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A multi-regional structural path analysis of the energy supply chain in China's construction industry

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HIGHLIGHTS

- We designed an optimized algorithm for multi-regional SPA.
- We extracted energy-intensive paths throughout the upstream supply chain.
- We explored self-sufficiency characteristic for provincial construction industries.
- We identified energy-intensive sectors hidden in higher-order supply chain.
- We developed an effective strategy for narrowing down the system boundary of SPA.

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ABSTRACT

The construction industry in China exerts significant environmental impacts and uses considerable resources because of rapid urbanization. This study conducted a structural path analysis (SPA) based on the multi-regional input–output table to quantify environmental impact transmission in the entire supply chain. Results indicated that the direct resource input (the first stage) along with on-site construction (the zeroth stage) consumed the highest amount of energy in the supply chain and accounted for approximately 50% of total energy consumption. Regional analysis showed that energy consumption in the construction industry at the provincial level was self-sufficient. Sectoral analysis demonstrated that the direct inputs from the sectors of “manufacture of non-metallic mineral products” and “smelting and pressing of metals” generated the most important energy flows, whereas the sectors of “production and distribution of electric power and heat power” and “extraction of petroleum and natural gas” significantly but indirectly influenced energy use. Sensitivity analysis exhibited that the system boundary of SPA could be narrowed down into the first two upstream stages that contained nearly 50% of energy flow information or expanded toward the first five upstream stages that represented 80% of total energy consumption.

1. Introduction

Construction-related energy problems have attracted worldwide concern. Nearly 40% of global energy consumption, 32% of global resources, and 25% of global carbon dioxide (CO_2) emissions are generated in the building sector (Metz et al., 2007; WBCSD, 2009; WGBC, 2010). In particular, as one of the largest primary energy users in the world, China is facing serious challenges in energy consumption and considerable environmental burden because of its rapid urbanization. Zhang and his colleagues conducted several studies on structural analyses of China's economy to systematically investigate the impact of industrial structure, energy sources, and economic growth on energy-related carbon emissions (Zhang and Da, 2015; Zhang et al., 2014, 2015a). The findings indicated that the economic growth is the major influence factor for carbon emission changes. Laurenzi et al. (2008) and Minx et al. (2011) reported that China and India were responsible for over 50% of global new construction; In addition, the annual increase rate of building floor area in China remained the fastest in the world. This rate might even increase because of rapid urbanization and the requirement to improve living standard. According to the 12th Five-Year Plan, the urbanization rate in China was estimated to reach a historic high of 51.5% in 2015, which would definitely result in considerable energy demand. Moreover, although the direct environmental impact from on-site construction processes is negligibly small, the embodied impact (e.g., greenhouse gas emissions and energy consumption) generated by the construction industry plays a dominant role in the economy of

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China according to studies by Liu et al. (2012b) and Chen and Zhang (2010). Therefore, China is an ideal country to investigate the effects of the construction industry on the environment because it does not only exert significant environmental impacts and consume considerable resources but also exhibit a distinctive feature because of its extensive construction projects.

Input–output (I–O) analysis has been commonly used in the past years for the structural analysis of environmental impacts resulting from economic interactions (Chang et al., 2011; Hong et al., 2016; Joshi, 1999; Wiedmann, 2009; Wiedmann et al., 2007). However, the conventional single-region input–output (SRIO) analysis calculates results based on a higher level of aggregation that may be invalid for a particular product due to lack of specificity. Moreover, this model also fails to identify hidden linkages in the economic network and regional differences among interregional trade flows (Peters and Hertwich, 2006a, 2006b; Wiedmann, 2009; Wiedmann et al., 2007). Specific regional characteristics, such as variations in climate zone, geographical location, natural resources, and level of economy, directly determine interregional import and export among regions, which results in cross-regional environmental shifting. By using provincial-level panel data to investigate the impact factors of China's provincial energy intensity, Yang et al. (2016) indicated that the provinces are crucial for reducing energy intensity in China. Therefore, it is critically important to conduct regional-level investigation in the environmental analysis. Fig. 1 shows the total economic output and the embodied energy consumption of 30 provincial construction sectors in 2007. It can be observed that sectoral embodied energy consumption is not linearly correlated with economic output. Such inconsistency results from the iterative effect of interregional energy interactions through the upstream supply chain. Therefore, a systematic structural analysis of adverse environment impacts is required for this infinite interrelationship. Structural path analysis (SPA) is a methodology that quantifies environmental transmissions in the upstream process and identifies important paths with the highest environmental improvement potential by tracing back the intricate production chain. Numerous studies have focused on environmental implications using SPA techniques. At the global level, SPA was adopted to provide insight into the structural linkages between the Norwegian economy and international trade (Peters and Hertwich, 2006c); Wood (2008) analyzed greenhouse gas emissions from international trade by combining SPA and decomposition analysis techniques. Minx et al. (2008) adopted an SPA method to identify environmentally important supply paths in the global supply chain of food products. At the national level, Lenzen (2002, 2003) conducted several studies that focused on supply paths with significant environmental impacts in the context of the Australian economy. Lenzen (2007) also presented a detailed discussion of SPA to extract a manageable number of paths from ecosystem networks via 16 case studies. However, only a few studies have been undertaken at the industrial level, particularly those that focused on the construction industry. Treloar et al. (1997, 2001a, 2001b) extracted embodied energy paths from the building sector by adopting a SPA method. They established a hybrid life-cycle assessment model by substituting case-specific data for energy-intensive paths. Chang et al. made a series of input–output analyses to simulate embodied energy use and environmental impact for the construction industry in China (Chang, 2011; Chang et al., 2011, 2013). However, most of these studies have considered environmental impacts from the national perspective but disregarded regional disparities

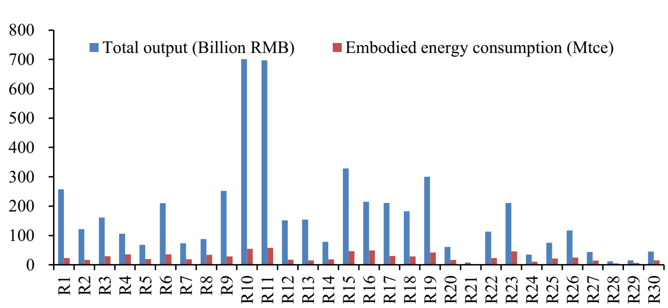

Fig. 1. Total output and embodied energy consumption of 30 provincial construction sectors in 2007. Data source: China Statistical Yearbook on Construction 2013 and Hong et al. (2016) * Mtce is the abbreviation of "million tonnes of coal equivalent.".

To fill in these gaps in the previous literature, the present study uses SPA in the multi-regional input–output (MRIO) model for the construction industry. This model was designed to simulate current energy consumption from the sectoral and regional perspectives. It provides an accurate assessment of environmental impact and reflects regional disparity and technological differences in environmental interactions (Chen and Chen, 2011a, 2011b; Friot and Gaillard, 2007; Lenzen et al., 2004a; Mäenpää and Siikavirta, 2007; McGregor et al., 2008).

The contribution of this paper consists of the following three aspects. First, an optimized algorithm was designed for multi-regional SPA, which can facilitate the structural analysis in a multi-regional context. Second, this paper systematically analyzes the inter-regional energy transfers and the indirect energy input in the upstream supply chain of the construction sector, which do not only provide sufficient understanding of hidden linkages and correlations among provincial construction sectors but also help decision makers formulate equitable energy reduction policies at the national or regional level. Third, this paper reinforces the importance of specific energy-intensive paths and explores the linkage between consumption and production in the interregional supply chain.

The remainder of this paper is organized as follows. Section 2 introduces the basic methodology of SPA and the optimized algorithm for path extraction. Section 3 presents the energy interactions throughout the upstream supply chain from the regional and sectoral perspectives. In Section 4, sensitivity analysis has been conducted on the changes in the cutoff threshold and the number of upstream stages to identify an appropriate system boundary for SPA. Section 5 presents the discussion, while the conclusions drawn from the study and several policy recommendations are provided in Section 6.

2. Methodology

2.1. Overview of SPA

SPA explores the transmission of environmental impact within an entire economic system by decomposing direct and indirect effects from upstream interconnections. Liu et al. (2012b) suggested that additional efforts would be necessary to further disaggregate the supply chain in the construction industry. Therefore, this study adopts SPA to provide an opportunity to inspect the calculation process of I–O analysis. The key paths and sectors in the production chain, wherein economic interactions with other sectors significantly influence the final output, are expected to be identified (Acquaye et al., 2011; Defourny and Thorbecke, 1984; Roberts, 2005). This study aims to determine direct and indirect linkages between exogenous final demand and total output by tracing back transmissions through the upstream production process. SPA has been rarely conducted in a multi-regional context. Although it has been applied in the construction sector in previous research (Crawford, 2008; Treloar, 1997; Treloar et al., 2001b), interregional environmental transactions through the upstream