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Characterizing embodied energy accounting with a multi-dimensional framework: A study of China's building sector

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A B S T R A C T

Given the substantial resource use and emissions generated from the building sector, China is seeking a more sustainable and greener mode of building construction. To grasp the characteristics of the embodied energy use of the building sector across provinces in China, a multidimensional framework is developed to examine the spatial and sectoral distributions through the whole supply chain using a multiregional input-output (MRIO) analysis and structural path analysis (SPA) as the underlying methods. The results show that from a regional perspective, Liaoning, Shandong, and Guangdong are identified as top contributors, while from a sectoral perspective, the manufacture of nonmetallic mineral products, smelting and pressing of metals, and transportation, storage, posts, and telecommunications are the largest energy suppliers. The upstream examination indicates that self-digestion is an obvious and dominant energy use behavior for most regions, while the relative importance of sectoral suppliers changes regularly with the increase in upstream stages. The energy capture that occurred in the cross-regional energy transfers indicates that Zhejiang and Hebei are the national leading net importer and net exporter of energy use in China's building sector, respectively.

1. Introduction

The building sector has become one of the most important contributors to the global growth of adverse environment impacts by exerting significant effects on resource consumption and emission generation. According to the data obtained from the previous research, two-fifths of global energy consumption, one-fourth of waste generation and water use, and one-third of the world's greenhouse gas (GHG) emissions are attributable to the construction and operation of buildings (Buildings and Initiative, 2009; Chau et al., 2015a; Dixit et al., 2015). Driven by mandatory energy reduction targets and an ambitious plan to reduce carbon dioxide emissions per unit of gross domestic product (GDP) by 60–65% by 2030, China is seeking to achieve a greener and more sustainable urbanization process by improving energy efficiency in the building sector. Although the operational phase consumes more energy in the lifecycle of a building, the significance of investigating the embodied energy use of a building has been gradually realized by the research community because of its vital role in achieving sustainability in the building sector (Emmanuel, 2004; Huberman and Pearlmutter, 2008; Jeong et al., 2012; Tucker et al., 1993).

The necessity of quantifying the embodied energy consumption of buildings may have caused the following issues to arise. First, with the growing emphasis on energy-efficient buildings, innovative materials and advanced technologies have been adopted in newly built buildings, thus causing the proportion of embodied energy to increase by 30–50% of a building's lifecycle energy consumption (Sartori and Hestnes, 2007). Second, lifespan directly impacts the contribution of the embodied phase from a lifecycle perspective. Additionally, in comparison to the operational phase, which has been extensively studied by more standardized methods (Copiello, 2016; Scheuer et al., 2003; Van Ooteghem and Xu, 2012), the attribution and mechanism of the embodied energy consumption in the construction process remain unclear (Dixit, 2017a). On the other hand, in contrast to the operational phase, where a broad range of advanced and energy-efficient appliances can be adopted to decrease operating energy, achieving energy

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conservation during the embodied phase of a building is difficult (Dixit et al., 2012).

Moreover, China's building sector was identified as one of the major energy consumers in China's economy (Wan et al., 2011; Yang et al., 2011), accounting for 25%–30% of the total national energy consumption according to relevant studies (Hong et al., 2016a). This relative contribution was projected to become even larger at 35% by 2020 due to the rapid urbanization process (Zhou et al., 2008). Therefore, it is evident that an effective exploration of the embodied energy performance of buildings is beneficial for China to achieve its overall energy conservation target (Fu et al., 2013).

Against this backdrop, multiple efforts targeting the mitigation of energy intensity in the building construction process have been undertaken from both national and industrial perspectives (Hong et al., 2016b). However, current regulations remain unable to reduce energy use effectively because of the presence of a number of barriers in China. First, due to China's vast territory, there are economic and resource distribution imbalances that lead to regional variations in productivity and energy efficiency. Those regional variations have an indirect but significant effect on the embodied energy use of buildings. Such cross-provincial differences are inclined to cause misinterpretations of the actual energy use embodied in the local building sector. Moreover, it has been demonstrated that the embodied energy consumption of the building sector is dominated by indirect energy interactions through the entire supply chain (Liu et al., 2012a, 2012b), while the direct energy use occurring in the onsite construction process only accounts for approximately 10% of total energy consumption (Hong et al., 2016b). Therefore, exploring the mechanism and relationship of indirect energy transmissions is of importance to achieve the energy conservation goals of the building sector in China (Azari and Abbasabadi, 2018; Dixit, 2017b; Lin et al., 2017; Xie, 2014). The complexity of upstream energy transmission also emphasizes the necessity of a production- and consumption-based quantification (Liu et al., 2015b; Tian et al., 2014). In general, the transitions in consumption and production patterns are two sides of the same coin. A consumption-based analysis affords insights into the allocation of direct and indirect energy consumption associated with the upstream production process to the final users. In contrast, production-based quantification explores the energy induced by the downstream final demand consumed in the upstream production process. An in-depth understanding of both production and consumption can provide the key solution to mitigate the adverse environmental impacts of China's building sector.

Regarding the methodological quantification of embodied energy consumption, Table 1 summarizes the existing angles of investigation for embodied energy quantification at the macro level. The existing quantitative modeling tools are, to some extent, weak in providing comprehensive quantification with multiple considerations. Therefore, a multidimensional and standardized model integrating the dimensions of region, sector, and supply chain is needed for an in-depth analysis of embodied energy use, with the consideration that quantifying embodied energy is a complicated and resource-intensive process (Copiello, 2016; Dixit et al., 2015).

Given the challenges posed by previous literature sources, the proposed analytical framework in this study will address the following three major gaps in previous studies (see Table 2). Because of construction practices, a widely recognized barrier for macro level embodied energy quantification is the lack of a comprehensive framework, which is coupled with a lack of information on the directions, magnitudes, and dynamics of energy flows through the supply chain (Buyle et al., 2013; Chau et al., 2015b). In fact, the lack of a standardized quantification framework that integrates technological data and geographic specificities is the major barrier impeding comparability across embodied energy studies (Azari and Abbasabadi, 2018; Dixit, 2017b). In addition, incomplete information of the upstream supply chain due to the subjective determination of system boundaries may cause a lack of chain management responsibilities (Chau et al., 2015b). Another commonly cited limitation is the cross-regional energy transfer, which creates a mechanism for end users to shift their responsibility for alleviating environmental pollution to others (Paroussos et al., 2015; Zhang et al., 2014). Such shifting may further distort the understanding of energy distribution induced by the building sector.

With such theoretical and practical vulnerabilities, this study develops a multidimensional framework that links the construction reality into the virtual energy quantification from regional, sectoral, and supply chain dimensions. The study's findings can contribute to the transition of the existing building sector from an energy-intensive pattern to a more sustainable and greener model, benefit the upgrading of energy structure in the provincial building sectors, and improve sectoral energy efficiency by advocating a more energy-efficient and value-added supply chain.

The remainder of this paper is organized as follows. Section 2 reviews the current dimensions for embodied energy quantification in China. Section 3 presents the methodological design of an integrated model for embodied energy simulation. Section 4 explores the key findings under the proposed model. Section 5 presents the discussion, while the conclusions drawn from the study and several policy recommendations are provided in Section 6.

2. Review of embodied energy quantification in China's economy

Substantial but fragmented work has been published for different dimensions relevant to embodied energy quantification at the macro level. From the perspective of a nationwide investigation, two obvious trends can be observed. One approach utilized a single-region input-output (SRIO) model to simulate embodied energy consumption with a particular consideration in only the sectoral dimension (Chang et al., 2010, 2015; Hong et al., 2017). These studies were conducted based on the assumption that the manufacturing technology in the domestic production process is the same as the technology used in foreign regions, which failed to reflect regional characteristics, such as the variations in the climate, geographical location, natural resources, and underlying economic activities, that directly determined the cross-regional environmental shifts (Wiedmann, 2009; Wiedmann et al., 2007). This oversight presents the challenge of investigating strategies from a

Table 1
The angle of major methods for macro-level embodied energy quantification.

	Dimension			Perspective	
	Regional	Sectoral	Supply chain	Production	Consumption
Single regional input-output analysis (SRIO)		✓			✓
Multi regional input-output analysis (MRIO)	✓	✓			✓
Structural path analysis		✓	✓	✓	✓

Table 2
Gaps addressed by the proposed framework.

Gap	Gaps addressed	References
Lack of a unified assessment framework	Integrating a multidimensional framework that links the construction reality into the virtual energy quantification from the region, sector, and supply chain dimensions.	Azari and Abbasabadi (2018), Dixit (2017b)
Lack of information on upstream industrial supply chain containing technological and geographical specificities	The use of regional input-output data coupled with energy statistics allows for the calculation of provincial embodied energy use, providing an understanding of regional disparities and technological differences.	Dixit (2017b), Chau et al. (2015)
Limited information on energy transfer mechanisms	The characterization under the supply chain dimension provides a resolution for tracing back cross-regional and intersectoral energy flows	Dixit (2017b), Buyle et al. (2013)

regional perspective. Consequently, a vast body of studies quantified environmental impacts generated from China's economy with the consideration of both regional and sectoral dimensions by using the MRIO model as the underlying method. Most of these works focused on the examination of regional differences and sectoral contributions in terms of energy consumption or CO_2 emissions induced by China's domestic trade (Guo et al., 2012; Meng et al., 2011; Mi et al., 2017; Yuan et al., 2015; Zhang et al., 2016, 2017).

Apart from nationwide investigation, a body of work has been published on industrial level analysis, aiming to explore the environmental impacts generated from a specific economic sector. A number of studies concentrated on the overall environmental performance of entire industrial sectors, with specific consideration of the high-energy consuming sectors in China (Song et al., 2014; Xu and Lin, 2016b; Yuan and Zhao, 2016). In contrast, some studies only focused on the environmental impact of a certain sector, such as the iron and steel industry (Lin and Wang, 2015; Xu and Lin, 2016a), cement industry (Song et al., 2016), agricultural industry (Wang et al., 2014), aluminum industry (Liu et al., 2016), and building sector (Chang et al., 2016; Guan et al., 2016; Hong et al., 2016a).

From the viewpoint of a supply chain analysis, investigations have been conducted in China's economy to determine the magnitude and strength of interconnections among sectors through the supply chain network. Measuring the quantity of energy and carbon emissions embodied in products via the supply chain is a topic of interest in this specific field (Hong et al., 2016b; Liu et al., 2015a, 2015b; Yang et al., 2015; Zhang et al., 2017). Of particular interest is the discussion of the relationship between production and consumption-based accounts using structural analysis methods (Tian et al., 2014; Yan et al., 2016).

However, all these studies that trace back environmental interactions embodied in interregional trades are conducted in different ways. Efforts are seldomly devoted in previous research to develop an integrated framework with a comprehensive consideration of regional, sectoral, and supply chain factors.

3. Methodology

3.1. Model development

This study developed an integrated framework to trace back and quantify energy flows under the dimensions of region, sector, and supply chain. The computational mechanism embedded in this framework is the integration of a MRIO analysis and a structural path analysis (SPA). MRIO is a top-down method that provides a highly specific assessment of the environmental impact, enabling researchers to measure the effects of regional disparities and technological differences in environmental interactions. It provides a theoretical foundation for the calculation of embodied energy use under regional and sectoral dimensions. SPA offers detailed information on energy flows through the supply chain dimension by decomposing the results obtained from the MRIO analysis in a systematic and structural way. The method aids decision-makers to trace back environmental interactions through the supply chain perspective.

In general, the basic energy equilibrium can be expressed as

$$e_i^r x_i^r = \sum_{k=1}^{m} \sum_{j=1}^{n} e_j^k a_{ji}^{kr} x_i^r + c_i^r x_i^r, \tag{1}$$

where e_i^r is the embodied energy intensity of products from sector i in region r; e_j^k is the embodied energy intensity of products from sector j in region k; x_i^r represents the total economic output of sector i in region r, and it is assumed that there are m regions, each of which has n sectors; a_{ji}^{kr} represents the direct monetary input from sector j in region k as intermediate use per monetary unit produced from sector i in region r (direct coefficient); and c_i^r andc_i^r is the direct energy intensity of sector i in region r, which is the direct energy consumption data reported from regional statistics.

Note that there are $m \times n$ equations established under the whole economy, and vectors and matrixes can therefore be introduced to simplify these mathematical expressions.

$$\text{Nominate } E^T = \begin{bmatrix} \begin{pmatrix} e_1^1 \\ \cdots \\ e_n^1 \end{pmatrix} \\ \cdots \\ \begin{pmatrix} e_1^m \\ \cdots \\ e_n^m \end{pmatrix} \end{bmatrix} C^T = \begin{bmatrix} \begin{pmatrix} c_1^1 \\ \cdots \\ c_n^1 \end{pmatrix} \\ \cdots \\ \begin{pmatrix} c_1^m \\ \cdots \\ c_n^m \end{pmatrix} \end{bmatrix}, X = \begin{bmatrix} x_1^1 & 0 & \cdots & 0 \\ 0 & x_2^1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & x_n^m \end{bmatrix}, \text{ and } A^T = \begin{bmatrix} \begin{pmatrix} a_{11}^{11} & \cdots & a_{1n}^{11} \\ \cdots & \cdots & \cdots \\ a_{n1}^{11} & \cdots & a_{nn}^{11} \end{pmatrix} & \cdots & \begin{pmatrix} a_{11}^{1m} & \cdots & a_{1n}^{1m} \\ \cdots & \cdots & \cdots \\ a_{n1}^{1m} & \cdots & a_{nn}^{1m} \end{pmatrix} \\ \cdots & \cdots & \cdots \\ \begin{pmatrix} a_{11}^{m1} & \cdots & a_{1n}^{m1} \\ \cdots & \cdots & \cdots \\ a_{n1}^{m1} & \cdots & a_{nn}^{m1} \end{pmatrix} & \cdots & \begin{pmatrix} a_{11}^{mm} & \cdots & a_{1n}^{mm} \\ \cdots & \cdots & \cdots \\ a_{n1}^{mm} & \cdots & a_{nn}^{mm} \end{pmatrix} \end{bmatrix},$$

where E^T and C^T are the embodied energy intensity vector and direct energy intensity vector with $(m \times n) \times 1$ dimensions, respectively; X is a diagonal matrix with $(m \times n)^2$ entries, the diagonal coefficients of which equal the total economic output. A is the direct coefficient matrix in the input-output table, with $(m \times n)^2$ entries. For the whole economic system, the above group of equations can be expressed in the form of a matrix-based equation:

$$XE^T = A^T XE^T + XC^T. \tag{2}$$

This equation can be further transformed to

$$E = C(I - A)^{-1}. \tag{3}$$

Consequently, a diagonal matrix $\widehat{V}$ representing the set of final commodities can be used to calculate the energy distribution under the region and sector dimensions:

$$F = E\widehat{V} = C(I-A)^{-1}\widehat{V}. \tag{4}$$

F is a $1 \times (m \times n)$ vector representing the sectoral embodied energy input to the building sector in each region.

To investigate the energy distribution under the supply chain dimension, the structural path analysis (SPA) method is integrated into the MRIO model. According to power series approximation theory, equation (4) can be further expanded as

$$F = E\widehat{V} = CI\widehat{V} + CA\widehat{V} + CA^2\widehat{V} + CA^3\widehat{V} + \ldots \tag{5}$$

Based on the computational algorithm implied in the SPA, the whole supply chain can be decomposed into an infinite tree. The value of $CA^t\widehat{V}$ represents the total amount of energy embodied in the production process in the t th upstream stage.

Based on the aforementioned two methods, an analytical framework can be proposed by integrating region, sector, and supply chain dimensions (see Fig. 1). The horizontal plane is the result of the energy distributed in the regional and sectoral dimensions. It can be seen that the number of units in these two dimensions is determined by the division rule in the MRIO table. The vertical axis represents the energy distribution through the supply chain. The units in this dimension are infinite given the intersectoral iterative effect occurring through the whole supply chain. Therefore, there is a need to determine an appropriate number of upstream stages that may enable investigators to concentrate on the most energy-intensive process.

In this analytical framework, each node denotes a flow with the amount of energy from a particular sector in a specific region within a certain upstream stage into the building sector. The node represents individual environmental contributions induced by the corresponding final demand from the building sector. Connecting nodes in a sequential way that follows the order from the upstream stage to the downstream stage represents a single energy path. From a production perspective, nodes in a certain stage represent the energy flow from a given production induced by the final demand (end point). From a consumption viewpoint, the value of a certain node is the sum of energy received from upstream suppliers. This energy transmission process established a linkage between the final demand purchased and its corresponding production. Consequently, every single path in the analytical framework represents a specific environmental linkage between the producers in the higher order stages of the upstream process to the final consumer.

For any node $x(m,n,u)$,

$$x = f(m,n,u), \text{ where } \begin{cases} 0 < m \leq 30 \\ 0 < n \leq 30 \\ 0 \leq u \end{cases}, \tag{6}$$

The value of a specific node $x(s,r,p)$ in the framework can be calculated from production and consumption-based perspectives. In general, the value representing a certain amount of energy produced or received from sector s in region r in the upstream p stage can be derived from the integration of SPA into the MRIO model. The results are shown in Table 3.

Moreover, each node defined in the framework should meet the following criteria:

- Exclusiveness: each node is unique and mutually exclusive;
- Finiteness: the number of nodes increases exponentially with the growth of upstream stages, while the number of upstream stages is finite; and
- Computability: each node in this model has a practical definition and can be calculated by appropriate equations.

Furthermore, this new methodological framework comprises three projective planes in which a set of coupled computation

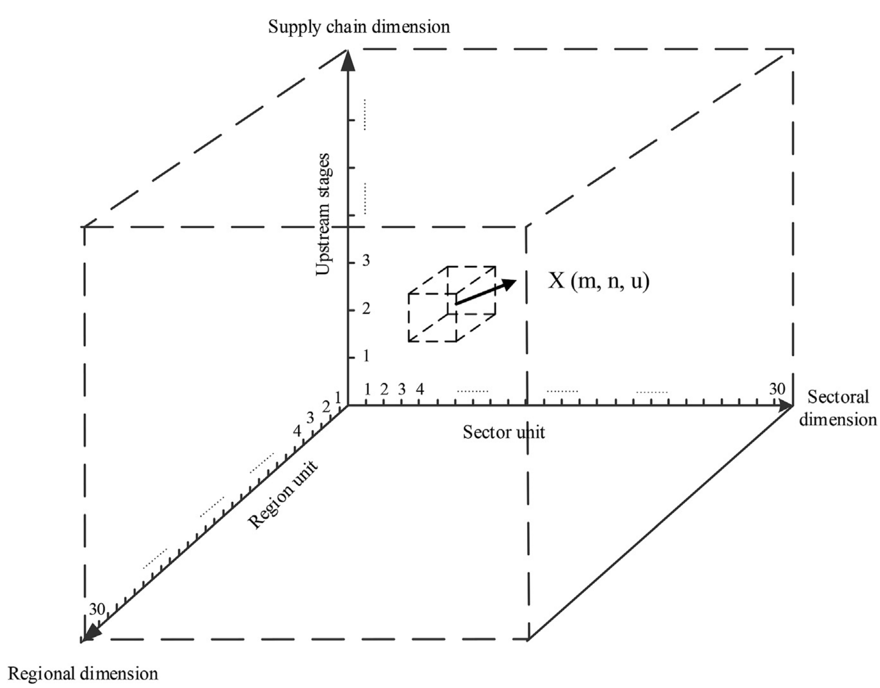

Fig. 1. A multi-dimensional framework for embodied energy quantification of the construction sector.

Table 3
Equations for calculating the value $x(s,r,p)$from consumption and production based perspectives.

Stages	Consumption-based	Production-based
0	$e_c^r v_c^r$	0
1	$\sum_{l=1}^{30}\sum_{k=1}^{30} e_l^k a_{ls}^{kr} v_s^r$, here sector $m$is the construction industry	$\sum_{n=1}^{30} e_s^r a_{sc}^{rn} v_c^n$
2	$\sum_{l=1}^{30}\sum_{k=1}^{30}\sum_{n=1}^{30} e_l^k a_{ls}^{kr} a_{sc}^{rn} v_c^n$	$\sum_{l=1}^{30}\sum_{k=1}^{30}\sum_{n=1}^{30} e_s^r a_{sl}^{rk} a_{lc}^{kn} v_c^n$
3	$\sum_{i=1}^{30}\sum_{h=1}^{30}\sum_{l=1}^{30}\sum_{k=1}^{30}\sum_{n=1}^{30} e_i^h a_{is}^{hr} a_{sl}^{rk} a_{lc}^{kn} v_c^n$	$\sum_{i=1}^{30}\sum_{h=1}^{30}\sum_{l=1}^{30}\sum_{k=1}^{30}\sum_{n=1}^{30} e_s^r a_{si}^{rh} a_{il}^{hk} a_{lc}^{kn} v_c^n$
p	$\underbrace{\sum_{i=1}^{30}\sum_{h=1}^{30}\cdots\sum_{l=1}^{30}\sum_{k=1}^{30}\sum_{n=1}^{30}}_{p+2} e_i^h \underbrace{a_{is}^{hr}\ldots a_{lc}^{kn}}_{p} v_c^n$, while $p \geq 1$	$\underbrace{\sum_{i=1}^{30}\sum_{h=1}^{30}\cdots\sum_{l=1}^{30}\sum_{k=1}^{30}\sum_{n=1}^{30}}_{p+2} e_s^r \underbrace{a_{si}^{rh}\ldots a_{lc}^{kn}}_{p} v_c^n$, while $p \geq 1$

routines manage regional data to provide a roadmap of suggestive and indicative information for decision-makers. These three projective planes will be discussed in detail in the following sections. Thereafter, an in-depth investigation can be conducted with respect to embodied energy flows induced by the building sector based on the monetary data across various regions, sectors, and upstream stages. The multidimensional approach provides a reinforced grounding for energy quantification in construction practices with supporting theories and evidence.

3.1.1. Region-sector plane

The value of each node in the region-sector plane represents the sum of all nodes distributed in the supply chain with the same region and same sector. Therefore, the value is determined by the specific region n and sector m), while the upstream stage p is equal to 0. The additive results obtained from this plane represent the total energy supplied from a certain sector in a specific region due to construction activities carried out in China. Practically, the calculated value is the sum of direct energy from the onsite construction process and indirect energy through the whole supply chain. In addition, the sum of sectoral energy use based on the region unit can provide insights into the regional energy contributions to China's building sector. Similarly, the sum of the regional energy supply for each economic sector enables investigators to examine the energy distribution from a sectoral perspective.

3.1.2. Region-supply chain plane

If we designate the value of each node in the region-supply chain plane as the sum of nodes with the same region and upstream stage, this plane can describe the total energy supplied from a certain regional economy in a specific upstream stage to the building sector. Such a projection can facilitate the ability to trace back the interconnections of energy flows through upstream stages with the unit of region entity.

3.1.3. Sector-supply chain plane

The projection of nodes into the sector-supply chain plane represents the total energy supplied from a certain sector in a specific upstream stage, where their value is equal to the sum of nodes with the same sector and upstream stage. This plane provides information on energy interactions through upstream stages with the unit of sector entity.

3.2. Data collection and consolidation

The data and methods needed under different dimensions are summarized in Table 4. This study used the MRIO table published in 2010, which was the latest available format compiled by the Chinese Academy of Science. To achieve structural consistency, the collected direct energy consumption data in each region were disaggregated to constitute the sectoral division in the MRIO table. The economic allocation rule was employed to ensure the energy use data among the affected subsectors.

4. Results and analysis

This study first presented energy flows simulated by the whole framework. Then, a discussion highlighting the interregional and intersectoral analyses in production and consumption-based perspectives was presented to explore net energy transfers induced by the building sector.

Fig. 2 shows the node distribution simulated by the developed framework. To alleviate the distraction from nodes with insignificant values, a threshold of 0.1% of total embodied energy consumption of the regional building sector was set to cut off redundant nodes. The shape of the overall distribution indicated that most energy intensive flows concentrated at the lower upstream stages, while both the reported value and number of nodes became negligibly small after the fifth stage. To further explore the features under different dimensions, an in-depth decomposition of the framework into region-sector, region-supply chain, and sector-supply chain planes has been conducted in the following sections.

4.1. Energy distribution in the region-sector plane

According to Fig. 3, it can be seen that regardless of the discrepancy in the amount of energy consumed by regional sectors, the economic structure is similar among different regions, where the relative proportion of sectoral energy contribution represented a regular distribution. From a regional perspective, Liaoning (R6), Shandong (R15), and Guangdong (R19) were the three top contributors to the total embodied energy consumption of China's building sector in 2010. From a sectoral perspective, owing to the intensive use of concrete and steel in the building construction process, the manufacture of nonmetallic mineral products (S13) and smelting and pressing of metals (S14) covered most of the energy consumed by the building sector. It is also worth noting that transportation, storage, posts, telecommunications (S25), the chemical industry (S12), general and special purpose machinery manufacturing (S16), production and distribution of electric power and heat power (S22), and other services (S30) also played a major role in supporting China's construction activities.

4.2. Energy distribution in the region-supply plane

Fig. 4 shows the energy distribution through the entire supply chain based on regional divisions. It can be found that in the zero stage, which was directly related to the onsite construction process, the energy consumptions of Shandong (R15) and Guangdong (R19) were more significant, which largely resulted from their large-scale

Table 4
Methods and data sources.

Method	Data needed	Data source	Information
MRIO model	● MRIO table (2010) ● Region-based sectoral energy consumption data	● Chinese Academy of Science ● Chinese Energy Statistical Yearbook (2011) ● Provincial Statistical Yearbooks (2011)	Monetary transactions and direct energy input data of 900 sectors in 30 regions in China (4 municipalities, 4 autonomous regions, and 22 provinces) (see Appendix I and II)

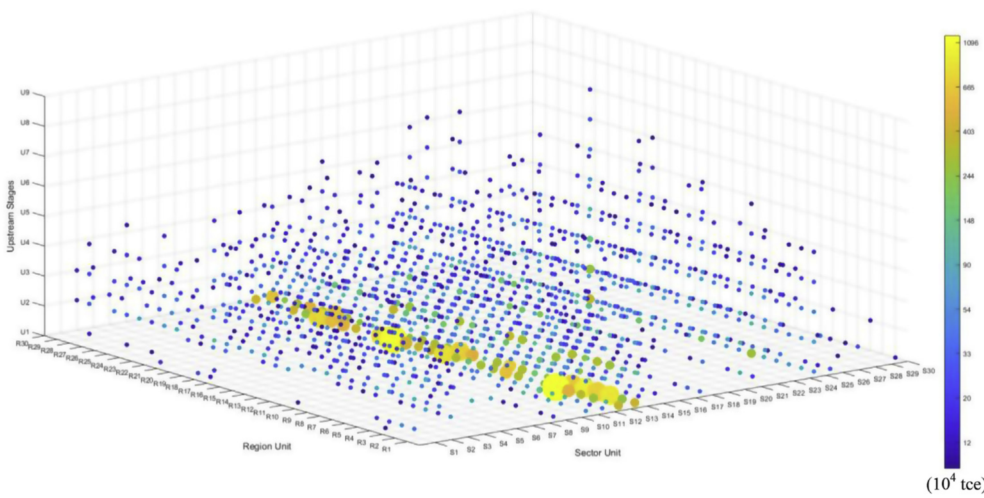

Fig. 2. Energy distribution under the analytical framework
(Note: The size of sphere represents the amount of energy embodied in each node).

construction activities and ongoing urbanization process. The regions in northern, central, and southwestern China were typical energy-intensive places for China's building sector. The driving factors leading to such high energy consumption were complex and multifaceted. This study attempted to discover the potential driving forces by analyzing the local affordability given the methodological superiority in structural decomposition from this framework. In fact, there were two different features regarding the energy supply behavior of the local building sector. Self-digestion was an obvious and dominant trend for most regions where the major leading factor for embodied energy consumption was the local construction volume. For instance, more than 90% and 80% of the total energy used in the building sectors of Shandong (R15) and Guangdong (R19) were attributed to the local economies, respectively. In contrast, some other regions produced energy not only for domestic use but also for the purpose of interregional trade. In this situation, the embodied energy consumption was the result of both local development and foreign trade. For instance, Hebei (R3), Henan (R16), and Liaoning (R6) exported more than 65%, 55%, and 35% of local energy to support the construction activities in other regions. More specifically, Hebei was the biggest exporter for the Jing-Jin-Ji area, contributing more than 25% and 14% of the total embodied energy consumption in the local building sector of Beijing (R1) and Tianjin (R2). Similarly, in the northeast area, 61.3% and 58.1% of Jilin's (R7) and Heilongjiang's (R8) embodied energy use can be traced back to Liaoning (R6), which was the major energy-supply province in this area.

4.3. Energy distribution in the sector-supply plane

Fig. 5 represents the energy distribution through the entire supply chain based on sectoral divisions. It can be found that the mining and washing of coal (S2), processing of petroleum, coking, and nuclear fuel (S11), S13, S14, S22, and S25 provided sustained energy through the whole supply chain rather than being significant in one or two upstream stages. It is understandable that these sectors were highly related to onsite building construction and the offsite material manufacturing and transportation processes. The widespread economic sectors contributing to energy consumed by the building sector emphasized the necessity and importance of mitigating energy intensity within the complete system boundary instead of only focusing on one or two specific manufacturing processes. In addition, the relative importance of economic sectors was changed regularly through the extension of the supply chain (see Fig. 6). For instance, the role of mining industries (e.g., S3 and S4), S11, and S22 became more important with the increase in upstream stages. It is evident that these sectors were basic economic departments for raw material production and energy supply for the entire economic system, from which goods and products were normally used as the secondary energy sources for the processing in the next stage. On the other hand, the energy contributions from the manufacture of metal products (S15) and the machinery industry (S16 and S18) were small in the higher upstream stages. This is mainly because the dependency of products from these sectors mainly occurred in the downstream stages of the building sector, in particular for the onsite construction process. Therefore, the demand became weak in the higher order upstream stages.

In summary, the region-supply and sector-supply planes can reflect the mechanism of energy interactions through the whole supply chain in the region and sector unit. The first, second and third stages were leading upstream production processes, contributing to the energy consumption of the building sector in China, followed by the zero stage and the fourth stage. It is straightforward to observe that the building sector was characterized by its large amount of indirect energy consumption, where

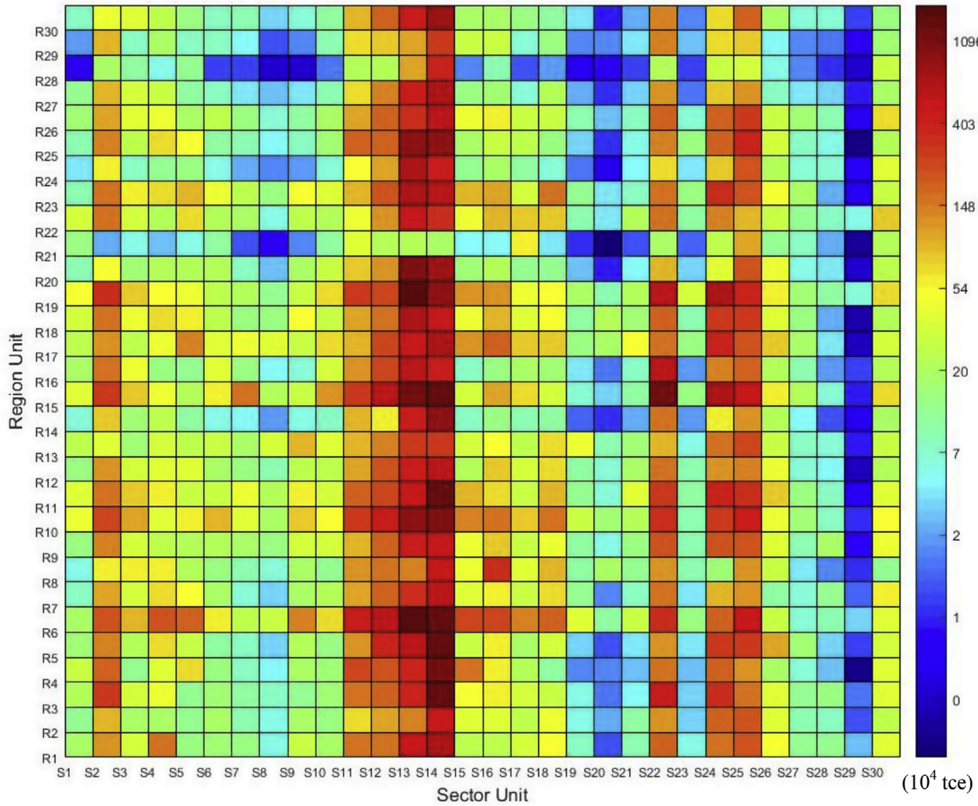

Fig. 3. Energy distribution in the region-sector plane.

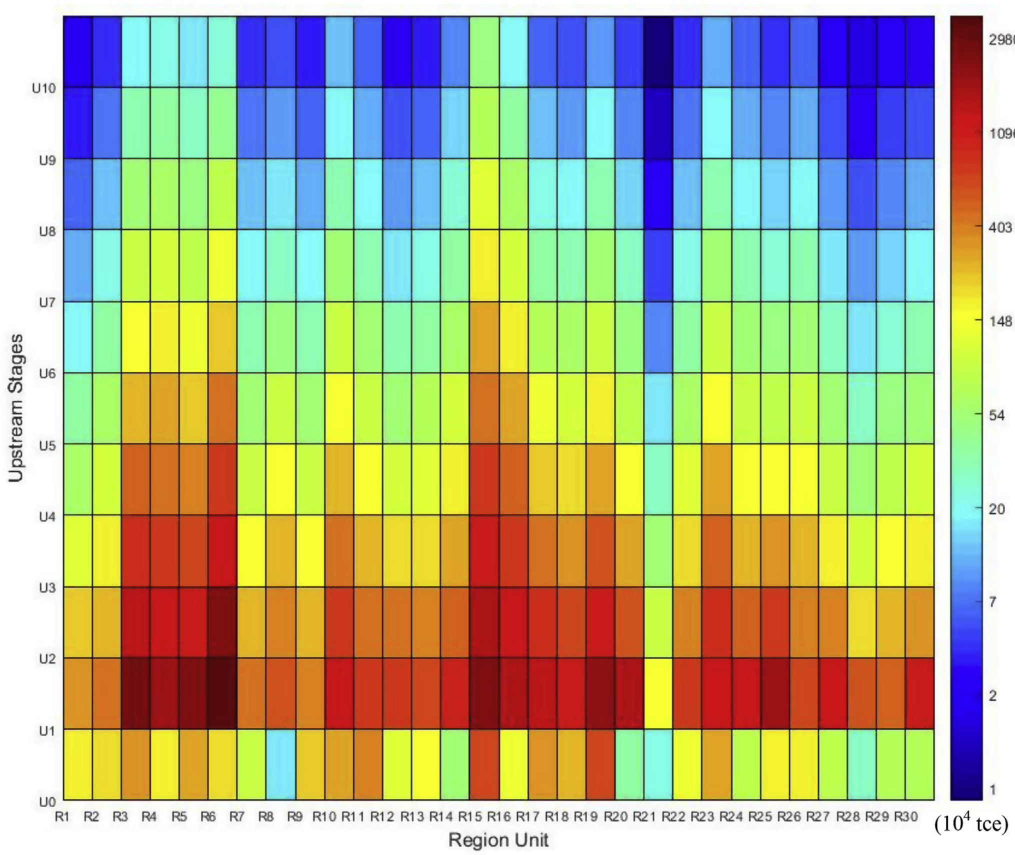

Fig. 4. Energy distribution in region-supply plane.

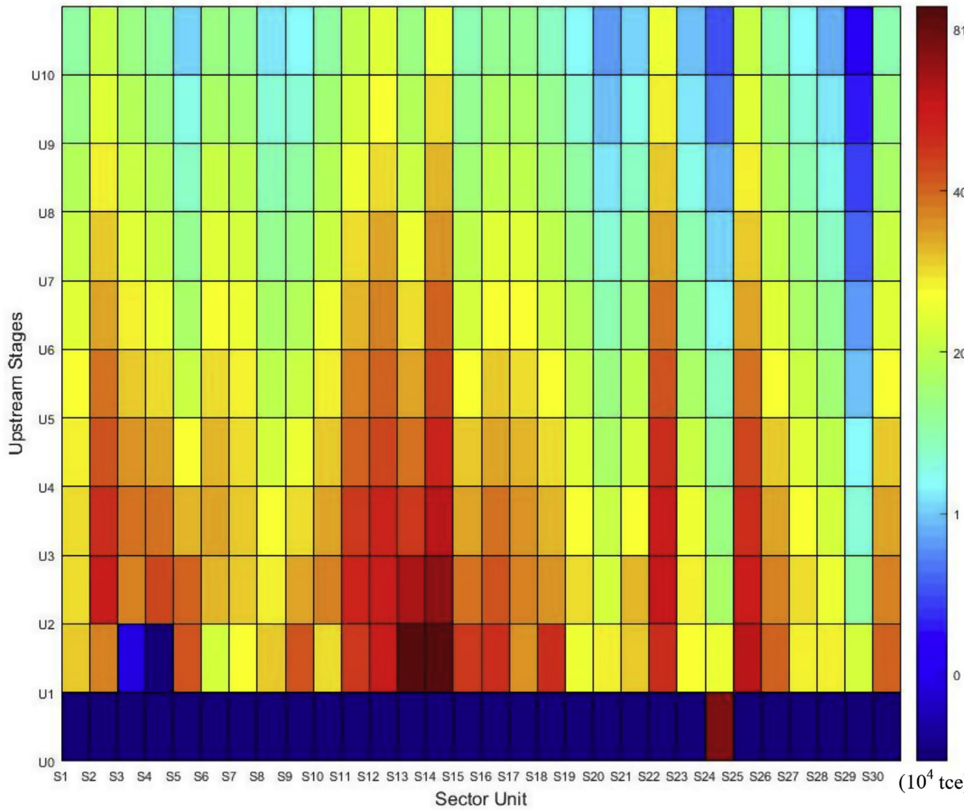

Fig. 5. Energy distribution of sector-supply plane.

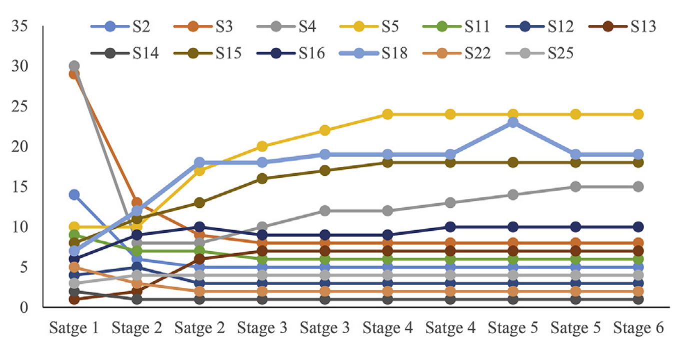

Fig. 6. Ranking changes of top energy intensive sectors.

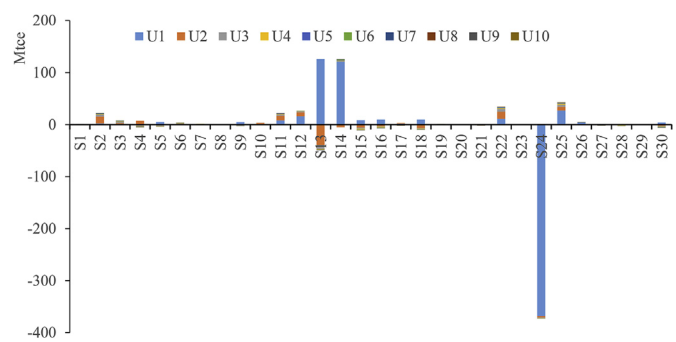

Fig. 8. Energy distributions among different sectors through the supply chain.

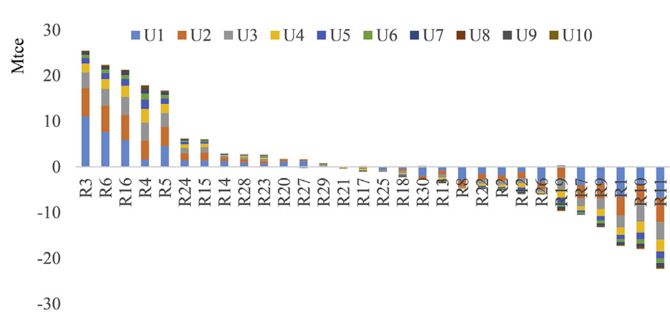

Fig. 7. Energy distributions among different regions through the supply chain.

energy supplied from upstream processes accounted for more than 90% of the total embodied energy use of the building sector. Apart from the dominance of the material-related impacts (40.7%), some higher upstream stages (e.g., stages 2, 3 and 4) also significantly contributed to the total embodied energy consumption (42.3%). The first ten upstream stages contributed more than 90% of the total embodied energy consumption, while 94.3% of it was due to the first five stages. This result provided an indicative threshold for cutting off the system boundary by retaining the most valuable information for embodied energy quantification in a rational manner.

4.4. Interregional and intersectoral analysis

To make a fair identification of energy conservation goals and allocation of regional responsibility in the building sector, it is imperative to conduct an in-depth analysis of interregional and intersectoral energy transfers nationwide. To achieve this, the interregional and intersectoral energy transmissions were investigated through the supply chain.

Fig. 7 explored the energy capture that occurred in the regional energy transfers via the supply chain. The understanding of energy capture is of significance in realizing the real energy use status of a region. Zhejiang was illustrated to be the nation's leading net importer of energy use in the building sector, followed by Jiangsu, Beijing, and Shanghai. Hebei, Liaoning, and Henan were the three leading net exporters for carrying on construction activities in China. Beijing was the largest sink region, where 85% of the total energy consumed in the local building sector was exported from foreign regions, followed by Shanghai and Jilin. Given the urgent needs for the improvement of living space and ongoing urbanization in these sink regions, this high-export reliance on external resources would continue to increase, which may torture the understanding of their real role in energy conservation nationwide.

According to Fig. 8, it can be observed that in the first upstream stage the building sector was the biggest and sole energy receiver, importing 368.2 Mtce from other sectors. Investigating the energy distribution through the supply chain allows a more comprehensive realization of the role transition among key sectors in terms of their supply behaviors. In fact, S13, S14, and S18, although they were identified as the major contributors to overall energy consumption, reversed their role from the suppliers to the receivers in the upstream stages. This fact implied that this group of sectors was still largely dependent on the energy from the upstream economy. In contrast, the role of mining industries (e.g., S2, S3, and S4), S22, and S25 were consistent through the whole supply chain, being identified as the major energy producers for the building sector. More specifically, the amounts of energy consumed by S2 and S22 in the higher order upstream stage were much higher than in the first stage. This is mainly because these two sectors provided basic raw materials and energy into the upstream supply chain of the building sector. Therefore, improving the energy and production efficiency of these source sectors was critical for energy reductions in the building sector.

5. Discussion and policy implications

This study designed a multidimensional framework for an embodied energy assessment at the industrial level. The application of this model can facilitate the understanding of the current energy consumption status in the aspects of region, sector, and supply chain in an integrated manner rather than analyzing each dimension separately. Every node under this unified computational framework represented a certain energy flow that can be measured by equations given in Section 3. The value of all simulated nodes can provide valuable information and a new approach for allocating the energy reduction responsibilities for different regions, which was critically crucial for the decision-making of local governments.

Regarding the computational design, the division of regions and sectors was determined by the inherent structure of the MRIO table, whereas the number of upstream stages in the supply chain dimension was given subjectively. Therefore, the determination of the upstream boundary was important for the framework's validity and reliability. The simulation results indicated that the cumulative energy contribution was negligibly small and converged after the fifth upstream stage. This massive reduction of nodes after the fifth stage implied a possible solution to further define the computational system boundary before being used in practical applications. Consequently, a ten-stage examination designed in the framework, to a large extent, can reflect the overall picture of interregional and intersectoral energy transfers through the supply chain.

Conducting an inadequate quantification of embodied energy consumption and ignoring cross-regional energy capture would give a misleading impression of the current state of the energy distribution induced by the building sector, which may invite failure in implementing equitable policy instruments for energy reduction. To link the findings with the policy practice, we summarized the role of critical regions identified in this study and the mandatory targets they faced during the 12th Five-Year Plan (see Table 5). It can be found that some findings of this study were highlighted in the national instruments by setting mandatory targets. For instance, Shanghai and Jiangsu, as typical sink regions and leading net importers for local construction activities, were encouraged to improve the sharing of newly built floor areas of energy conservation buildings up to more than 30%, which was much higher than for the surrounding regions. However, although these targets were considered to be stratified in accordance with their diverse role and status in energy consumption at the beginning of 12th Five-Year Plan period, it was still insignificant in the inner area context. For instance, Hebei was the largest producer of steel, accounting for more than 25% of the total national output (China Steel Yearbook, 2011). As a result, in addition to supplying products that satisfy local needs, Hebei also produced necessary

Table 5
Features of critical regions and their mandatory targets during the 12th Five-Year Plan.

Area	Region	Feature	Mandatory target		
			a	b	c
Jing-Jin-Ji	Beijing	• Leading net importer • Largest sink region	6.1%	17%	23%
	Hebei	• Leading producer	6.0%	17%	41%
North	Liaoning	• Leading net exporter • Leading consumer	4.5%	17%	34%
	Jilin	• Typical sink region	9.8%	16%	49%
	Shandong	• Leading net importer • Leading consumer	4.5%	17%	–
Yangtze River Delta	Shanghai	• Typical sink region	12%	18%	34%
	Jiangsu	• Leading net importers • Leading consumer	43.5%	18%	32%
	Zhejiang	• Leading net importer • Leading consumer	15%	18%	10%
Central	Shanxi	• Leading energy producer	2.5%	16%	–
	Inner Mongolia	• Leading energy producer	5.0%	15%	–
	Henan	• Leading net exporter	5.0%	16%	–
South	Guangdong	• Leading consumer	30%	18%	–

Note: “a” represents the ratio of non-fossil energy in primary energy; “b” represents the percentage reduction in energy intensity per GDP capita; “c” represents the ratio of newly-built floor area of energy conservation buildings in urban existing buildings.

Table 6
Customized strategies for different roles.

Role	Strategies
Consumer	• Controlling the volume of construction activities • Transferring energy conservation responsibility from the local government to construction companies • Increasing the scale of green buildings • Adopting green construction technologies • Reducing energy intensity of the construction process • Adopting tax deduction or exemption for energy service enterprises
Producer	• Advancing industrial upgrading • Improving energy efficiency in energy-intensive industries • Improving the sharing of renewable and clean energy • Advancing energy conservation techniques • Encouraging green investment by providing stimulations • Establishing green capital market by controlling loan growth for energy-intensive enterprises

materials supporting construction in other regions, which favored Hebei as the leading energy exploiter in China. However, in the energy conservation target responsibility system (ECTS), Hebei faced the same reduction pressure as Beijing, which failed to capture the real energy supplier in this area.

Therefore, the customized strategies and technical suggestions should be designed according to the different roles of regions (see Table 6). For the leading energy consumers, e.g., Zhejiang and Jiangsu, their local energy supply was insufficient to support the large-scale infrastructure construction and ongoing urbanization process. As such, concerted efforts from consumption sides were needed to progress towards sustainable construction. They were encouraged to shoulder more responsibility in their bargaining process by urging suppliers to implement low-carbon and cleaner production. Regarding the top energy producers, a tight regulation can be implemented as a constraint that encourages them to provide more value-added and energy-efficient products.

In summary, the embodied energy consumption of the building sector was more dependent on downstream energy transmissions rather than the higher order upstream process from the perspective of sector interactions, where S13 and S14 were identified as the largest contributors. Such a sectoral feature emphasized the importance of mitigating the energy burden in materials production of the building sector. Therefore, accelerating the technological progress of the leading sectors responsible for material production is an effective way to achieve short-term and instant energy conservation. Furthermore, cross-regional energy shifts represented an equal distribution among different upstream stages. The similarity of regional economic structures was the main reason to form such upstream distributions. Consequently, from a long-term perspective, apart from the mitigation efforts with short-term effects, actions should be taken on a comprehensive upgrading of the present structure by transiting the entire economy to a more sustainable, service-based, and high value added system, thus improving each upstream stage's energy efficiency through the entire supply chain.

6. Conclusions

This study integrated a multidimensional framework to systematically quantify and trace back the embodied energy use of the building sector from regional and sectoral perspectives. The developed framework provided a holistic map for exploring interregional and intersectoral energy flow paths and interactional mechanisms through the supply chain. The key findings are as follows.

(1) This study established a linkage between real construction practices and virtual energy quantification by integrating a multidimensional framework. Every node under this model was clearly definable, theoretically computable, and mutually exclusive with a sole value.
(2) Regarding the total embodied energy use, Liaoning, Shandong, and Guangdong were identified as the three top contributors from a regional perspective; the manufacture of nonmetallic mineral products, smelting and pressing of metals, and transportation, storage, posts, and telecommunications were the largest energy suppliers from a sectoral perspective.
(3) Regarding the upstream distributions of the building sector, the regional analysis indicated that self-digestion was an obvious and dominant trend for most regions, while the others produced energy not only for domestic use but also for interregional trade purposes. The sectoral spread demonstrated that the manufacture of metal products and the machinery industry contributed more in the downstream process, while the mining industries, chemical industry, and power sector became increasingly important through the entire supply chain.
(4) The interregional simulation indicated that Zhejiang and Hebei were the national leading net importer and exporter of energy use in the building sector, respectively. The intersectoral analysis indicated that the sectors might change their supply behaviors from producers to consumers through the upstream stages.

The focus of energy distribution through the lens of the region, sector, and supply chain dimensions highlights the intricate and interactive nature of the embodied energy use of the building sector and underlines the importance of developing an integrated framework for a systematic and comprehensive quantification. The results show that the whole framework is effectively performed with the integration of MRIO and SPA, which explicitly simulates the network structure of energy flows induced by the building sector. The findings of this study support the identification of key factors influencing the energy performance of the building sector and development of equitable energy reduction strategies to achieve sustainable construction. Although a multidimensional assessment of embodied energy use of the building sector remains several steps away from achieving effective energy reductions, such action is instrumental for creating a solid reference for allocating energy reduction responsibilities from regional and sectoral perspectives.

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