

An integrated framework for embodied energy quantification of buildings in China: A multi-regional perspective

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Abstract

The construction industry has grown as the major energy consumer in China's economy with the rapid development of urbanization, continually increasing the stress on the environment, healthcare, and economy. Therefore, this study developed an integrated framework for embodied energy quantification of China's buildings from a multi-regional perspective. This article builds on previous work on embodied energy quantification and develops an optimized algorithm that illustrated how the technological difference and the regional features are calculated as indices of embodied energy quantification at the project level, using multi-regional inputoutput (MRIO) analysis, structural path analysis (SPA), and process-based LCA model as the underlying methods. The structure of the proposed framework using calculative modules as well as the data sources are specified. The application of the analytical framework in real building cases demonstrates that it can provide valuable information of detailed embodied energy distribution through the whole supply chain. The implementation of the proposed framework can facilitate decision-makers to examine the effects of changes in geographical location, building type, and building structure on the total embodied energy consumption.

1. Introduction

Building-related energy problems are the main concern in China. The entire construction industry is identified as one of the major energy consumers in China's economy. The high-speed growth rate of urbanization in China produces high energy demand in future decades, continually increasing the stress on the environment, healthcare, and economy (Liang et al., 2016). In fact, the construction industry was responsible for almost 30% of the total embodied energy consumption of China in 2007 (Hong et al., 2016a). This percentage is projected to increase with the acceleration of the urbanization process in China.

The importance of investigating the embodied energy consumption of buildings has been gradually realized by the research community due to its significant role in the creation of sustainability in the building sector (Emmanuel, 2004; Huberman and Pearlmutter, 2008; Jeong et al., 2012; Tucker et al., 1993). Regardless of extensive studies on the wide-range impact of building operation on life-cycle energy use (Scheuer et al., 2003; Van Ooteghem and Xu, 2012), the attribution and mechanism of the embodied energy consumption still remain unclear.

Moreover, the room for embodied energy improvement is also limited according to findings by Dixit et al. (2012). The consumption of embodied energy is a physical process highly related to material inventory flows (e.g., bill of quantity), which actually have been determined at the design or pre-construction stage; thus, the implications obtained from a post-construction energy assessment only play a fairly limited role in the embodied energy reduction. In addition, other motivations underlying the relevant investigations also include the lagging effect of the macro-level policy coordination. The effect of the macro-level reduction regulations may not be evident at the project level in a short period. Therefore, the research community has to seek solutions to mitigate the energy demand of newly built buildings by developing innovative reduction methods at the project level.

A vast body of work highlighting on the embodied energy assessment in the construction field has been conducted with different research scopes. Multiple efforts have been made at the industrial investigation based on the national average data and public statistics, which are beneficial for framing the overall skeleton of the sectoral energy performance and identifying the promising areas with the leading energy saving potential (Acquaye and Duffy, 2010; Chang et al., 2010; Hendrickson and Horvath, 2000; Huang and Bohne, 2012; Nässén et al., 2007). The project-level investigation mainly focused on the life cycle energy performance of a specific building. These findings provide implications either on identifying energy-intensive materials and components during the building construction process (Asif et al., 2007; Jeong et al., 2012; Ortiz et al., 2010; Van Ooteghem and Xu, 2012) or examining the effect of adopting innovative construction technologies on the total embodied energy use (Aye et al., 2012; Hong et al., 2016b; Monahan and Powell, 2011; Rincón et al., 2013).

A sufficient number of studies have been undertaken to develop assessment methods for embodied energy quantification, which mainly include four primary approaches (Dixit et al., 2012). Statistical analysis is a traditional method to estimate energy consumption based on historical data (Hong et al., 2016b). It requires a more consistent and sufficient data source, which is unfortunately rare in the construction field. The process-based model is built based on the accumulation of the resource and energy use in the different life cycle stages. Such additive process largely depends on the step-by-step data collection, which is time and cost consuming. Moreover, the subjective determination of the system boundary may also cause truncation errors and variations. The input-output (I-O) model quantifies the energy consumption by integrating energy flows into sectoral monetary transactions in the I-O table. The utilization of the I-O table enables decision makers to measure all the infinite interconnections in the entire economy, but results in the lack of product specificity owing to the use of the national average data. The hybrid model is developed to address the weaknesses of both the process-based and I-O models. The scientific basis of this model is

to integrate process-based inventory flows into the I-O derived value, which enables the analyst to incorporate the detailed process information within a complete system boundary (Bullard et al., 1978; Joshi, 1999; Suh and Huppes, 2005).

After comprehensively reviewing the recent development of the embodied energy assessment in the current construction field, a number of gaps, which impede a more accurate assessment of the embodied energy consumption of buildings, are identified. First, most of the results from previous studies are irreproducible and incomparable in their reported values, primarily because of variations in computational structures (Crawford, 2008; Rowley et al., 2009; Sharrard et al., 2008; Suh and Huppes, 2005). Second, investigating building-level energy consumption needs a methodological framework that integrates multiple levels of inventory complexity and data specificity. Therefore, searching an appropriate interface in an objective and automatic way can ensure both the level of system completeness and assessment accuracy. Third, the effect of the regional characteristics was rarely considered in previous studies. The reported values of the embodied energy vary significantly within and across geographic regions due to differences in the local process data. Ignoring the regional disparities and technological differences may lead to misinterpretation of the actual energy consumption. Especially in China, an imbalance of economy between the eastern coast and the western interior exists. Regional construction activities may differ in terms of building materials, construction processes, and modes of transportation. Consequently, the regional productivity of a specific building being studied may be very different from the national average level. Such a difference may further exacerbate the errors between the simulated value and the actual consumption. Fourth, apart from spatial disparities, the temporal difference is another factor influencing the technological differences. Technological efficiencies of the same economy can vary in different years (Shao et al., 2014b).

Therefore, measuring these indices is crucial in obtaining robust estimations. To address regional disparities, some scholars built multiscale input-output analysis (MSIO)-based database to comprehensively account the embodied life-cycle carbon emissions of a building (Chen et al., 2011; Han et al., 2013; Shao et al., 2014a). They extended the local economic I-O table with multi-scale external economic systems, which enables to capture the technological difference in embodied energy accounting of a building. However, this multi-scale system is designed for assessing embodied energy use of buildings in a specific region, with methodological restrictions on the multi-regional comparison. From a practical perspective, the embodied energy assessment is commonly undertaken after the completion of a certain project, thus missing an opportunity for timely improvement at the beginning stage. Moreover, given that a building is unique according to the specificity in design, structure, and the quantity of material use, assessment results and optimization strategies are irreproducible for other projects, thereby minimizing the environmental benefits from the embodied energy assessment.

Therefore, this study aims to establish an integrated framework for embodied energy accounting of a building by taking regional disparities and temporal differences into consideration. The contributions of this study include the following aspects: first, the findings can enhance the comparability of reported results with uniformed computational structure by objectively determining the interface between the process-based data and regional I-O data; second, this work provides insights into technological difference caused by regional characteristics and temporal effects in building embodied energy accounting.

The remainder of this paper is organized as follows: Section 2 introduces the basic methodology and the configuration of the integrated framework. Section 3 presents the basic profile of building cases and verifies the reliability and effectiveness of the developed framework. Section 4 presents the discussion and conclusions drawn from the study.

2. Framework development

The proposed framework comprises three calculative modules in which a set of coupled computation routines manage both process-based and regional statistical data to provide an overall picture of energy use embodied in the extraction of raw materials, manufacturing,

transportation, onsite work, and offsite services at the project level. The detailed information of each calculative module has been illustrated as follows.

2.1. Region-based sectoral energy intensity module

To reflect the effect of the regional disparities and temporal effects on energy intensity, this study initially employed a multi-regional input-output (MRIO) model with time-series data to quantify the sectoral energy intensity from the top-down perspective. The theoretical foundation of this model aims to use the sectoral monetary interconnections to simulate the environmental flows. This method provides a highly specific assessment that enables the researchers to measure the effect of the regional disparities on the environmental interactions (Chen and Chen, 2011a,b; Lenzen et al., 2004; Mäenpää and Siikavirta, 2007; McGregor et al., 2008). The specific computational process is provided in the Supporting information part I.

As a result of the time-series based MRIO analysis, this module contains the sectoral embodied energy intensity information of 900 sectors in total 30 regions in year 2007, 2010, and 2012, respectively, which can be utilized as a computational foundation to measure the sectoral energy contribution to a specific building by considering the regional characteristic and time-varying technological difference. By multiplying the total cost of a specific building, the embodied energy intensities of provincial construction sectors provide a possible solution to estimate the total embodied energy consumption at the project level. However, it is also expected to improve the accuracy of this sketchy estimation by integrating the case-specific process data in other modules.

2.2. Process-based energy intensity module

The methodology of MRIO is vital for ensuring the system boundary and providing regional and temporal information in the proposed framework, but in order to meet the needs on case specificity, this computation framework must be re-developed from the economy-wide scale to the scale of the project level. Therefore, the process-based inventory data are integrated to provide a more accurate assessment. Given that the MRIO-derived values are mutually exclusive, integrating the process-based inventory flows into the computational structure of the MRIO analysis is rational because the substitution of the MRIO derived values with the process-based data from a supply chain perspective may not result in the unwanted iterated effects on the rest of the model. Such incorporation provides analysts with access to detailed process information within a complete system boundary, which can improve the specificity and accuracy of the result. In summary, the process-based module should include two types of data according to the features of the building construction process, they are delivered quantity and energy intensity for each related construction activity.

2.3. Computational structure module

The computational structure module is the operating core of the proposed framework, which aims to build a mathematical foundation by integrating the case-specific process data into the multi-regional framework. The major challenge encountered in the integration process is to allocate the bottom-up process-based data into the top-down sectoral divisions within a manageable manner. Therefore, an algorithm is developed to allocate and substitute the process-based inventory data for the energy-intensive flows extracted from the MRIO model (See Fig. 1). The whole integration and allocation processes involve several sequentially nested steps. The first step is to conduct an overall calculation

of all energy flows induced by the construction industry (See Supporting information part I). The second one is to extract energy-intensive paths and identify key sectors through the regional supply chain (See Supporting information part II). The third step is the allocation of phase-based construction activities into the key sectors identified in each region and the substitution of the case-specific process data for the corresponding MRIO derived value in the computational framework (See Supporting information part III). This allocation process summarized in Table S2 in the Supporting information established a multi-regional based database that explicitly indicates the category, format, and source of data, offering a possible solution for combining multiple data sources. Consequently, the extent of the process-based data specified in a building can be determined intuitively after completing the allocation of the phase-based construction activities into the energy-intensive flows.

2.4. Framework configuration

Consequently, with the module integration and data consolidation, this study designed an integrated framework to measure the regional disparities and temporal differences in the embodied energy assessment of buildings. The entire framework comprised four separate functional layers (see Fig. 2). The input layer was designed to provide the basic building profile and material inventory information, including the location, building type, gross floor area, and total cost. The inventory data were mainly derived from the design drawings, project documents, and bill of quantities, reflecting the quantity information of typical construction activities. The integration layer aims to apply and integrate the methodologies and database that foster the theoretical fundamentals of how the entire framework develops and functions. The output layer is a set of outcomes that provide multi-scale embodied energy information for a specific building project. The fourth layer presents key users that can benefit from and apply this assessment framework. Project-related stakeholders (e.g., clients, contractors, project managers, suppliers, and so on) and policymakers can use this framework as a basic assessment and benchmark tool to inspect the embodied energy use at the project and regional levels.

2.5. Data preparation and consolidation

Three categories of data are collected for further consolidation. First is the time-series MRIO tables. The MRIO tables in 2007 and 2010 were collected from the Chinese Academy of Sciences. The MRIO table in 2012 can be obtained from the findings by [Mi et al. \(2017\)](#). All the MRIO tables provide the basic monetary flow of 900 sectors in 30 regions in China (including 4 municipalities, 4 autonomous regions, and 22 provinces). Second is the time-series sectoral direct energy consumption data obtained from two public sources: the provincial statistical yearbooks and the regional energy balance tables in the Chinese energy statistical yearbook. An assumption that the energy contributions of subsectors are proportional with their economic output has been made to map the statistical data into MRIO table given the inconsistent format between them. Third is the process-based inventory data for major construction activities identified in the integration process. Given that the process-based embodied energy intensities are critically important in the next-step analysis; thus, they have been extensively investigated from different sources in this study. A detailed review of 24 studies has been conducted in and out of China. The detailed data information is provided in [Appendix A](#). More specifically, the major factor causing the changes of process-based energy intensity is the specific techniques implemented in the manufacturing process. Therefore, this study adopted the energy intensity data representing the most typical production process for each construction activity.

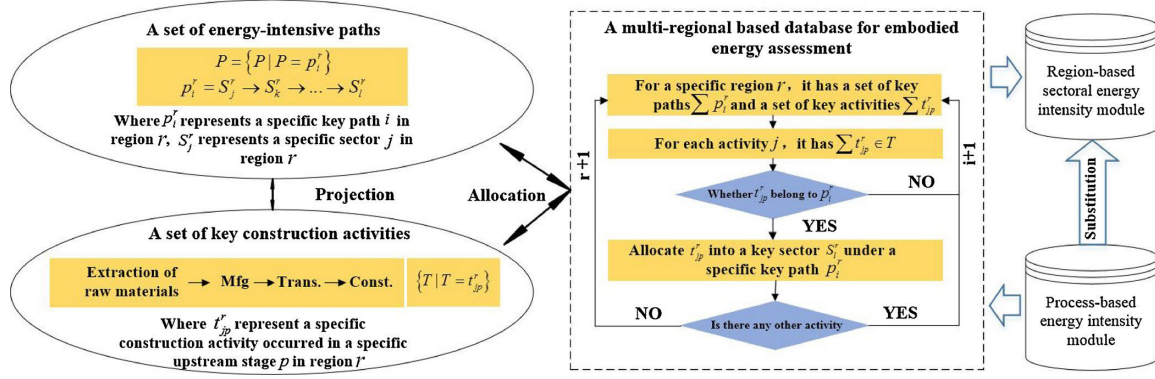


Fig. 1. An algorithm for the allocation and integration process.

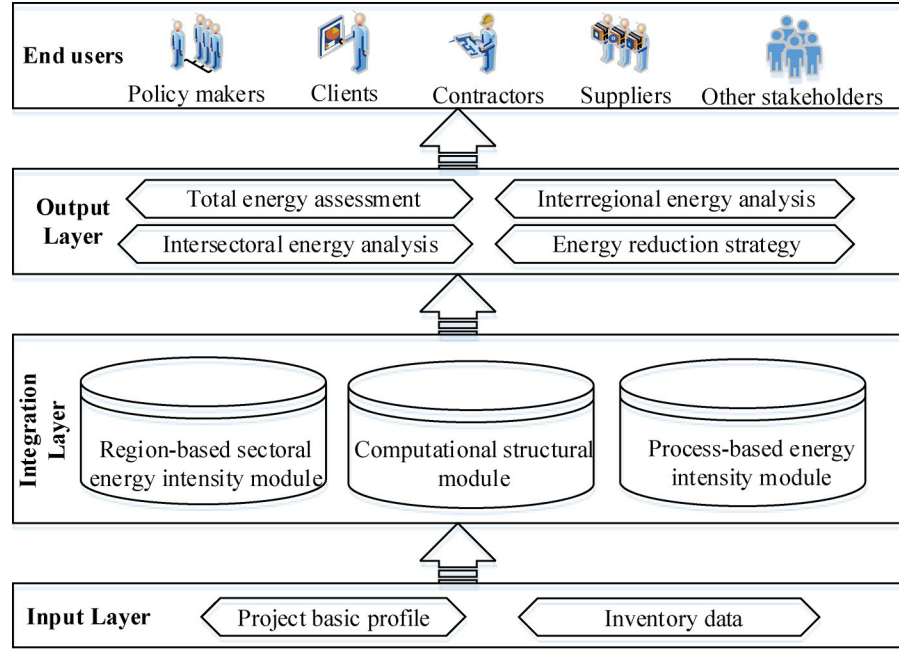


Fig. 2. A multi-regional framework in assessing the embodied energy of buildings.

3. Verification of the proposed methodology

To verify the reliability and feasibility of the default functions, this study applied the proposed framework in real building cases. The comparative analysis is designed to validate the reliability of the developed framework. The empirical analysis continues to verify the feasibility and effectiveness of the default functions.

3.1. Results of the comparative analysis

By comprehensively reviewing previous research, this study selected six building cases for the next comparison. Table 1 summarizes the basic building information, including the location, building type, structure, gross floor area, and the original method used in assessing the embodied energy consumption in each case. As most of the information of material suppliers was unavailable in previous studies, this study

conducted a scenario analysis to examine the impacts from changes of material origins on total embodied energy consumption by using all the 30 regions as alternative suppliers.

The results of comparative analysis have been shown in Table 2. Although a discrepancy still exists in the value obtained from the original studies and the proposed framework, they are still in the same order of magnitude. Owing to the integrated computational structure, the multi-regional framework was superior in the comprehensive consideration of infinite sectoral interactions through the entire upstream supply chain.

When the results are unscrambled from a spatial perspective, the sample buildings in the regions with a higher level of economic development and production efficiency (e.g., cases 2 in Jiangsu and 3, 4,

Table 1

Basic profile of different buildings.

Case	Location	Building type	Structure	Gross floor area (m ²)	Method	Source
		Office				Chang et al. (2012)
1	Hebei		Frame-shear wall	49166	Hybrid LCA	
2	Jiangsu	Office	Brick-concrete	1460	Process-based	Li et al. (2013)
3	Beijing	Office	Reinforced-concrete frame	35685	BEPAS	Zhang et al. (2006)
4	Beijing	Residential	Frame-shear	7000	Process-based	Gu et al. (2006)
5	Beijing	Residential	Brick-concrete	5050	Process-based	Zhong (2005)
6	Beijing	Residential	Reinforced-concrete frame	26717	Process-based	Zhong (2005)

Table 2

Results of comparative analysis.

	Original results (GJ/m ²)	Multi-regional framework (GJ/m ²)			Gap (%)		
		07	10	12	07	10	12
Case 1	6.46	14.03	10.50	10.24	117.2%	62.5%	62.5%
Case 2	4.31	3.91	3.23	2.43	−9.3%	−25.1%	−43.6%
Case 3	4.49	5.94	3.88	3.86	32.3%	−13.6%	−14.0%
Case 4	4.21	5.76	4.05	4.02	36.8%	−5.8%	−4.5%
Case 5	4.17	5.25	3.56	3.55	25.9%	−14.6%	−14.9%
Case 6	7.50	6.81	4.78	4.76	−9.2%	−36.3%	−36.5%

5, and 6 in Beijing) represented lower values of energy intensity in comparison to the original results. In contrast, the modified results of the case in Hebei is higher than the original one. These gaps were due to the fact that the original results were calculated by utilizing energy intensity data at the national average level, while the implementation of the multi-regional framework enabled the measurement of the productivity difference caused by regional disparities.

From a temporal perspective, because of the improvements in energy efficiency and production structure, the embodied energy intensities for all cases were decreased from 2007 to 2012. It is worth noting that the decline rate during the period from 2007 to 2010 was higher than

the latter period. It is mainly because the former interval covered almost the entire period of 11th Five-Year Plan, where a number of mandatory targets for energy conservation in the nationwide were released.

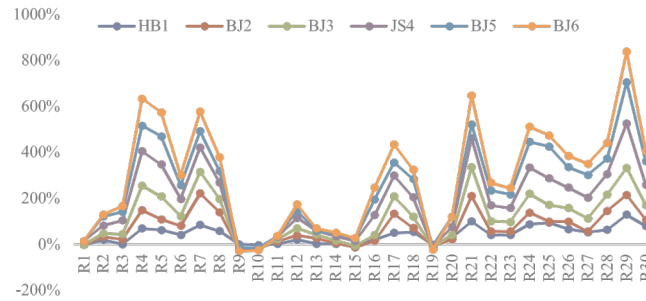


Fig. 3. Percentage changes of embodied energy intensity of case buildings with the change of material origins.

The results of a scenario analysis based on the embodied energy intensities obtained in 2012 were shown in Fig. 3. It can be found that with the change of material suppliers, the value of embodied energy intensity was fluctuated due to the technological disparities among different regions. Ningxia (R29), Hainan (R21), and Shanxi (R4) were three material origins with the largest embodied energy intensity of sample buildings.

In addition, the application of this integrated framework can also quantify the difference in the total embodied energy consumption induced by the changes of geographical location, building type, and structure. For instance, with the same building type and structure, the energy intensity of the office building in Hebei (Case 1) was much higher than that of office buildings in Jiangsu (Case 2) and Beijing (Case 3). Similarly, based on the same geographical location and building type, the buildings with frame-shear (Case 4) and concrete frame structure (Case 6) were more energy intensive than the brickconcrete structure (Case 5).

3.2. Results of empirical analysis

This section applies the framework into construction practice, with the aim of verifying the feasibility and effectiveness of the default functions in the actual building projects of China. Table 3 summarizes the basic building profile and inventory data of sample buildings. The buildings are located in Guangdong and Sichuan provinces where a remarkable gap exists in terms of economic development and production efficiency. The difference is expected to reflect the effects of the environmental diversity on the total embodied energy consumption.

Table 3

Building basic profile and project inventory data.

	Project 1	Project 2	Project 3
Location	Guangdong	Sichuan	Guangdong
Building type	Residential + commercial	Residential	Office
Structure	Reinforced concrete frame	Frame-shear	Reinforced concrete frame
Gross floor area (m2)	11508	6890	20105

Sand (t)	124.86	1202.90	216.25
Gravel (t)	4863.76		
Insulation (t)	158.27		
Paint (t)	1.13	29.85	1.80
Concrete (m3)	4443.45	4348.88	16736.95
Cement (t)	11,536.50	612.32	120.13
Glass (t)	86.03	21.4	189.44
Ceramic product (t)	14.65	10.20	
Plaster (t)	0.06		
Lime (t)	6.76		
Brick (t)	14.38	51.29	1730.40
Steel (t)	2286.19	331.81	1375.00
Aluminum (t)	29.65	48.59	86.00
Copper (t)	0.30	1.20	0.50

Table 4

Results of empirical analysis (GJ/m²).

	2007	2010	2012
Project 1	9.37	6.31	6.08
Project 2	7.33	6.18	5.70
Project 3	5.26	3.37	3.23

The inventory data of the primary materials in each target building were collected by referring to the project-related documents, including the bill of quantities, accounting receipts, stakeholder reports, and secondary data from the procurement agency. Apparently, with the same geographical location, project 1 was more steel-intensive than project 3 because of the construction of a commercial area where the weight of steel accounted for 12% of the total materials. Moreover, upon close examination of the construction-related documents, project 3 was awarded as the three-star green building in China. Clients adopted a number of green technologies during the building construction process. First, contractors were encouraged to use less energy-intensive materials wherever possible. Second, recycled materials were also widely applied to save energy, the ratio of which to total materials was 8.1%. Third, localized materials were dominant in the material supply chain. In fact, the weight of the materials supplied in the scope of 500 km accounted for almost 98% of the total weight. Such supply localization strategy can effectively reduce the energy consumption embodied in the transportation process.

The results of the empirical study from 2007 to 2012 were shown in Table 4. Similar with the results of comparative analysis, the embodied energy intensities of three target projects represented a declined trend during the investigated period with the value at 6.1, 5.7, and 3.2 GJ/m² in 2012, respectively. The outcomes from the output layer can be specified at the regional and project level. Taking the results obtained from 2012 for instance, this integrated framework is capable of providing insights into interregional energy transfers of a specific building. In

particular, by specifying the origin of the materials during the computational process, the developed framework can provide specific information regarding the energy distribution through the upstream supply chain, which is beneficial for the local government to alleviate the environmental pressure at the regional level by reallocating suppliers. According to Fig. 4, the energy suppliers of the target projects were localization dominant, where the local energy supply accounted for more than 80% of the total energy use. More specifically, the geographical connection and resource characteristic were the two factors that influenced the cross-regional energy transfers. For instance, Hunan and Guangxi, as the geographically closest neighbors of Guangdong, were major energy exporters to the project 1 and 3. Similarly, Henan and Shaanxi were the two major non-local energy suppliers for the target building in Sichuan due to their advantages in location and resources. A breakdown of the total embodied energy consumption by sectors indicated that the chemical industry (S12), manufacturing of non-metallic mineral products (S13), smelting and pressing of metals (S14), production and distribution of electric power and heat power (S22), and transportation, storage, posts and telecommunications (S25) consumed the largest amount of energy during the embodied phase of projects (See Fig. 5).

To explore the energy contribution from a specific type of building material rather than strictly following the sector classification, the integrated framework also provides an in-depth energy assessment of the primary materials in each sample building.

Project 1



Project 2



Project 3



Fig. 4. Inter-regional analyses of three building projects.

In Fig. 6, the distribution of the energy use embodied in materials was also consistent with the building characteristics. For instance, the energy use embodied in the steel production in project 1 accounted for almost 60% of the total energy consumption because of its steel-intensive features. The result obtained from the developed framework demonstrated that the energy use embodied in the transportation was around 5%, which was much higher than the expectation and other related studies (Thormark, 2000, 2002; Verbeeck and Hens, 2010). The main reason is that this study not only quantified the direct energy input in the material transportation process from the offsite factory to the construction site but also considered the indirect energy use embodied in the relevant transportation in the entire supply chain. In fact,

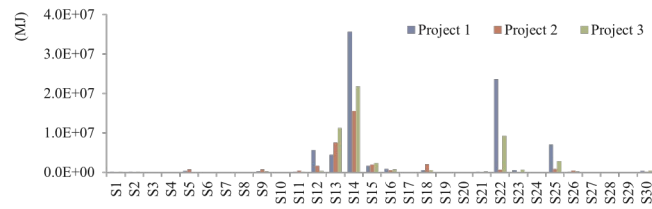


Fig. 5. Inter-sectoral analyses of three building projects.

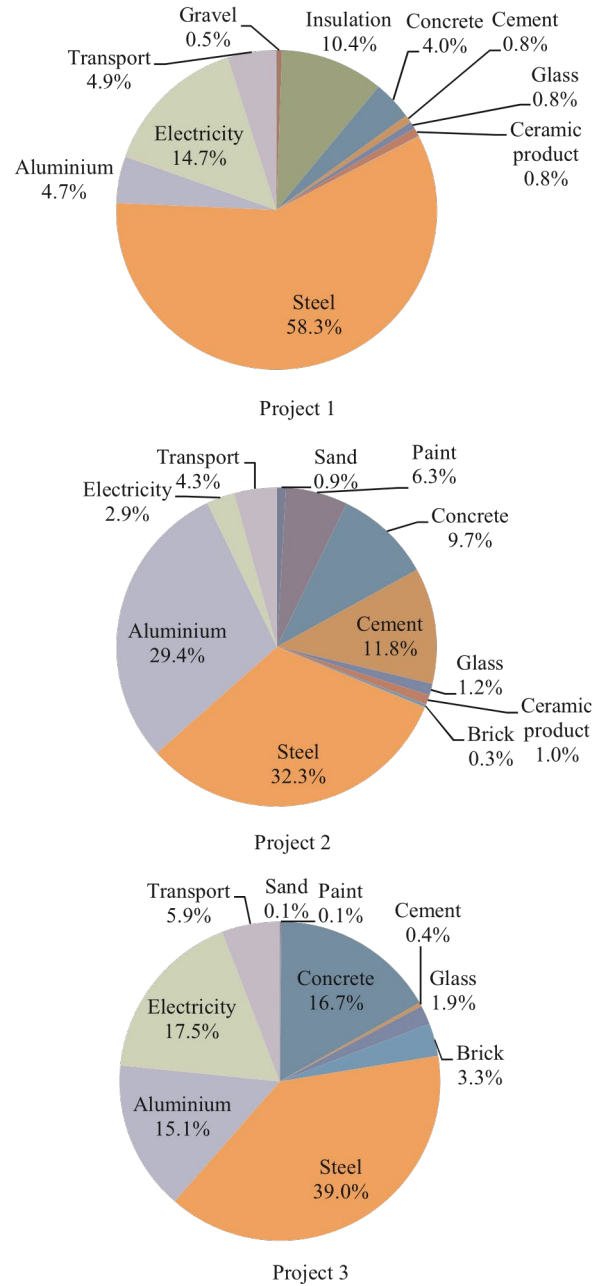


Fig. 6. Percentage of embodied energy use of construction materials.

such a proportion may be even underestimated because of the assumption that all the materials used in the target buildings were from local suppliers. The actual value can be larger when cross-regional procurement occurs during the building construction process.

In summary, the application of the integrated framework can reflect the essential impact from the use of materials, construction technologies, and geographical locations on the amount of embodied energy use.

The embodied energy intensity calculated for project 1 was almost twofold than that of project 3 because of the difference in the material composition, that is, higher content of steel in project 1. Similarly, the green features in project 3 further widened the gap of the energy intensity between these two projects. Moreover, the embodied energy intensity of the electricity supply in project 2 was much lower than that of the other two cases. The main reason is that electricity in Sichuan province is dependent, to a large extent, on hydropower generation, which is a more carbon-clean and energy-efficient technology in comparison to the coal-powered method. Such geographical resource feature was also measured in the integrated framework.

4. Discussions and conclusions

In China, where an economic imbalance between the eastern coast and western interior exists, the regional productivity of a specific building being studied may be significantly different from the national average level. The benefits from such multi-regional investigation can be inspected according to different types of stakeholders.

The local government and clients can use this framework as a benchmark tool to quantify the embodied energy consumption of buildings. Such preliminary estimation can help policymakers identify the essence of energy-related problems and explore specific energy interaction information in the upstream supply chain. The application of the developed framework can also facilitate the measurement of the energy intensity baseline of the local construction industry by conducting benchmark studies. This statistical foundation gives an implication of the current energy consumption status of local buildings. Given the different levels of energy intensity, the local government can provide a specific financial support plan with different levels of subsidies for new buildings. Such an incentive can cause a rapid return in the cash flow of the clients, which is important for the operation of their companies. For contractors, the results of the embodied energy analysis can provide an understanding of the energy consumption from the regional and sectoral perspectives. Such exploration could help project managers establish an overall energy flow map for the target project, and provide possible alternatives to further reduce energy use by reallocating the origins of materials.

Therefore, the multi-regional framework is an effective tool to preestimate the embodied energy use at the design stage of a specific building, which could provide incentives to industry practitioners to consider sustainability.

This study developed an integrated framework that illustrated how the technological difference and the regional features are calculated as indices of embodied energy quantification at the project level, using multi-regional input-output (MRIO) analysis, structural path analysis (SPA), and process-based LCA model as the underlying methods. The key findings are as follows:

- (1) An algorithm was designed to integrate the process-based inventory data into the regional average data in the MRIO model, which can both reflect the regional characteristic and project specificity in the result of the energy assessment.
- (2) A multi-regional based database was established to improve the compatibility of multiple data sources in embodied energy assessment by employing uniform data format and transparent data sources.

- (3) The developed framework enables the exploration of the “hidden” energy suppliers that were theoretically ignored because of the cutoff rules in the process-based analysis. According to this study, apart from the energy consumed in the extraction of raw materials, energy production and service sectors in the high-order upstream stages accounted for a significant proportion of the total energy use.
- (4) The multi-regional feature of the framework can provide valuable information on the inter-regional and inter-sectoral energy transfers of a specific building, and reflect the effects of changes in the geographical location, building type, and building structure on the total embodied energy consumption.

In summary, the developed framework provided a uniformed computational structure from a multi-regional perspective, enhancing the comparability of reported values among different regional contexts. The energy-intensive paths extracted through SPA can facilitate researchers to determine the interface of case-specific data and regional I-O data in an objective and automatic way. More importantly, the findings of this study can address the discrepancy in building energy assessment caused by regional disparities and temporal differences in China, which

Appendix A. Review of process-based energy intensity

See [Tables A1–A3](#)

Table A1

enables policymakers and practitioners to adopt specific energy conservation actions at the project level.

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Review of process-based energy intensity for primary materials in the building construction.

	Concrete (GJ/m ³)	Cement (GJ/t)	Steel (GJ/t)	Glass (GJ/t)	Aluminum (GJ/t)	Insulation (GJ/t)	Ceramic tiles (GJ/t)	Brick (GJ/t)	Plaster (GJ/t)	Lime (GJ/t)	Copper (GJ/t)	Paint (GJ/t)	Sand (GJ/t)	Gravel (GJ/t)
Li et al. (2013)	1.6	5.5	29–32.8	16	180		15.4	2	3.8	5.3	71.6		0.6	0.2
Zhang et al. (2009)		6.8	34.5	19.9				2.1	2.6	5.7				
Gu et al. (2006)		5.5	29	16	180	117	15.4			7.8	70	61.5		0.2
Gong (2004)		2.3–3.6	24.7–32.8	24										
Zhao et al. (2004)	1.6	5.5	29	16	180	117	15.4	1.2–2.0	6	0.1	71.6	60.2	0.6	0.2
Zhong (2005)	1.6	5.3	26.5	17.6	421.7		29.4	2	3.8	5.3	71.6	77.6	0.6	0.9

Yang (2009)	2.5	7.8	56.6	14.1		90.3		2	2.9	6.2			
Huberman and Pearlmutt (2008)	1.15		35	18	211	116		1.08					0.79
González and Navarro (2006)	1.2		32	16	191	117	2.5		6.1				2.5
Scheuer et al. (2003)		3.7	28	8	207	94.4	5.5	2.7		0.1	71.6	60.2	0.6 0.2
Kofoworola and Gheewala (2009)	1.3	3.6	22.1	18	216.5		2.2	1.9			81.5	0.2	0.1
Asif et al. (2007)	1.0–1.6	5.8	35	16	191–227			1					
Bribián et al. (2011)	1.1	4.2	24.3	15.5	136.8	103.8	15.6	2. 2-6.3			35.6		
Thormark (2001)	1.6		23	18.6	180	120		3.1	6		71.5	29.5	0.005 0.005

Table A2

Review of process-based eneration										
i	Region	Year	Average	Coal	Oil	Hydro	Nuclear	Natural gas	Wind	
EPD (2008)	Hong Kong	2007	6.425							
May and Brennan (2003)	Australia	2003		12.704				5.771		
Vattenfall (2005)	Sweden	2005	0.068	7.778	6.2	0.056	0.034	4.622		0.135
Phumpradab et al. (2009)	Thailand	2009		7.778				6.087		
Lee et al. (2004)	Korea	1998	5.185							
	Japan	1997	4.283							
	Europe	1994	4.960							
Gagnon et al. (2002)	Canada	2001		11.836	8.770	0.023	0.169	4.994		
EURELECTRIC (2011)				11.283	9.469	0.045	0.18	5.287		0.135

Table A3

Energy intensity for different transportation methods.

Source	Transportation method	Energy intensity (MJ/tkm)
Ecoinvent v2.0	Lorry 3.5–7.5t	7.44

	Lorry 7.5–16t	3.29
	Lorry 16–32t	1.89
	Lorry > 32t	1.32
Zhong (2005)	Road transportation (gasoline)	3.04
	Road transportation (Diesel oil)	2.06
	Rail transportation	3.05
Yang (2009)	Road transportation	5.45
	Rail transportation	2.09

Appendix B. Region division and sector classification in the MRIO table

Tables A4, A5

Table A4

Region division.

	Region
R1	Beijing
R2	Tianjin
R3	Hebei
R4	Shanxi
R5	Inner Mongolia
R6	Liaoning
R7	Jilin
R8	Heilongjiang
R9	Shanghai
R10	Jiangsu
R11	Zhejiang
R12	Anhui
R13	Fujian
R14	Jiangxi
R15	Shandong
R16	Henan
R17	Hubei
R18	Hunan
R19	Guangdong
R20	Guangxi
R21	Hainan

R22	Chongqing
R23	Sichuan
R24	Guizhou
R25	Yunnan
R26	Shaanxi
R27	Gansu
R28	Qinghai
R29	Ningxia
R30	Xinjiang

Table A5

Sector classification.

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

(continued on next page)

Table A5 (continued)

	Sector
S25	Transportation, storage, posts and telecommunications
S26	Wholesale trade and retail trade
S27	Hotel and restaurants
S28	Tenancy and commercial services
S29	Research and experimental development
S30	Other services

Appendix C. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.resconrec.2018.06.016>.

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