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

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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.

Keywords: Multi-regional input-output model, Structural path analysis, Construction industry, 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; Zhang et al., 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 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., 2007b). 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, b; Wiedmann, 2009; Wiedmann et al., 2007a). 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. Figure 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 and Wang, 2011; Chang et al., 2011; Chang et al., 2013). However, most of these studies have considered environmental impacts from the national perspective but disregarded regional disparities

Insert Figure 1 here

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; Chen and Chen, 2011b; Friot and Gailllard, 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 supply chain remain insufficiently understood. This shortcoming may be further highlighted in the construction industry, wherein the upstream supply chain is characterized to be the most energy and carbon intensive in previous studies (Chen and Zhang, 2010; Liu et al., 2012b; Minx et al., 2011). Hong et al. (2016) reported that the direct energy input defined as the energy consumed during the on-site construction process only accounted for 5% of energy consumption in each provincial construction industry. The lack of knowledge on such interregional indirect impact from the upstream process can misinterpret the important role of the construction industry in understanding energy challenges in China. By contrast, examining all energy paths through supply chain is challenging given the exponential increase in the number of paths. An optimized algorithm with predetermined thresholds is used in the present study to manage intricate path tree without losing important energy path information (Johnson, 2013; Weiss, 1998).

Finally, multi-regional SPA also suffers from uncertainties. The first type of uncertainty results from inherent computational problems such as proportionality, homogeneity, and outdated I–O data (Treloar et al., 2004). The second type is attributed to the subjective determination of threshold and system boundary. In general, methodological uncertainties are mostly unavoidable and difficult to estimate in the computational process (Weber, 2009). By contrast, uncertainties from subjective manipulation can be quantified and improved through sensitivity analysis.

2.2 Model development

This study used the latest available MRIO table to conduct the following analysis given that multi-regional I–O tables can reflect regional diversity and technological differences (Hong et al., 2016; Lenzen et al., 2004b; Peters et al., 2004; Zhang et al., 2015b).

In general, the basic monetary balance for sector i in region r in the I-O table can be expressed as

$$O_i^r = \sum_{k=1}^{m}\sum_{j=1}^{n} a_{ij}^{rk} O_i^r + \sum_{k=1}^{m} v_i^{rk} \tag{1}$$

where O_i^r represents the total output of sector i in region r. We assumed that there are m regions and each region has n sectors; a_{ij}^{rk} represents the inter-industry coefficient of sector i in region r for sector j in region k; v_i^{rk} represents the total final demand of region k provided by sector i in region r that normally includes the final use (e.g. rural and urban households, government consumption, gross fixed capital formation, and stock increase), exports, and other balance items.

Note that the $m \times n$ equations can be established under the whole economy; therefore, we nominate:

$$O = \begin{bmatrix} \begin{pmatrix} o_1^1 \\ \dots \\ o_n^1 \end{pmatrix} \\ \dots \\ \begin{pmatrix} o_1^m \\ \dots \\ o_n^m \end{pmatrix} \end{bmatrix} \qquad A = \begin{bmatrix} \begin{pmatrix} a_{11}^{11} & \dots & a_{1n}^{11} \\ \dots & \dots & \dots \\ a_{n1}^{11} & \dots & a_{nn}^{11} \end{pmatrix} & \dots & \begin{pmatrix} a_{11}^{1m} & \dots & a_{1n}^{1m} \\ \dots & \dots & \dots \\ a_{n1}^{1m} & \dots & a_{nn}^{1m} \end{pmatrix} \\ \dots & \dots & \dots \\ \begin{pmatrix} a_{11}^{m1} & \dots & a_{1n}^{m1} \\ \dots & \dots & \dots \\ a_{n1}^{m1} & \dots & a_{nn}^{m1} \end{pmatrix} & \dots & \begin{pmatrix} a_{11}^{mm} & \dots & a_{1n}^{mm} \\ \dots & \dots & \dots \\ a_{n1}^{mm} & \dots & a_{nn}^{mm} \end{pmatrix} \end{bmatrix}$$

$$V = \begin{bmatrix} \begin{pmatrix} \sum_{k=1}^{m} v_1^{1k} \\ \dots \\ \sum_{k=1}^{m} v_n^{1k} \end{pmatrix} \\ \dots \\ \begin{pmatrix} \sum_{k=1}^{m} v_1^{mk} \\ \dots \\ \sum_{k=1}^{m} v_n^{mk} \end{pmatrix} \end{bmatrix}$$

Then all the equations can be expressed in matrix form, as follows:

$$O = (I - A)^{-1} V \tag{2}$$

If we consider environmental intensity, then total environmental impact can be expressed as

$$F = E(I-A)^{-1}V \tag{3}$$

where $E = \left[e_i^r\right]_{1\times mn}$ is a vector of the direct environmental impact per monetary unit of $n\times m$ sectors. In this study, sectoral direct energy intensity e_i^r was obtained from provincial statistical yearbooks and the provincial energy balance tables in the Chinese Energy Statistical Yearbook.

The equation can be further expanded based on a power series approximation theory (Waugh, 1950), which is the theoretical foundation for SPA analysis, shown in Eq. 4:

$$F = E(I-A)^{-1}V = \overbrace{EIV}^{Stage0} + \overbrace{EAV}^{Stage1} + \overbrace{EA^2V}^{Stage2} + \overbrace{EA^3V}^{Stage3} + \overbrace{EA^4V}^{Stage4} + \ldots \tag{4}$$

In modern economies, sectoral interactions proceed infinitely in an upstream direction, which can be mapped onto an infinite tree (Rowley et al., 2009). Equation 4 enables investigators to trace back a higher order of environmental contributions through upstream production processes. In particular, total environmental impact is the sum of the direct impact from the product manufacturing process (the zeroth stage) and the indirect inputs from all upstream production processes (e.g., stages 1, 2, and higher-order stages). In this study, the zeroth stage is the energy input that directly results from on-site construction, including energy consumption from construction equipment, onsite transportation, construction electricity supply, and assembly works, whereas higher-order stages refer to indirect energy input resulting from other upstream construction-related activities, such as the energy input to the manufacture of construction equipment. This study established an infinite tree based on the computational algorithm implied in SPA. The path tree explores inter-sectoral and interregional connections in different stages of the upstream production process. Each node in a connected graph denotes a particular sector in a specific region within its economic system. It represents individual environmental contributions induced by the corresponding final demand. According to Eq. 4, the number of nodes is exponential with the growth of stages.

The path tree can be further inspected from the horizontal and vertical perspectives. A horizontal expansion represents direct energy transactions from economic sectors for a certain order of upstream production stage. The sum of the total environmental impact for sector i in each stage can be expressed in Eq. 5. For example, the zeroth stage represents the direct energy input to on-site manufacturing, which can be assessed by the formula $e_i \sum_{k=1}^{m} v_i^k$. Similarly, the first stage represents the direct energy required to provide direct inputs to the zeroth stage, which can be calculated by using the formula $\sum_{j=1}^{m \times n} e_j a_{ji} \sum_{k=1}^{m} v_i^k$. Subsequently, energy consumption in higher order of stages can also be calculated accordingly.

$$
\begin{aligned}
&F_{stage0} = e_i \sum_{k=1}^{m} v_i^k \\
&F_{stage1} = \sum_{j=1}^{m\times n} e_j a_{ji} \sum_{k=1}^{m} v_i^k \\
&F_{stage2} = \sum_{l=1}^{m\times n} \sum_{j=1}^{m\times n} e_l a_{lj} a_{ji} \sum_{k=1}^{m} v_i^k \\
&\ldots\ldots
\end{aligned}
\tag{5}
$$

A vertical expansion represents energy inputs that start from producers in the higher order of upstream stages to the final consumer in the zeroth stage. Energy transfers in the vertical direction can be decomposed into a group of energy paths with varying lengths. For example, the energy consumption embodied in a single path for sector i in region k induced by the final demand can be described as:

$$
\overbrace{e_i v_i^k}^{Stage0} + \overbrace{e_j a_{ji} v_i^k}^{Stage1} + \overbrace{e_k a_{kj} a_{ji} v_i^k}^{Stage2} + \ldots \tag{6}
$$

The value of $e_j a_{ji} v_i^k$ represents the amount of direct energy input from sector j in upstream stage 1 to sector i in stage 0. Given that the combination of energy suppliers from different upstream stages for a single path is unique, each energy path in the path tree is independent, and all paths are mutually exclusive.

Adopting Eq. 5 and 6 enables us to trace back the supply chain intuitively, and consequently, allows us to investigate energy transmissions in the construction industry from a production-based view. For each energy path extracted in this study, the starting point is the final demand of the construction industry (consumption) in a certain region. The end point represents the direct energy input to a given construction process. This energy transfer process establishes a linkage between the purchased final demand and its corresponding production (Peters and Hertwich, 2006a). Therefore, examining the total energy use from both consumption and production perspectives can effectively establish a holistic map of energy interactions in the construction industry. Such map will enable policy makers to formulate a fair and equitable energy reduction policy.

2.3 Algorithm

In general, each node in a path tree represents the direct energy input from a certain sector and the path between nodes shows the direction of energy transfer. The total embodied energy consumption of the construction industry is a result of direct energy input from on-site production processes and indirect energy consumption from upstream processes (Chen and Chen, 2013). Previous studies have indicated that direct impact is negligibly small, whereas the indirect impact of consumption is dominant (Hong et al., 2015; Liu et al., 2012b). Therefore, upstream sectoral interactions in the construction industry may be extended to span the whole economy and exert substantial environmental impact. Considering the crucial role and dominant contribution of indirect energy consumption, an optimized algorithm that focuses on a specific degree of order within a sound number of paths is necessary. Such algorithm should be able to exclude redundant paths with negligible values while retaining the most valuable information for critical energy flows from the production-based perspective. This study integrated SPA into multi-regional analysis to consider region-specific characteristics, which led to an algorithmic difference in methodology with the conventional method.

In general, the iterative recalculation of 900×900 matrices during SPA results in an exponential increase in the number of nodes. Therefore, manually examining an energy path tree is impossible when higher-order upstream processes are considered (e.g. maximum stage = 10). In addition, exploring energy paths from such computational processes makes mathematical operations challenging. Consequently, an optimized algorithm was designed to extract energy paths. The algorithm examines all possible paths by enumerating all possible sectors on each stage and pruning them through trial and error. During enumeration, a vector of thresholds is set to prune branches with negligible embodied energy. This conditional pruning process can dramatically reduce the number of paths and help focus on the most energy-intensive paths. Figure 2 shows the basic iterative processes for the construction industry in a certain region r.

Insert Figure 2 here

2.4 Data collection

This study employed the latest available MRIO table compiled by the Chinese Academy of Science and the National Bureau of Statistics of China to conduct further structural analysis (Liu et al., 2012). Consequently, the computational process and results obtained in this study are based on the 2007 economic level. The MRIO table provides economic interaction data on 30 regions in China (4 municipalities, 4 autonomous regions, and 22 provinces) across 30 sectors (see Appendix I). The compilation of the MRIO table was based on the non-competitive import assumption, where import items from international trade have been omitted to avoid the misrepresentation of energy use embodied in inter-regional trade (Su and Ang, 2013; Zhang et al., 2013).

Sectoral direct energy input data were collected from provincial statistical yearbooks and the regional energy balance tables in the Chinese Energy Statistical Yearbook. However, the direct energy use data in statistical yearbooks were compiled based on a higher level of sector aggregation, whereas the economic and trade data in MRIO table was more specific. This mismatch is exacerbated by the inconsistent format of the provincial statistical yearbooks across different regions. Therefore, this study adopted the data processing method used by Guo et al. (2012) in case of the lack of statistics on sectoral energy consumption.

3. Analysis of results

3.1 Overview

The number of energy paths and their corresponding relative contributions for each stage are presented in Table 1. It can be observed that the energy paths in the first stage consumed the most energy in the supply chain and accounted for approximately 40% of the total energy consumption in the construction industry. In addition, the number of energy paths in the second stage is nearly fourfold the number of paths in the first stage. This result indicates that sectoral interactions have been extended to span the whole economy in the second stage of the construction industry.

Insert Table 1 here

Although emphasis has been placed on the embodied energy use of the construction industry from the supply chain perspective, very few studies have focused on the structural disaggregation and the systematic analysis of upstream processes in the construction industry (Kahrl and Roland-Holst, 2008; Liu et al., 2012b). The present study addressed this issue by holistically reviewing and disaggregating the whole supply chain, particularly the paths in higher-order stages. Table 2 describes the top three energy paths of the provincial construction industry in 30 regions. The top three paths in each region cumulatively account for over 20% of the total energy consumption in the provincial construction industry. For paths in the zeroth stage, direct energy consumption on the construction site is generally insignificant in most regions, except in Beijing (R1) and Hebei (R3). By contrast, all provincial construction sectors are characterized by a considerable amount of indirect activities, which potentially cause significant environmental impact. As shown in Table 2, three energy suppliers, namely, the manufacture of non-metallic mineral products (S13), the smelting and pressing of metals (S14), and transportation, storage, posts, and telecommunications (S25) are the largest contributors to most provincial construction industries. Most energy paths that start from these three sectors make first-order contributions, which are related to direct resource inputs to construction processes, such as cement and steel consumption as well as the transportation of building materials from the off-site factory to the construction site. Some energy paths belong to the second stage due to intra-sector purchase. Other concerns of the supply chain for the construction industry are the higher-order contributions from the chemical industry (S12), the production and distribution of electric power and heat power (S22), and mining industries, including the mining and washing of coal (S2), and the mining and processing of metal ores (S4) and non-metal ores (S5). On the one hand, the products provided by the chemical and mining industries are necessary for manufacturing metallic and non-metallic mineral products. The energy supply from mining industries is significant, particularly in resource-abundant regions such as Henan (R16), Qinghai (R28), and Ningxia (R29) (see Table 2). On the other hand, the power supply sector (S22) does not only provide direct on-site electricity supply but also export energy to higher-order stages in upstream production processes of the construction industry.

Insert Table 2 here

3.2 Regional analysis

Multi-regional SPA can provide insight from the regional perspective, particularly regional interactions among higher-order upstream stages in the construction industry. This study aggregated sectoral information at the regional unit. To clearly represent the geographic relationship between energy suppliers and the main areas of China, the regions in the zeroth stage were further aggregated into eight areas (Table 3). Consequently, Figure 3 can be used to represent interregional energy linkages within the whole supply chain of the construction industry in China. The width of the line represents the amount of energy use transferred from one place to another. Self-sufficiency is the major characteristic for first-order interregional energy transactions, except in Beijing. This fact emphasizes the importance of improving local productivity and energy efficiency to reduce the energy consumption of the provincial construction industry. According to Figure 3, most energy consumed in Beijing is imported from Hebei. As the capital of China and a major world metropolis, Beijing faces numerous challenges and pressures for local resources because of its rapid urbanization and growth. According to previous findings, Beijing is a typical energy receiver in inter-regional energy transactions that has to import resources from energy-rich adjacent regions (Liu et al., 2012a; Zhang et al., 2013).

Moreover, Hebei and Inner Mongolia are major energy suppliers for the construction industry in northern China. Henan has been identified as a hub for energy import in the construction industry in eastern and western regions because it is rich in energy resources and is geographically close to these two areas. The eastern coast (A4) has to import energy from a number of resource-abundant regions (e.g., Hebei, Henan, Inner Mongolia, Shaanxi, and Guangdong) because of its extensive construction activities. Moreover, interregional energy flows decrease sharply in higher-order upstream processes. This situation further emphasizes the importance of improving local production technology and energy efficiency, which directly determine the energy intensity of local construction activities.

Insert Table 3 here

Insert Figure 3 here

3.3 Sectoral analysis

This section aggregates regional information from the sector unit. The objective of sectoral analysis is to diagram energy paths into sector categories for different upstream stages. Inter-sectoral transactions of up to three stages are illustrated in Figure 4. The results show that energy inputs from the mining and processing of non-metal ores (S5), the manufacture of non-metallic mineral products (S13), the smelting and pressing of metals (S14), the chemical industry (S12), and transportation, storage, posts, and telecommunications (S25) to the construction industry are significant in the first stage. Considering the basic features that are relevant to the construction industry, such energy consumption is mainly attributed to the extensive use of rubber, plastic, cement, and steel during construction processes. Manufacturing these materials is typically energy-intensive, which probably leads to inefficient energy consumption in the upstream supply chain (Minx et al., 2011; Mok et al., 2014).

Moreover, compared with the conventional embodied energy assessment process, this study took a step further in sectoral analysis to search for hidden determinants in the higher-order upstream supply chain. In the third stage, a number of hidden sectors that are generally ignored in traditional analysis have been explored. The power supply sector (S22) makes a higher order of contributions by exporting energy to most of the energy suppliers in the construction industry. The extraction of petroleum and natural gas (S3) is the major supplier of raw materials for oil derivatives and coke products (S11), and the products in S11 are one of the basic energy sources for manufacturing metallic and non-metallic products. In summary, critical sectors hidden behind the upstream process include direct suppliers (e.g., manufacturers of metallic and non-metallic products, the power supply sector, and the transportation sector) and indirect suppliers (e.g., chemical and mining industries).

Insert Figure 4 here

4. Sensitivity analysis

Treloar et al. (2001a) extracted 90% of total energy consumption in the first five upstream stages using a 113-sector format table. Peters and Hertwich (2006c) analyzed upstream structural contributions from the first eight stages of the supply chain by considering 97.8% of total emissions. In the present study, a threshold value of 0.005% of the embodied energy consumption of provincial construction industries was used to filter nearly 80% of the overall impacts in the first five stages. Such empirical results provide a cutoff indicator for tracing back valuable information on upstream energy transfers in the context of China. However, the cutoff threshold and the upstream system boundary were subjectively predetermined. Therefore, the SPA result, to a large extent, depends on the nominated arbitrary threshold and the inspected upstream stages. These subjective choices are unavoidable during the computational process; thus, quantifying these uncertainties and their effects on the final results by conducting sensitivity analysis is vital.

4.1 Sensitivity of the number of paths

Many studies have summarized the appropriate number of paths to focus on the environmental bottlenecks in the supply chain (Peters and Hertwich, 2006c; Wood and Lenzen, 2009). This study provides a possible solution to the number of paths that can efficiently review upstream interactions. Figure 5 shows the changing trend of energy use embodied in each path according to their rankings. The change rate evidently decreased continuously with the increasing number of paths. On the basis of this trajectory, an optimized number of paths (X_0) can be identified to cut off paths with insignificant impact while retaining the most valuable information for the whole supply chain. The value of X_0 in this study is approximately 4500. Comparing this number with those provided in Table 1 implies that the optimized number suggested in Figure 5 is nearly equal to the number of paths in the first two stages (4081). This number accounts for 10.3% of the total number of paths while consuming nearly half of the total energy.

In addition, a comparative analysis between the present study and related research was also conducted. The results are presented in Table 4. The number of paths in the first two stages is different from those in previous research because the total number of paths in the upstream process has been determined directly by the scale of the I–O table. Moreover, although the computational system boundary and the number of paths in each stage vary among different studies, the percentage in the total number of paths and the relative proportion in total energy use are consistent. This finding implies that the paths in the first two stages or the path percentage of 10% can be regarded as the key cutoff points to simplify the calculation process and identify key paths with the largest potential for energy reduction.

Insert Figure 5 here

Insert Table 4 here

4.2 Threshold sensitivity

As previously mentioned in the methodology section, the cutoff threshold for mapping upstream interactions in this study is 0.005% of the total energy consumption of the provincial construction industry. In general, a number of thresholds (e.g., 0.001%, 0.005%, and 0.004%) have been adopted in the previous literature (Peters and Hertwich, 2006c; Treloar et al., 2001a; Treloar et al., 2001b). Determining such cutoff value is arbitrary, which is to a certain extent dependent on the research objective proposed. Therefore, a series of values from 0.002% to 0.015% has been adopted to examine the sensitivity of the threshold. In addition to contributions to the uncertainty analysis, the selected threshold can also assist the provincial government in achieving energy conservation targets in construction practices. An appropriate threshold enables decision makers to identify the most sensitive and energy-intensive paths, which enables the adoption of appropriate energy reduction measures and accelerates the energy conservation process in the construction industry in China. The percentage changes in the number of paths and the sum of the embodied energy use for each stage according to different thresholds are shown in Figures 6 and 7, respectively. The first two stages (stages 0 and 1) are clearly unaffected by the change in threshold. This result is primarily attributed to the fact that paths that represent on-site energy consumption and direct resource input are considerable and larger than the maximum threshold assumed in the sensitivity analysis. Moreover, the change in threshold is sensitive to the number of paths, that is, the threshold is reduced by nearly 80% in the 0.015% scenario and increased over 1.8 times in the 0.002% scenario. By contrast, the change in threshold has minimal influence on the sum of the embodied energy use for each stage, which only leads to approximately 60%

changes in the final results. A close examination of Figure 6 indicates that the number of paths is more sensitive to threshold reduction than to threshold increase. This result implies that a lower value of threshold can lead to an explosion in energy paths, which may cause additional efforts and time for further processing. By contrast, an appropriately higher value of threshold (0.005%–0.01%) can simplify the computational process by cutting down insignificant paths and retaining the most valuable energy information. Such characteristic of threshold determination provides indicators to reduce distractions from insignificant energy suppliers and enable policy makers to concentrate on the most energy-intensive contributors. It is also effective for the provincial government to adopt a threshold according to their construction practice. On the one hand, a higher threshold value is recommended for energy-inefficient regions as it will enable decision makers to identify the essence of energy-related problems directly. On the other hand, a lower threshold value is more appropriate for regions with higher energy efficiency as it can help explore detailed information on upstream energy interactions and improve the overall energy performance of the local construction industry.

Insert Figure 6 here

Insert Figure 7 here

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4.3 Sensitivity of the number of stages

Figure 8 shows the change in cumulative energy consumption according to different thresholds by stages. The change in the cumulative energy consumption is less obvious in higher-order stages. A comprehensive review of all the alternative thresholds shows that cumulative energy consumption has increased dramatically in the first four tiers (stages 0, 1, 2, and 3). However, the impact on total contributions becomes negligibly small in higher-order stages. This finding provides a possible solution to further narrow down the computational system boundary of SPA before being in practical applications in the construction industry. The optimized number of stages can provide a solid reference for promoting a green supply chain. The central government has enacted a number of national energy reduction guidelines and policies for lower-order upstream stages. The major upstream stages and sectors that are targeted for improvement by implementing national regulations for the construction industry are listed in Table 5. Consequently, focusing on these most sensitive stages is more effective than investigating all possible stages, which is both time-consuming and unnecessary.

Insert Table 5 here

Insert Figure 8 here

5. Discussions

The basic attribute of SPA emphasizes the importance of system boundary in presenting energy paths. In general, the limit of system boundary is mainly dependent on the research purpose proposed before the analysis. The excessive decomposition of the supply chain can generate infinite energy paths, which may draw focus away from the most important paths and increase computation difficulties. To address this drawback, an appropriate cutoff rule for accurate estimation in SPA is reported in this study.

Investigating the energy paths in the first five stages or calculating 90% of total energy consumption is commonly used as the maximum scope for narrowing down system boundary. In this study, the energy paths in the first five stages provide 80% of the energy consumption information for upstream interconnections. However, such detailed investigations are both labor- and time-intensive. By contrast, many studies have focused only on top-ranking paths (e.g., top 9, 10, 20, 25, 30, and 100) for further investigation (Minx et al., 2008; Peters and Hertwich, 2006c; Wood, 2008). This simplified process is time-saving and work-efficient, particularly in small-scale I–O analyses. However, this strategy excludes region-specific characteristics during computation. For example, the present study decomposes the supply chain within region-specific data and extracts energy-intensive paths from the regional and sectoral perspectives. Thus, a simple enumeration of the top paths may disregard a considerable number of paths that may not be highlighted in the whole economy but are critical for regional energy reduction. Therefore, selecting an appropriate number of paths and stages for investigation is crucial for SPA in the multi-regional context. The findings of this study show that the energy paths extracted from the first two stages are important and only account for 10% of total energy paths but consume nearly 50% of total energy consumption. In addition, the paths in the first two stages can also avoid the uncertainty of threshold selection because they are basically unaffected by the subjective threshold proposed before the analysis.

Finally, the multi-regional SPA adopted in this study is still conducted based on a higher level of aggregation (30 sectors in each region). Weber (2009) indicated that sector aggregation level is the most critical factor that influences uncertainty in structural decomposition. Therefore, future works should focus on collecting specific and detailed sectoral monetary transaction data at the regional level, which can improve data quality and provide accurate simulation in future research.

6. Conclusions and policy implications

This study used multi-regional SPA to map energy flows in the entire supply chain of the construction industry. By considering both regional-specific characteristics and technological differences, this study revealed the direct and indirect interconnections in the whole supply chain from the regional and sectoral perspectives. The findings of this study are as follows.

(1) Inspecting the entire structure of the path tree indicates that energy suppliers in the first upstream stage consume the highest amount of energy. Sectoral interactions begin to extend the breadth of the entire economy in the second stage. This finding emphasizes the importance and necessity of investigating higher-order upstream production processes in the construction industry.

(2) The top three energy paths of the 30 target regions indicates that apart from direct energy consumption during the on-site construction process, energy input from the manufacture of non-metallic mineral products (S13) and the smelting and pressing of metals (S14) are the most important energy sinks in the provincial construction industry.

(3) The regional analysis explored the self-sufficiency characteristic for the embodied energy consumption in provincial construction industries. Hebei and Inner Mongolia are the major energy suppliers for the construction industry in northern China. Henan was identified as a hub for energy imports to the construction industry in eastern and western China.

(4) The sectoral analysis obtained the critical determinants hidden in the higher order of supply chain. The manufacture of non-metallic mineral products (S13), the smelting and

pressing of metals (S14), and transportation, storage, posts and telecommunications (S25) were identified as the major energy suppliers in the first stage. The chemical industry (S12), the production and distribution of electric power and heat power (S22), and mining industries also exert significant indirect impact on the construction industry.

(5) The systematic analysis of the changes in the threshold and system boundary demonstrated that a higher threshold value (0.005%–0.01%) would be preferred because of its advantages in simplifying the computational process while retaining the most valuable information. Depending on different research objectives, system boundary could be narrowed down into the first two stages, which contained nearly 50% of the energy flow information, or expanded toward the first five upstream stages by representing 80% of total energy consumption.

In summary, given the rapid urbanization in China, the central government should switch the economic growth pattern from energy-intensive to energy-efficient models in the construction industry. To further relate the findings of this study with the policy practice in China, energy conservation policies launched at the national and industrial levels were reviewed. Figure 9 summarized a set of important national energy reduction policies from 2000 to 2015. The central government has enacted a wide range of policies to promote cleaner production in

China. The 11th Five-Year Plan initiated the targets of energy conservation and emission reduction. These targets were further highlighted and enhanced in the 12th Five-Year Plan. However, heavy industries have attracted increasing attention and received considerable efforts in current Chinese policies for energy conservation. By contrast, concern on energy-intensive sectors from the supply chain perspective (e.g., the construction industry) remains insignificant. Such lack of understanding may lead to the unfair implementation of energy reduction policies. In particular, national authorities have promulgated a number of policy instruments for the construction industry with regard to energy conservation. As shown in Figure 10 and Table 6, the major concern of current energy regulations for buildings remains in the operational phase rather than the upstream supply chain. Priorities have been set on reducing operational energy intensity by developing green buildings in new construction and green retrofitting in existing buildings, whereas the emphasis placed on upstream processes such as material production and transportation is less. Although policies are increasingly biased toward the upstream supply chain, such as implementing the evaluation label for green building materials, further steps can still be taken according to the results of this study. Policy recommendations for the construction industry have been formulated across three levels.

Insert Figure 9 here

Insert Figure 10 here

Insert Table 6 here

At the national level, the central government should restrict irrational increases from speculations. Consistent efforts on the macro-control of property markets are required to further narrow down profit margins. This policy is expected to suppress the enthusiasm of investors and return the entire market to rationality.

Moreover, the central government, along with relevant economic departments, should continue to enhance structure reconstruction and upgrading in both the regional and national economy. This policy orientation can make the entire supply chain sustainable and high-value added. In particular, to promote industrial upgrading processes, sectoral technological innovations and apply measures should be enhanced to create a favorable environment for further upgrades.

At the regional level, the local government should be the leading authority responsible for managing energy reduction in the provincial construction industry since the characteristic of energy flows through the supply chain is more self-sufficient than interregional energy transmissions. Formulating energy conservation policies will be more effective by considering regional technological differences and the resource-carrying capacity of the local economy instead of implementing a national policy by the central government. In addition, the primary energy suppliers for the construction industry in northern, western, and eastern China are Hebei, Inner Mongolia, and Henan. Thus, these provinces are the most important regions for the sustainable development of the construction industry in China. From the production-based perspective, building products manufactured from these regions should be restricted by imposing strict policies. From the consumption perspective, regions on the eastern coast and southern area of China import energy from several resource-abundant regions. Such energy mobility requires the local governments in these developed areas to assume additional responsibilities to reduce the volume of energy use in the construction industry.

The local government should take responsibility for production technology improvements because most significant energy contributions came from the local economy according to the decomposition results in this study. An effective method is to switch the traditional resource-intensive model to standard, resource-efficient, and modular construction processes. Precast construction techniques provide a controlled condition to facilitate the standard design of building materials, units, and components. These advances can help achieve direct energy reduction in the first stage of the upstream production process. The Ministry of Housing and

Urban–Rural Development should assume additional responsibilities in promoting its application in building practices.

At the sectoral level, the national energy administration and relevant industrial departments should also conduct energy reduction measures at the sector level. On the one hand, focus should be placed on optimizing the energy consumption structure and improving the proportion of renewable and clean energy in these sectors. In addition to gas and electricity, shale gas is also an important energy source with considerable potential as a clean fuel for construction. On the other hand, traditional resource-intensive materials should be replaced with energy-efficient and environment-friendly materials to reduce overdependence on heavy industries.

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Appendix I

30 regions

R1	Beijing	R16	Henan
R2	Tianjin	R17	Hubei
R3	Hebei	R18	Hunan
R4	Shanxi	R19	Guangdong
R5	Inner Mongolia	R20	Guangxi
R6	Liaoning	R21	Hainan
R7	Jilin	R22	Chongqing
R8	Heilongjiang	R23	Sichuan
R9	Shanghai	R24	Guizhou
R10	Jiangsu	R25	Yunnan
R11	Zhejiang	R26	Shaanxi
R12	Anhui	R27	Gansu
R13	Fujian	R28	Qinghai
R14	Jiangxi	R29	Ningxia
R15	Shandong	R30	Xinjiang

30 sectors

S1	Farming, forestry, animal husbandry and fishery	S16	Manufacture of general and special purpose machinery
S2	Mining and washing of coal	S17	Manufacture of transport equipment
S3	Extraction of petroleum and natural gas	S18	Manufacture of electrical machinery and equipment
S4	Mining and processing of metal ores	S19	Manufacture of communication equipment, computers and other electronic equipment
S5	Mining and processing of nonmetal ores	S20	Manufacture of measuring instruments and machinery for culture activity and office work
S6	Manufacture of foods and tobacco	S21	Other manufacturing
S7	Manufacture of textile	S22	Production and distribution of electric power and heat power
S8	Manufacture of textile wearing apparel, footwear, caps, leather, furs, feather(down), and related products	S23	Production and distribution of gas and water
S9	Processing of timber, manufacture of furniture	S24	Construction
S10	Manufacture of paper, printing, manufacture of articles for culture, education, and sports activity	S25	Transportation, storage, posts and telecommunications
S11	Processing of petroleum, coking, processing of nuclear fuel	S26	Wholesale trade and retail trade
S12	Chemical industry	S27	Hotel and restaurants
S13	Manufacture of non-metallic mineral products	S28	Tenancy and commercial services
S14	Smelting and pressing of metals	S29	Research and experimental development
S15	Manufacture of metal products	S30	Other services

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