed rank correlation coefficients for both vertex and edge betweenness centralities for CO_2 emissions and energy consumption. Finally, we discuss a more direct relationship between CO_2 emissions and energy consumption with a focus on vertex and edge betweenness centralities in Section 5.

The remainder of this paper is organized as follows: Section 2 revisits vertex betweenness centrality as proposed in Liang et al. (2016); Section 3 develops edge betweenness centrality consistent with input-output analysis; Section 4 presents the mathematical relationship between vertex betweenness centrality and edge betweenness centrality; Section 5 presents and discusses the results; and finally Section 6 concludes the paper.

2. Vertex betweenness centrality proposed in Liang et al. (2016)

The vertex betweenness centrality of a specific sector proposed in Liang et al. (2016) was defined as the sum of environmental emissions associated with the supply-chain paths passing through the specific sector. Fig. 1 illustrates the vertex betweenness centrality of sector *v* in a supply-chain network with seven vertices and six edges. In the figure, e_a, e_b, and e_c are respectively the environmental emissions in upstream sectors *a*, *b*, and *c* triggered by the transactions among downstream sectors, *d*, *e*, and *f*. In this case, the vertex betweenness centrality of sector *v* can be calculated as $b_v = e_a + e_b + e_c$.

Following Liang et al. (2016), the vertex betweenness centrality b_v of a specific sector *v* can be formulated as:

$$b_v = \sum_{s=1}^{n}\sum_{t=1}^{n}\sum_{r=1}^{\infty} q_r \times w(s, k_1, k_2, \ldots, k_r, t) \tag{1}$$

where $w(s, k_1, k_2, \ldots, k_r, t)$ is the environmental emissions associated with all supply-chain paths from sector *s* to sector *t* passing through *r* sectors, sector $s \rightarrow$ sector $k_1 \rightarrow$ sector $k_2 \rightarrow \cdots \rightarrow$ sector $k_r \rightarrow$ sector *t* via sector *v*, and q_r is the number of times that sector *v* appears in the supply-chain paths. $w(s, k_1, k_2, \ldots, k_r, t)$ also means the environmental emissions associated with all supply-chain paths from sector *s* to sector *t* with a path length of $r+1$. Following the idea of structural path analysis (e.g., Lenzen, 2003; Defourny and Thorbecke, 1984), $w(s, k_1, k_2, \ldots, k_r, t)$ can be formulated as $f_s a_{sk_1} a_{k_1k_2} \cdots a_{k_r t} y_t$, where y_t is the final demand of sector *t*, $a_{k_1k_2}$ is the intermediate input from sector k_1 *directly* required for producing one unit of output in sector k_2, and f_s is the direct environmental emissions per unit of output of sector *s*. Accordingly, $a_{sk_1} a_{k_1k_2} \cdots a_{k_r t}$ represents the intermediate input from sector *s indirectly* required for producing one unit of output in sector *t*. It should be noted that if $r = 1$ and $k_1 = v$, we have $b_v = \sum_{s=1}^{n}\sum_{t=1}^{n} f_s a_{sv} a_{vt} y_t$ from Eq. (1).

We further define the following supply-chain path:

$$b_v(l_1, l_2) = \sum_{1 \le k_1, \cdots, k_{l_1} \le n} \; \sum_{1 \le j_1, \cdots, j_{l_2} \le n} f_{k_1} a_{k_1k_2} \cdots a_{k_{l_1} v} a_{vj_1} \cdots a_{j_{l_2-1} j_{l_2}} y_{j_{l_2}} \tag{2}$$

where $b_v(l_1, l_2)$ represents the environmental emissions associated with supply-chain paths that pass through sector *v* that has upstream industrial supply chains with path lengths of l_1 and downstream industrial