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# A multi-regional based hybrid method for assessing life cycle energy use of buildings: A case study

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Abstract

Although sustainable development in the construction industry has attracted much attention, relevant studies on the regional scale analysis of industrial energy performance are still rare in China, especially for Guangdong province, which is currently on the frontier and fast track of national low-carbon development. In response, this study integrates a multi-regional input-output method with fieldbased operational data to quantify the total embodied energy consumption and energy transfers from the construction industry and assess the life cycle energy use of residential and office buildings in Guangdong Province. The results show that the embodied energy consumption of the provincial construction industry is localization dominant and fossil fuel oriented, which accounts for approximately 18.6% of the total regional energy consumption. The geographical connection and resource characteristic are the two factors that influence the interregional energy transmissions induced by construction activities in Guangdong province. The result of uncertainty analysis indicates that the mean value of energy intensities simulated by Monte Carlo simulation is highly consistent with the deterministic results. It is crucial to improve the accuracy of the input-output analysis by providing sufficient economic information. At last, a number of recommendations are given through the technology, product, and management aspects at the industrial and building levels. The local government and construction department can benefit from implementing such environment-friendly, technology innovative and multi-disciplinary solutions in the full-process management and improvement of energy reduction of buildings.

1. Introduction

The construction industry is attracting increasing attention as a significant contributor to global energy consumption and carbon dioxide ($CO_2$) emissions. The building sector consumed more that 40% of global primary energy and about 30% of global greenhouse gas emissions from human and economic activities in its materials production, construction, use, maintenance, and demolition phases (Baum and Council, 2007; Dixit, 2016; Dixit et al., 2012; Metz et al., 2007). In addition, the operational energy use of buildings accounts for 20%e40% of the total national energy consumption in developed

countries (AIA, 2008; Perez-Lombard et al., 2008 ). However, all these figures considered the building sector in a fragmental manner, either excluding energy consumed in building operations or ignoring energy embodied in the materials production and transportation phase. Meanwhile, as the largest primary energy contributor in the world, China faces enormous environmental challenges in the process of rapid urbanization, which has inevitably impeded the pace of sustainable and ecological development in the modernization of China. Apart from this, the construction sector consumes approximately 30% of the total national energy consumption, half of which is attributed to the building materials production process (Hong et al., 2016a, 2016c). There is also an imbalance of economy between the eastern coast and the western interior in China, where regions may differ regarding materials production, construction processes, and modes of transportation. Consequently, the life cycle energy simulation of buildings may be very different at the regional level. However, relevant discussions on the regional scale, such as potential significance and growing roles of the regional construction industry in the national energy conservation process are still rare studied.

On the other hand, Guangdong province, as one of the most important provinces regarding its GDP contribution and geographic location, also significantly influences the progress of sustainable construction in China. Table 1 summarizes the current sustainability achievements and the crucial role of Guangdong province in advancing sustainable development in China. It can be seen that apart from the economic contribution and high-speed urbanization, Guangdong is also on the frontier and fast track of low-carbon development in China, being a pilot area in several national energy conservation and emission reduction projects. Therefore, a success assessment of life cycle energy use of buildings in Guangdong province can contribute to the promotion of specific building energy codes, avoid the failure from traditional policy instruments, and provide engines of further energy optimization in buildings at the regional level. Such an understanding is also vital to further mitigate the increasing energy demands arising from the accelerated urbanization process and help local decision makers in developing effective energy reduction policies.

This study aims to develop a hybrid method to evaluate the life cycle energy performanceofbuildingsinGuangdongprovincebyalso considering geographical features and technological differences, thus providing a holistic understanding of energy use behavior of both regional construction industry and buildings. A multi-regional inputoutput (MRIO) model is therefore applied to manifest the geographical boundary and technological differences between Guangdong province and other regions. This method provides a solution to quantify inter-sectoral and inter-regional energy flows from a top-downperspective (Chen and Chen, 2013; Hong et al., 2016a). By taking account of regional characteristics and sectoral differences, MRIO model has been extensively studied within different research scopes. Most of the studies have focused on quantifying energy consumption and carbon emissions embodied in international trade

(ChenandChen,2011a,2011b;HertwichandPeters,2009;Hongetal., 2017; Lenzen et al., 2004, 2013). These studies measured environmental burdens from a global perspective while remaining the challenge of understanding sustainable strategies from a regional level. In particular in the context of China, the relevant studies are relatively rare. Guo et al. (2012) applied an MRIO model to quantify $CO_2$ emissions and simulate the basic emission flows in China. Su and Ang (2014) developed a hybrid multi-region model to provide insights for interregional $CO_2$ emissions. Chen and Chen (2015, 2016) conducted a series of investigations by combing MRIO method and network analysis. At the regional level, they developed a hybrid network model to track interregional carbon flows in the Jing-Jing-Ji Area. At the urban level, by employing energy flow analysis, inputoutput (I-O) analysis, and ecological network analysis, they quantified urban energy consumption of Beijing to reinforce a better understanding of sustainable energy use from different insights.

Table 1

| Aspect | Source | Content |
| --- | --- | --- |
| Economic contribution | Guangdong Statistic Yearbook 2016 | The construction and real estate industries together contributed 10.4% of provincial GDP in 2015. |
| Urbanization rate | Annual Report of Housing and Urban-Rural Development in Guangdong Province | The urbanization rate in Guangdong province reached the highest in China in 2013, increasing from 16.3% in 1978 to 67.8% in 2013. |

| | | |
|---|---|---|
| Low carbon strategy | National Development and Reform Commission | C The first batch of selected localities in "low-carbon province and low-carbon city" national experimental project<br>C Largest number of ecological towns in China |
| Green building strategy | C Annual Report of Housing and Urban-Rural Development in Guangdong Province | C In 2014, Guangdong had 151 green buildings with the completed floor area of 16.5 million square meters. |
| | C TheOrdinance on Energy Conservation of Buildingsin Guangdong Province | C One of the top provinces (2nd) with the largest cumulative and annual floor areas of green buildings in China. |

Current role of Guangdong province in achieving sustainable construction in China.

In this study, two types of buildings, namely residential buildings and office buildings, are considered in life cycle energy quantification in Guangdong province due to their increasing importance in achieving sustainable construction in the construction industry. According to the International Energy Agency (IEA), the residential and commercial sectors accounted for almost 40% of the final energy use in the world, with the major part of this energy being consumed in buildings (Birol, 2010). In fact, the total floor area of office buildings completed in China increased from 69.3 million $m^2$ in 2000 to 204.9 million $m^2$ in 2012, representing an annual increase rate of 10.4% over the past decades (NBSC, 2013). The completed gross floor area of residential buildings in 2012 accounted for 65.4% of all completed building floor area and is responsible for more than 60% of the total economic output of the construction industry (NBSC, 2013). Such a rapid growth rate has a significant effect on the amount of energy used in both the production process and the daily operation of buildings. Therefore, this study utilized a multi-regional based hybrid method to provide geographical and methodological solutions for a life cycle energy assessment of buildings at the regional level. The specific objectives are as follows:

(1) To quantify the total energy consumption and energy transfers of provincial construction industry from the sectoral and regional perspectives;
(2) To develop a multi-regional based hybrid method to assess life cycle energy consumption of buildings at the regional level;
(3) To provide specific policy implications by considering the energy consumption features of buildings in Guangdong province.

The remainder of this paper is organized as follows: Section 2 describes the basic methodology and data collection process in the study, Section 3 discusses the energy simulation results of the provincial construction industry as a whole and the specific results for residential and office buildings. An examination of effects from data quality, sector aggregation, and result's reliability is presented in Section 4. The implications for policy are discussed in Section 5, while Section 6 concludes the study.

## 2. Methodology

## 2.1. Hybrid model development

This study utilizes a multi-regional input-output (MRIO) model to simulate the embodied energy consumption of the construction industry in Guangdong province and calculate embodied energy intensity for residential and office buildings. The construction industry defined in the MRIO table is composed of building construction, civil engineering construction, installation and decoration; covering the entire range of on-site construction activities. The results of MRIO analysis can provide holistic insights into the regional and sectoral interactions through the whole supply chain of the construction industry, which is beneficial for policy makers to understand the "hidden" inter-regional energy connections induced by construction activities in Guangdong province. This method provides a highly specific assessment that enables researchers to measure the effect of the regional disparities and technological differences on the environmental interactions.

Consequently, a hybrid method is proposed to explore the lifecycle energy performance of residential and office buildings in a given region (e.g. Guangdong province). First, the MRIO analysis is used to investigate the total energy consumption during building embodied phase. Then operational data obtained from the field survey are used to calculate energy consumption during the building use stage, with secondary data from previous research being used to calculate the energy intensity of the building demolition phase.

The physical balance of energy flows in the MRIO analysis can be expressed as:

m n

ari ori ¼ XXakj urkji þqri (1)

k¼1 j¼1

where $a^r_i$ is the embodied energy consumption per monetary unit (tonnes of coal equivalent (tce)/$10^4$ Yuan) of products from sector i in region r, $o^r_i$ is the total economic output of sector i in region r, $u^{rk}_{ji}$ is the monetary input from sector j in region r to sector i in region k, and $q^r_i$ is the direct energy use of sector i in region r. Let

OX ¼ ½is a diagonal matrix with the coefari 1mn, U ¼ ½urkji mnmn, Q ¼ ½qrifi1cients at a diagonal line equalmn and O ¼ ½ori mnmn where

to $o^r_i$ . Then (1) can be expressed in the form of a matrix:

X ¼ QðOUÞ$^1$ (2)

Subsequently, the embodied energy consumption per monetary unit of the regional construction industry $a^r_c$ can be extracted from the vector X, with embodied energy use per square meter

Eer ¼ arcorcsr (3)

where $E_e^r$ is the embodied energy intensity of buildings in the region r, $o^r_c$ is the total monetary output of the target type of buildings completed in the region r and $s^r$ is the completed area of the target type of buildings in the region r.

Additionally, the life cycle energy intensity of buildings can be expressed as:

E ¼ Ee þEo þ$E_d$ (4)

where E is the life cycle energy intensity, $E_o$ and $E_d$ represent the energy intensity of the building operation and the demolition phases, respectively. The operational intensity $E_o$ is calculated based on the process-based data collected from field investigation and $E_d$ is the secondary data obtained from previous research findings.

A hybrid model is therefore created for comprehensively evaluating the life cycle energy use of residential and office buildings in Guangdong province. The data sources and necessary procedures for implementing hybrid model are shown in Table 2 and Fig.1. The MRIO model is first applied to calculate the energy use embodied in the building material production and transportation phase. Then, the process data, including the operational data from field investigation and secondary data for the building demolition phase, are used to calculate the life cycle energy use of buildings.

Thepurposeof applying thefieldinvestigationdatainthebuilding operation phase is to address the uncertainties bundled in the assumptions before estimating the operational energy consumption in the traditional analysis. Most previous studies simulate the operational energy consumption by using the cooling and heating loads of buildings. However, operational energy use is determined by a large number of variables, such as the intended use of buildings, types of appliances, and occupant behaviors, which are uncertain and difficult to measure. Here, the actual usable floor area is adopted based on the building rental and vacancy rates, with real-time electricity use data to calculate operational energy consumption.

## 2.2. Data collection and processing

Two categories of data are required in this study. First is the latest available MRIO table compiled by the Chinese Academy of Science, which enables to reflect the monetary interactions of 30 sectors across 30 regions in the modern economy (Ichimura and Wang, 2003; Liu et al., 2012; Zhang and Qi, 2012). In a typical MRIO table, it contains 4 municipalities, 4 autonomous regions, and 22 provinces. Guangdong province is the target region where the local economy is connected to the national economic network by sectoral monetary flows. The second is the field investigation data that are obtained to reveal the real energy consumption behavior of occupants in Guangdong province. To holistically reflect energy performance during the operational phase, a field survey is implemented through the combined methods of site investigation, questionnaire and face-to-face interviews with senior property managers and other stakeholders associated with the target project. However, the collection of operational field data was relatively difficult, mainly because of their confidential nature for the property management company. Despite this, operational data were eventually collected from 17 residential buildings and 18 office buildings with the assistance of the local developers and the subordinate property management companies.

The questionnaire comprises three parts as summarized in Table 3. The first is designed to understand the basic information of the target building. The second part examines the major energyconsuming building service systems including air-conditioning, lighting, water supply system, elevator, and water heating system, which aims to explore the features of the sample buildings and establish the quantitative basis for energy simulation. The third part investigates the monthly electricity use data from 2008 to 2012 according to the categories of public lighting, central air conditioning, and household electricity use.

In summary, the original operational data from 2008 to 2012 are collected through mixed field survey methods (Appendix I and Appendix II). National and regional building design standards are used as supplementary documents to identify the design parameters of old buildings in case data are unavailable. The investigated buildings cover a broad range with different heights, gross floor areas, and building vintages. On the other hand, the structural framework, envelope pattern, basic design parameters, and building service systems are often similar to the same type of buildings. Therefore, the field investigation data could be regarded as the representative of typical residential and office buildings and could equally be applied to other buildings in a similar geographic climate in China.

## 3. Analysis of the results

### 3.1. Energy use embodied in the construction industry

Fig. 2 summarized the embodied energy consumption of regional construction industries in China. It can be found that

Table 2

Model and data sources.

| | Method | Data source | Energy type |
|---|---|---|---|
| Materials production and transportation | MRIO model | Chinese Academy of Science | Total energy |
| Construction | MRIO model | China Statistic Yearbook | Coal |
| Operation | Process-based analysis | Field investigation data | Coke |
| Demolition | Process-based analysis | Literature review | Crude oil |
| | | | Gasoline |
| | | | Kerosene |
| | | | Diesel oil |
| | | | Fuel oil |
| | | | Natural gas |

Electricity

Guangdong's construction industry consumed 84.2 million tonnes of coal equivalent (tce), accounting for approximately 18.6% of the total energy consumption in Guangdong Province. In contrast to other regional construction industries, Guangdong performed higher energy efficiency with the energy intensity being 23.3% lower than the national average level but suffered from heavier energy burden by consuming 61.0% more energy than the national average amount. Therefore, the primary driver behind the energy increase in Guangdong's construction industry was the large scale construction activities rather than the energy-intensive construction process.

A further decomposition of the total energy use in the construction industry has been shown in Fig. 3. Non-renewable primary energy dominated all energy types due to the large quantity consumed in producing building materials such as concrete, cement, and metals. The energy structure of the construction industry in Guangdong province is fossil fuel oriented, with coal being the largest contributortothetotal energyconsumption.Infact, coalandcrude oil were the primary fuelsused inmanufacturing cement and steel while cement (71%) and steel (22%) comprised 93% of the major building materials used in Guangdong Province in 2012 (NBSC, 2013). Such preference for the type of materials directly determines the energy consumption structure and the amount of energy use in the construction industry.

Fig. 4 represented the inter-regional energy flows induced by the construction industry in Guangdong province. First, it is worth noting that the embodied energy consumption was localization dominant, where the local energy supply accounted for more than 80% of the total energy use. On the other hand, in the cross-regional energy transfers, the geographical connection and resource characteristic were the two primary factors that influenced the interregional energy transmissions. For instance, Hunan and Guangxi, as the geographically closest neighbors, were major energy exporters to Guangdong province because of the convenience in material transportation. Yunnan, Sichuan, and Henan were also the primary energy suppliers due to their construction-related services (e.g. labor, finance, and real estate services) and abundant natural resources provided for Guangdong province. Fig. 5 summarized the primary sectoral energy input to the construction industry in Guangdong province. It can be found that the economic sectors

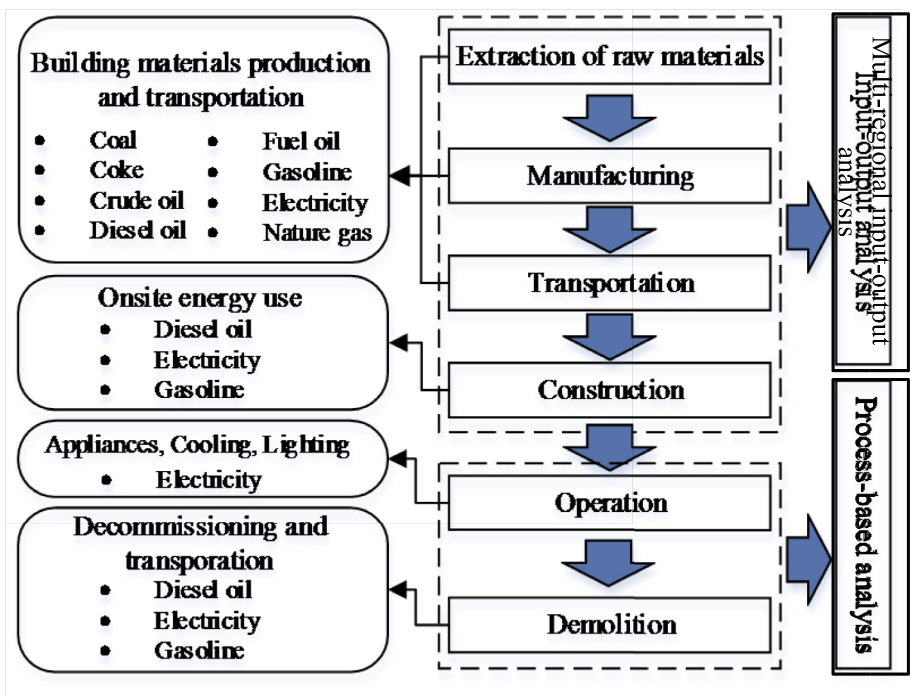



Fig. 1. System boundary and basic procedures for building life-cycle energy assessment.

Table 3

Description of the questionnaire.

| Part | Content | Office buildings | Residential buildings |
|---|---|---|---|

| | | |
|---|---|---|
| Part I | Basic information | Location, building age, gross floor area, rental rate, height, Residential type, location, building age, gross glass curtain wallfloor area, vacancy rate, external window type |
| Part II | Building service system | air-conditioning, lighting, water supply and drainage system, elevator, water heating system |
| Part III | Monthly electricity use data | public lighting, central air conditioning, household electricity use |

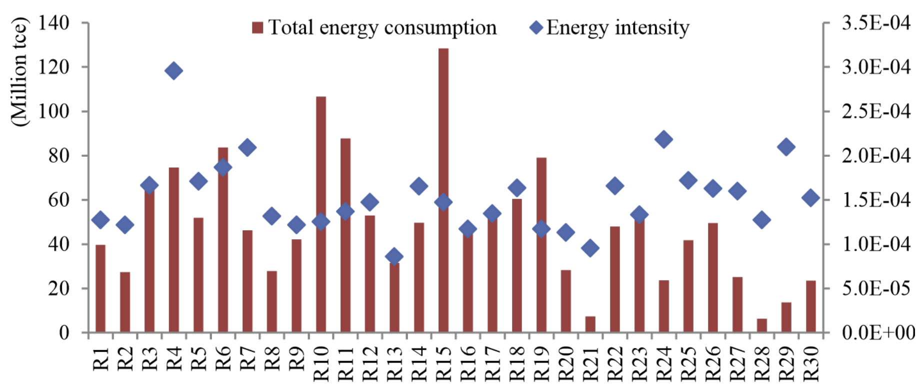



Fig. 2. Embodied energy consumption of regional construction industries in China (Please see Appendix I for more specific regional information).

closely associated with the building material production process, such as manufacturing of non-metallic mineral products, smelting and pressing of metals, manufacturing of metal products, and transportation sectors, accounted for a significant proportion of the total energy use in the construction industry of Guangdong province. The manufacturing of non-metallic mineral products and smelting and pressing of metals were the two major sectors supplying cement and steel for building construction, which together accounted for nearly half of the total embodied energy use of the construction industry.

### 3.2. Life cycle energy performance of residential and office buildings

#### 3.2.1. Embodied phase

The completed floor areas of residential and office buildings were 81.9 million $m^2$ and 7.5 million $m^2$ in Guangdong Province in 2012, with an economic output of 117.4 billion and 12.4 billion Yuan respectively (NBSC, 2013).

In general, energy consumed during building embodied phase is defined as the sum of the primary energy consumed by all of the processes relevant to the delivery of buildings, from the extracting and processing of raw materials to manufacturing, transport, administration, and product delivery. In particular, onsite energy consumption is the result of fuel consumed by onsite construction equipment and vehicles; energy input to onsite assembly and processing work; and electricity used in site lighting.

According to Table 4, residential buildings consumed 13.2 million tce in the materials production and transportation process which was almost ten times more energy than office buildings

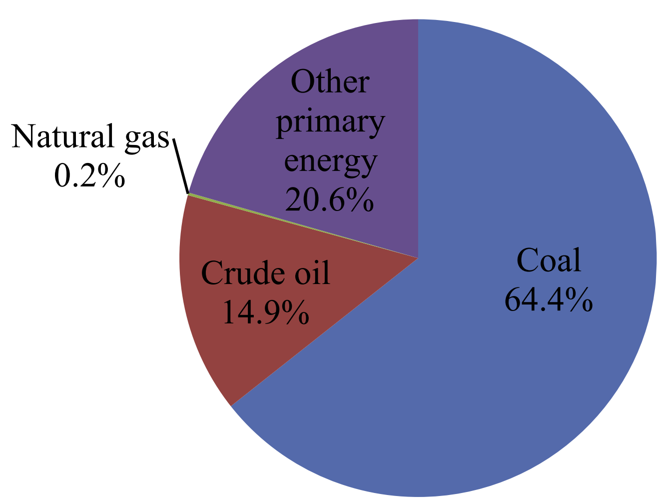


Fig. 3. Proportions of different energy sources in the construction industry in 2012.

because of their larger share of economic output in the construction industry of Guangdong province. The embodied energy intensity of residential buildings was 4.7 $GJ/m^2$, which was consistent with previous findings that ranged from 3.6 $GJ/m^2$ 8.8 $GJ/m^2$ (Ding, 2007). In addition, the embodied energy intensity of office buildings was 5.7 $GJ/m^2$, which was also in-line with the embodied energy intensity of office buildings derived in previous studies (3.5e11 $GJ/m^2$) (Kofoworola and Gheewala, 2009; Van Ooteghem and Xu, 2012; Xing et al., 2008). The direct onsite energy consumption was 529.4 thousand tce and 58.1 thousand tce for residential and office buildings, which were equal to 0.19 $GJ/m^2$ and 0.23 $GJ/m^2$ respectively. In this phase, coal, diesel oil and electricity were the most consumed due to the operation of constructionrelated daily activities such as on-site transportation, assembly, machinery operation and lighting.

### 3.2.2. Operation phase

The operation phase is the most critical stage during the lifecycle energy consumption of buildings. It has attracted much interest from the research community over the past years because of its huge proportion (40%e80%) in total energy consumption. However, it is difficult to provide an accurate simulation to reflect real energy consumption behaviors during this period. This is mainly because it is difficult for practitioners to make an appropriate and precise assessment of the critical impact factors that may affect real-time energy consumption during the building operational phase, such as the intended use of buildings, types of appliances, and occupant behaviors. Therefore, this study addresses this problem by using field investigation data collected from the practical operation of buildings. With assistance from local developers, five years of monthly-based electricity data are collected for each building. Given the actual usable floor area of buildings, the operational energy intensity can be calculated as shown in Table 5. The descriptive analysis of the collected data indicates that the year-on-year mean operational energy intensity is similar to a particular type of building. As Table 5 indicates, the office buildings consume more energy than the residential buildings during their operation phase.

Since all the buildings cover a broad range of floor area, height, and vintage, these empirical results can be regarded as representative of typical residential and office buildings in Guangdong province. In 2012, the operational energy intensity was 0.12 GJ/$m^2$ yr and 0.42 GJ/$m^2$ yr in residential and office buildings, respectively. According to the findings concluded from previous studies, operational energy intensity ranged from 0.14 GJ/$m^2$ yr to 2.4 GJ/$m^2$ yr for residential buildings (Blengini and Di Carlo, 2010a; Utama and Gheewala, 2008; Verbeeck and Hens, 2010; Zabalza Bribian et al., 2009) and 0.36 GJ/$m^2$ yr to 4.1 GJ/$m^2$ yr for office buildings (Ding, 2007; Scheuer et al., 2003; Van Ooteghem and Xu, 2012; Xing

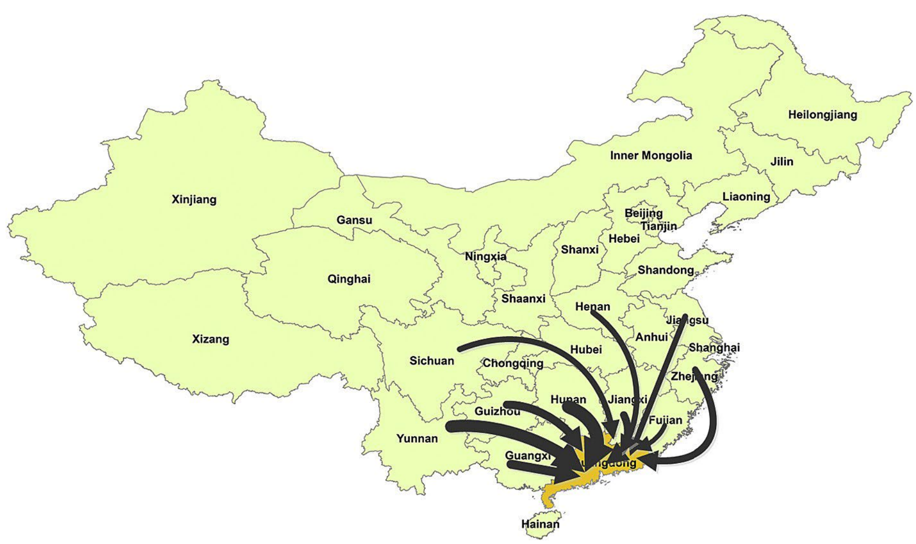


Fig. 4. Inter-regional energy flows induced by the construction industry in Guangdong province.

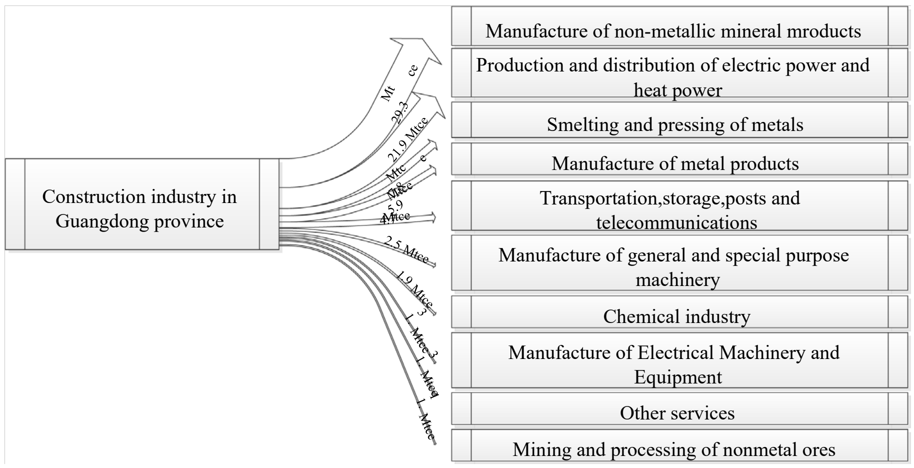



Fig. 5. Inter-sectoral energy flows induced by the construction industry in Guangdong province.

Table 4

Embodied energy consumption of residential and office buildings.

| | Residential buildings | | Office buildings | |
|---|---|---|---|---|
| | Energy consumption (Thousand tce ) | Energy intensity (GJ/m $^2$) | Energy consumption (Thousand tce ) | Energy intensity (GJ/m $^2$) |
| Materials production and transportation | 13 220.6 | 4.7 | 1398.4 | 5.5 |
| Construction | 529.4 | 0.19 | 58.1 | 0.23 |

et al., 2008). These field investigation data can be considered reliable and valid given that the heating system is rarely used in such warm winter areas as Guangdong province.

### 3.2.3. Demolition phase

Traditionally, the type of energy sources involved in the demolition phase mainly includes energy use embodied in the building deconstruction, transportation, recycle and reuse of materials, and landfill disposal. Variables such as the amount of recyclable materials, the use of on-site equipment, and distance from a demolition site and landfills may affect the value of energy intensity to a large extent in the demolition phase. Demolition practices are also influenced by the requirement of customers, contractor preferences and market regulations (Scheuer et al., 2003). Therefore, the calculation of demolition energy intensity suffers from a number of uncertainties. Moreover, public sources such as government reports and process data associated with building demolition process are rare. Only a very few studies focus on the quantification of the environmental load during the building demolition phase by using a detailed process-based life-cycle assessment (LCA) model. The secondary data are therefore used in this study to calculate the demolition energy intensity. Given the lack of data, the potential for energy saving from recycled and reused materials is not considered. Table 6 summarizes the demolition energy intensity calculated in previous studies.

It can be found that energy intensity varies widely with different building structures and locations. Considering the similarity in climate zone, building type and geographic location, the results calculated in case studies in Singapore and Hong Kong were used here as the energy intensity of the decommissioning process. Assuming the transportation distance to be 50 km in Guangdong Province, the transportation energy intensity calculated by Junnila et al. (2006) was adopted. In summary, the total demolition energy intensity was 85 MJ/m$^2$.

Table 5

Field-based operational data from 2008 to 2012.

| Year | | Residential building | | Office building | |
|---|---|---|---|---|---|
| | | kWh/m$^2$·a | GJ/m$^2$·a | kWh/m$^2$·a | GJ/m$^2$·a |
| 2008 | Mean | 30.67 | 0.11 | 131.97 | 0.48 |

| | | | | | |
|---|---|---|---|---|---|
| | Std dev | 13.94 | 0.05 | 34.94 | 0.13 |
| 2009 | Mean | 35.62 | 0.13 | 125.31 | 0.45 |
| | Std dev | 16.11 | 0.06 | 32.98 | 0.12 |
| 2010 | Mean | 36.02 | 0.13 | 121.13 | 0.44 |
| | Std dev | 17.54 | 0.06 | 31.06 | 0.11 |
| 2011 | Mean | 32.95 | 0.12 | 112.95 | 0.41 |
| | Std dev | 16.54 | 0.06 | 25.71 | 0.09 |
| 2012 | Mean | 34.67 | 0.12 | 118.35 | 0.42 |
| | Std dev | 15.24 | 0.06 | 28.12 | 0.10 |

#### 3.2.4. Life cycle energy use of office buildings and residential buildings

Under the assumption that the life span of residential and office buildings is 50 years, the percentage of energy consumption for each phase is represented in Fig. 6. Apparently, building material production and transportation and the operation phase together are the most energy consuming over the entire life cycle of buildings, accounting for approximately 95% of total energy consumption, while energy use embodied in the construction and building demolition phases is negligibly small (1.2e2.5%). More importantly, the energy consumed by office buildings was more operationdominant than the residential one, implying a larger energy reduction potential for such type of buildings.

According to the empirical data obtained from the interviews and questionnaire survey, some reasons can explain such difference in operational energy performance between residential and office buildings to some extent in Guangdong province. First, the types of external walls may vary according to different kinds of buildings. In fact, the concrete or block-made external walls in residential buildings performed much better in thermal coefficients such as heat conductivity and thermal transmittance, being more efficient than the glass curtain walls of office buildings regarding thermal insulation during the building operation phase (See Appendix II

Table 6

| Reference | Location | Building feature | Energy intensity (MJ/m²) | Transportation energy intensity (MJ/m²) | Feature |
|---|---|---|---|---|---|
| ATHENA (1997) | Canada | - Office building<br>- Steel structure | 130e220 | | Energy use of remove of structural systems |
| | | - Office building<br>- Steel structure | 350 | | Total decommissioning energy |
| Junnila et al. (2006) | Finland | - Office building<br>- Steel-reinforced concrete system<br>- Four floors with 4400 m² of gross floor area | 182 | 68.2 (Assumption of 50 km) | Energy use in equipment and transportation of materials |

| | | | | | |
|---|---|---|---|---|---|
| | | - Office building<br>- Steel-reinforced concrete system<br>- Five-story with 4400 $m^2$ of gross floor area | 750 | 42.8 (Assumption of 64 km) | Energy use in equipment and transportation of materials |
| Wu et al. (2012) | China | - University office building<br>- Reinforced concrete<br>13-floor building with 36,500 $m^2$ of gross floor area | 194 | | Energy use in equipment and transportation of materials |
| Kua and Wong (2012) | Singapore | - Commercial building<br>- Six-story with 52,094 $m^2$ of gross floor area | 17.4 | | Energy use in demolition equipment and tools |
| Chen et al. (2001) | Hong Kong | - Residential building<br>40-story with a usable floor area of | 16.1 | | Decommissioning energy |

| | | | | | |
|---|---|---|---|---|---|
| | | 39,040 $m^2$ | | | |
| | Hong Kong | - Residential building 40-story with a usable floor area of 26,600 $m^2$ | 17.6 | | Decommissioning energy |
| Scheuer et al. (2003) | United States | - Hall building - Six-story with 7300 $m^2$ of gross floor area | 548 | 198 (Assumption of 8e320 km due to different materials) | Energy use for decommissioning, demolition and transportation |

Building demolition energy intensity in previous studies.

and Appendix III). Second, given the difference in the function of these two types of buildings, the shading coefficient of residential buildings was higher than that of office buildings, which was also beneficial to the natural ventilation during the operation phase. Third, the use of electricity by the air-conditioning system played a significant role in daily energy consumption. Some old residential buildings adopted natural ventilation instead of equipping airconditioning, which may further lead to energy savings during the building operation phase.

Theoretically, life cycle energy analysis should be conducted under a uniform energy category (e.g. primary energy). However, it is still beneficial to take into account electricity and diesel oil consumption because they are the primary energy sources consumed during the building operation and demolition phases. Such manipulation provides a direct indication for their relative proportions, which may enable policy makers to improve their understanding of the energy consumption structure of residential and office buildings. Consequently, a more specific breakdown of the life cycle energy use is given in Fig. 7. This shows the dominance of operational electricity use in all types of energy sources, accounting for approximately 50% and 80% in residential and office buildings respectively, followed by coal and crude oil. Although the use of electricity is regarded as a carbon-clean process, electricity production in China mainly depends on coal combustion, which is certain to produce significant carbon emissions (see Table 7). Also, diesel oil from the demolition phase contributed 0.3% and 0.8% of total energy consumption. Other types of primary energy are mainly consumed in the building embodied phase. In summary, the life cycle energy use in residential and office buildings remains fossil fuel energy oriented, generating a significant adverse impact on the global environment.

## 4. Uncertainty analysis

### 4.1. Data quality

The transparencyand reliability of data used in this study require

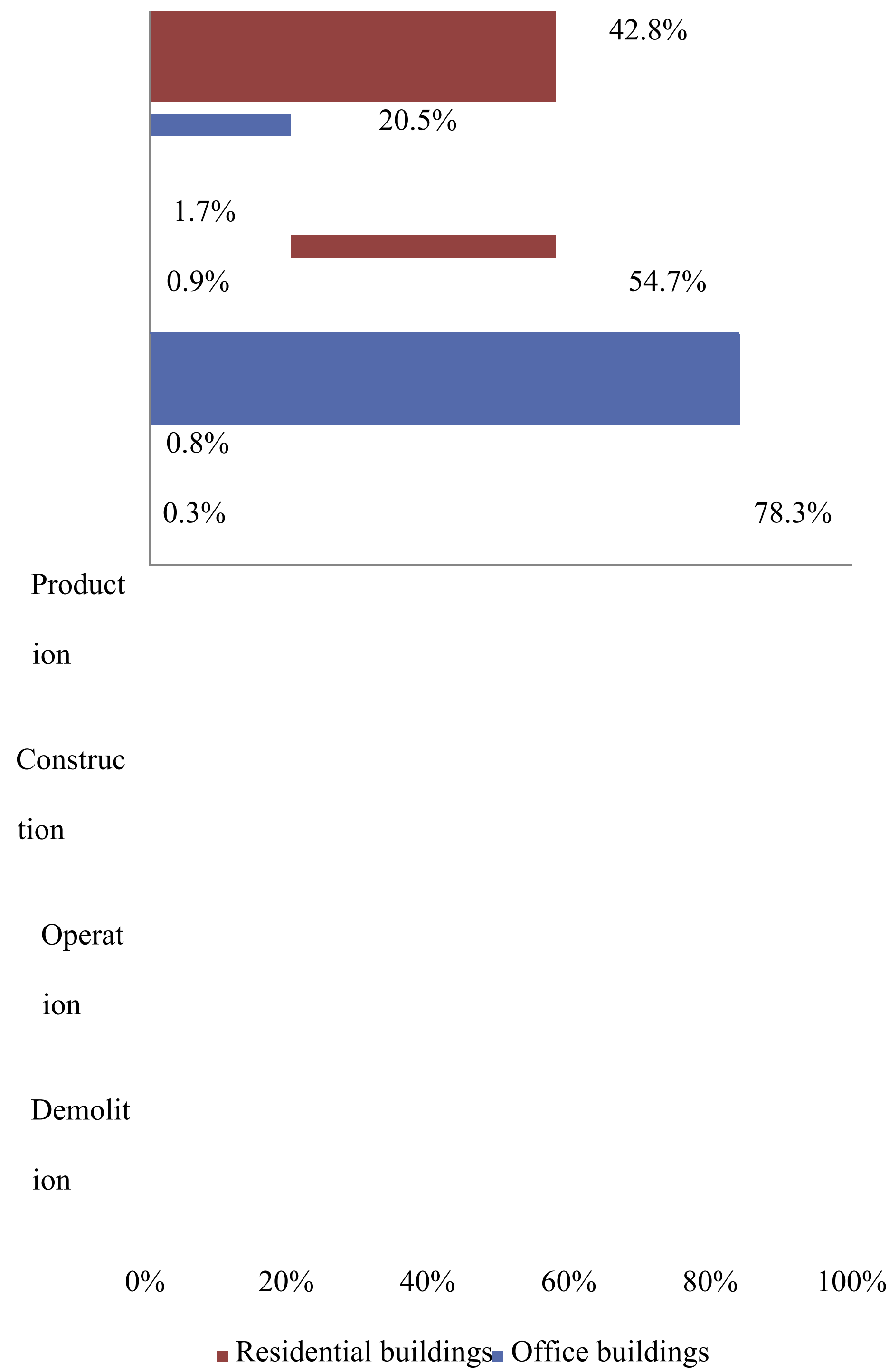



Fig. 6. Percentage of energy use in different phases of residential and office buildings.

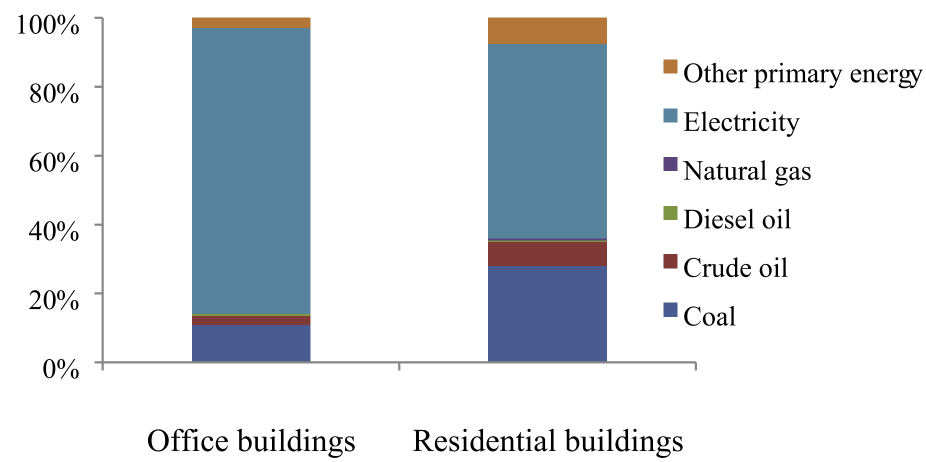



Fig. 7. Breakdown of the life cycle energy use of residential and office buildings.

Table 7

Electricity production by different methods.

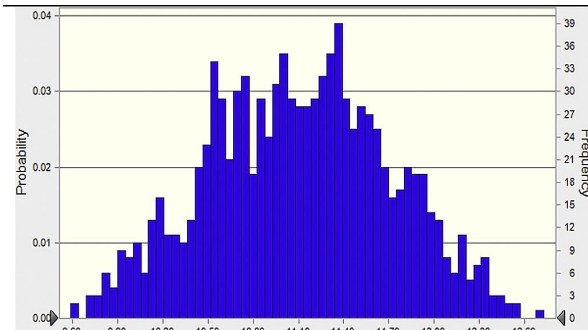
| Country | Total Production of Electricity (Million KWh) | Electricity Generation from Coal (%) | Electricity Generation from Oil (%) | Electricity Generation from Gas (%) | Electricity Generation from Hydro (%) | Electricity Generation from Nuclear (%) |
|---|---|---|---|---|---|---|
| China | 4,715,716 | 79.00 | 0.20 | 1.80 | 14.80 | 1.80 |

Source: China Energy Statistical Yearbook 2015

Table 8

Data quality assessment (5 ¼ maximum quality, 1 ¼ minimum quality).

| | Measurement method | Data source | Temporal correlation | Geographic Correlation | Technological correlation |
|---|---|---|---|---|---|
| Materials production and transportation | 4 | 5 | 4 | 3 | 2 |
| Construction | 4 | 5 | 4 | 3 | 2 |
| Operation | 5 | 4 | 5 | 5 | 4 |
| Demolition | 3 | 3 | 4 | 4 | 1 |



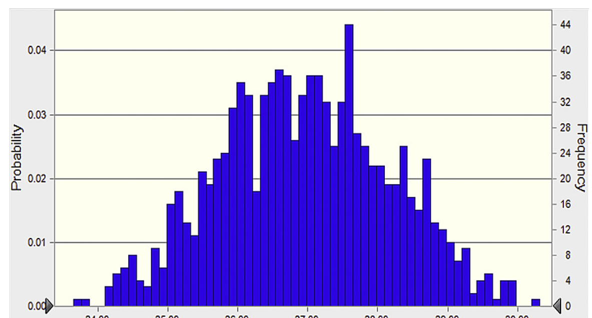




Fig. 8. Results of MCS for residential buildings. Fig. 9. Results of MCS for office buildings.

Table 9

Results of the sensitivity analysis.

| | 30-sector format | 42-sector format | 135-sector format |
|---|---|---|---|
| Residential buildings | 18.4% | 2.7% | 0.65% |
| Office buildings | 11.4% | 5.6% | 4.8% |

further examination to guarantee the accuracy and certainty of the final result. The MRIO model has weaknesses in both model preassumptions (e.g. proportionality and homogeneity) and data quality problems such as data age and applicability. Most of the monetary data used in the MRIO analysis are outdated because the MRIO table can only reflect the sectoral interrelationships and productivity in its publication year, which lags behind the current level of production technology. This temporal flaw may cause the underestimation or overestimation of the embodied energy consumption in material processing, transportation, and the construction process. In this study, the MRIO analysis is complemented with field-based process data. Therefore, conducting data quality assessment is necessary to validate the results. According to the uncertainty assessment methods introduced by Weidema and Wesnæs (1996), Wu et al. (2012) and Hong et al. (2016b), data quality can be evaluated in five categories (see Table 8). The results derived from the MRIO analysis have the advantage of boundary completeness while suffering from the disadvantage of outdated data and weak technological correlation. The operation data collected based on field investigation are restrictedbythe numberof samples. Although the data quality is relatively poor in the demolitionphase, such uncertainty is still acceptable because the building deconstruction process consumes only a slight amount of energy. To further quantify the uncertainty arising from data quality, this study employed a semi-quantitative method introduced by Hong et al. (2016b). This method combines both data quality index (DQI) and probabilistic approach to facilitate uncertainty assessment in a

Table 10

Summary of the life cycle energy consumption of different types of buildings.

systematic manner. Based on the subjective quality scores provided by experts, a probability distribution can be determined for a given activity (e.g. materials production, construction, operation, and demolition). Subsequently, the cumulative results, the coefficient of variation (CV), and confidence intervals for life cycle energy intensity of buildings can be determined by running Monte Carlo Simulation (MCS) in the Crystal Ball software. Figs. 8 and 9 show the results of MCS in calculating life cycle energy intensity of residential and office buildings. The mean values of MCS were 11.04 GJ/m$^2$ for residential buildings with a CV at 5.5% and 27.0 GJ/m$^2$ for office buildings with a CV at 4.5%, which were highly consistent with the deterministic results of 11.09 GJ/m$^2$ and 26.93 GJ/m$^2$ calculated in Section 3 in this study.

### 4.2. Sensitivity analysis

Data quality analysis can provide a subjective judgment for the overall uncertainties arising from the calculation process. Meanwhile, sensitivity analysis can build a quantitative basis for the reliability and validity of the results. According to the basic categories of uncertainty involved in the LCA process, the most sensitive factor influencing the accuracy of the results is the level of sector aggregation (Weber, 2009). In fact, the level of sector aggregation, which was determined subjectively before the analysis, directly affects the final results of the I-O analysis.

The I-O table is more specific on the sectoral monetary flows than the statistic energy input data in the provincial yearbooks. As a result, a sector disaggregation strategy has to be implemented to match these two systems. One strategy is to aggregate the I-O sectors to match the sectoral energy data in the statistic report, which has the advantage in avoiding additional assumptions but suffers from a weakness in missing detailed sectoral interaction information. An alternative is to disaggregate energy consumption

| Ref. | Year | Type | Place | Climate | Structure | Embodied energy (%) | Operation energy (%) | Life cycle energy (%) |
|---|---|---|---|---|---|---|---|---|
| [1] | 2004 | Ra | New Zealand | Temperate | Wood/concrete/ super insulated | 8.0 | 4.9 | 3.5 |
| [2] | 2009 | R | Italy | Subtropical | | 1.3 | 4.2 | 5.3 |
| [3] | 2009 | R | Spain | Subtropical | Masonry/steel frame house | 7.0 | 43.3 | 11.2 |
| [4] | 2012 | R | Belgian | Temperate | | 22.8<br>41.4<br>e | 673.4<br>113.3<br>179.6 | 350.4<br>40.0<br>e |
| [5] | 2008 | R | Indonesia | Tropical | Clay-based/cement-based | 65.2 | 128.3 | 38.1 |
| [6] | 2010 | Ra | Italy | Subtropical | | 81.0 | 159.2 | 48.0 |
| | | | | | Reinforced concrete frame | 192.9 | 11.7 | 84.4 |
| [7] | 2000 | Ra | Australia | Tropical þ Subtropical | Brick veneer | 199.4 | 150e | 161.9e |
| [8] | 2000 | R | Sweden | Temperate þ Subfrigid | Timber/concrete /clay based | 32.1 | e | |
| [9] | | R | | | | 34.1 | e | |
| [10] | | R | Germany | | Concrete/wood | 9.7 | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 201 | | Sweden | Temperate | | 23. | 140 | e |
| | 2 | | | Temperate | | 6 | 250.8 | e |
| | 201 | | | þ Subfrigid | | 5.1 | 79.2 | 62.0 |
| | 0 | | | | | 6.2 | | 134 |
| | | | | | | | | 41.7 |
| [1 | 200 | R | Canada | Temperate | Brick/wood | 8 | e | e |
| 1] | 9 | O | Sweden | þ frigid | intensive | 3 | 12.2 | e |
| [1 | 201 | O | China | Temperate | Reinforced- | . | 11. | 21.3 |
| 2] | 1 | O | Thailan | þ Subfrigid | concrete | 4 | 9 | 27.2 |
| [1 | 200 | | d | Subtropica | Concrete/steel | e | 2.2 | 11.5 |
| 3] | 8 | | | l | Concrete | 46.7 | 44.9 | |
| | | | | | | 29.0 | | |
| [1 | 200 | | | Tropical | | | | |
| 4] | 9 | | | | | 26.5 | | |
| [1 | 200 | Ob | Austral | Tropical þ | | 190.4 | 33.9 | 32.1 |
| 5] | 7 | O | ia | Subtropica | | 70.6 | 187.1 | 107.5 |
| [1 | 201 | | China | l | Reinforced- | | | |
| 6] | 2 | | | Temperate | concrete | | | |
| [1 | 201 | C | Canada | Temperate | Steel/timber | 62.6 | 321.9 | 176.9 |
| 7] | 2 | O | Spain | þ frigid | Blocks/masonry | 9.3 | 32 | 271.8 |
| | | | | | | 0.1 | 0 | 23.1 |
| [1 | 201 | O | Singap | Subtrop | | | | |
| 8] | 0 | | ore | ical | | 8.4 | 3.4 | 8.4 |
| | | | | Tropical | | 88.5 | 49.3 | 67.8 |

| | | |
|---|---|---|
| [1<br>9] | 201<br>2 | 51.5 |

Note: (1) “a” indicates that the target building studied in the original research is a green building; (2) “b” indicates that the data represented in this table is the average value of 20 secondary schools in Australia; (3) references include: [1] Mithraratne and Vale (2004); [2] Blengini (2009); [3] Zabalza Bribian et al. (2009) ; [4] Rossi et al. (2012); [5] Utama and Gheewala (2008) [6] Blengini and Di Carlo (2010b); [7] Fay et al. (2000); [8] Thormark, 2000; [9] Konig and De Cristofaro (2012)€ ; [10] Brunklaus et al. (2010); [11] Salazar and Meil (2009); [12] Wallhagen et al. (2011); [13] Xing et al. (2008); [14] Kofoworola and Gheewala (2009); [15] Ding (2007); [16] Wu et al. (2012); [17] Van Ooteghem and Xu (2012); [18] Rossello-Batle et al. (2010) ; [19] Kua and Wong (2012).

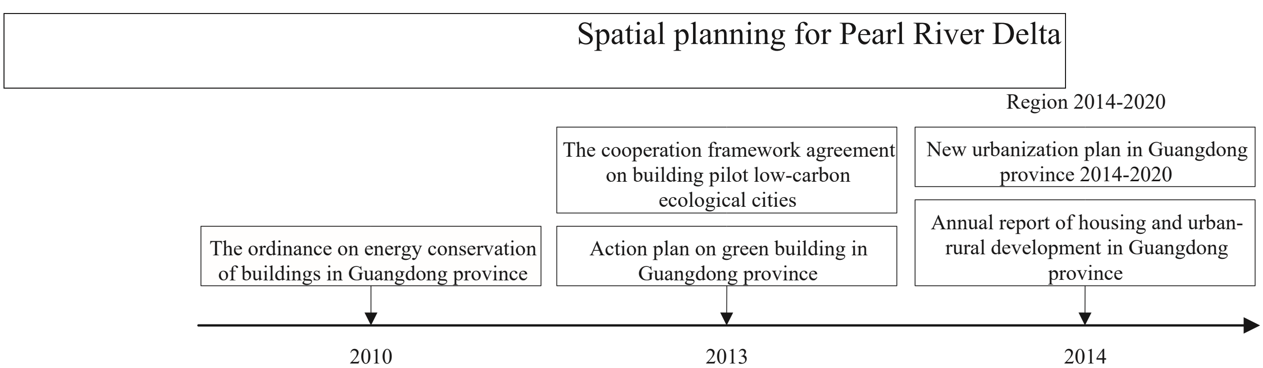



Fig. 10. Policy instruments in Guangdong province from 2010 to 2015.

Table 11

Recommendations for the local government and construction department.

| Industrial level | Building level |
|---|---|

| | | |
|---|---|---|
| Technology | C Use renewable and clean energy sources (e.g. nature gas, solar energy, shale gas, and biomass energy)<br>C Encourage technological innovation in energy-intensive sectors | C Green retrofit<br>C Efficient energy conversion and storage<br>C Precast construction |
| Product | C Advocate high value-added products<br>C Adopt low carbon/energy efficient materials | C Photovoltaic panel<br>C Energy saving appliance<br>C Solar water heater<br>C Modular component<br>C high-performance envelope |
| Management | C Optimize energy consumption structure<br>C Optimize industrial economic structure<br>C Provide multi-disciplinary solutions | C Establish electricity use index for new buildings<br>C Establish tiered pricing system for electricity use in buildings<br>C Establish air-condition temperature control standard<br>C Adopt energy performance contracting |

| | | |
|---|---|---|
| Establish norms and rules to guide and constrain constituents | | Select localized materials suppliers |
| Financial incentive | | |
| | C | Provide quantitative index for building energy intensity measurement |

data to match the I-O table to retain all economic information but with the drawback of estimating of energy use of sub-sectors by making subjective assumptions.

Therefore, this study employed multi-scale I-O tables to conduct sensitivity analysis. The I-O tables with 30, 42, and 135 sectors were used to verify the impact of the level of sector aggregation. The I-O table in 30-sector format was the result of recombining the sectoral products with a similar production process in the original table. The 42-sector and 135-sector tables were provided by the China National Bureau of Statistics in 2012. Table 9 shows the results of the sensitivity analysis. Sacrificing sector specificity by aggregating sectors was sensitive to the embodied energy simulation. The results of the I-O analysis with 30 sectors have been changed considerably due to the loss of detailed information on economic data, resulting in a change of 18% and 11% of the life cycle energy intensity for residential and office buildings, respectively. Such a discrepancy indicated that accounting the detailed sectoral information was critical to improve the accuracy of the I-O analysis. Therefore, it is necessary to perform the I-O analysis based on sufficient economic information. On the other hand, the energy intensity obtained from the original analysis was very close to the result derived under the 135-sector scenario. This similarity also demonstrates the reliability and validity of the final result calculated in this study.

4.3. Comparative analysis

Model selection may also have a direct impact on the life cycle energy analysis. The process-based model is applied extensively in the building construction field due to its comparatively higher evaluation accuracy. However, it also suffers from weaknesses such as a limited system boundary and truncation errors. In contrast, this study employed a hybrid assessment method, which enabled the quantification of building energy consumption by both retaining case-specificity and system completeness. Therefore, it is necessary to compare the original results with previous findings obtained from the traditional process-based model. Table 10 summarizes the percentage changes of life cycle energy intensity of office and residential buildings in previous research compared with the energy intensity obtained in this study.

It can be seen in Table 10 that the structure of residential buildings includes reinforced concrete, steel, masonry-concrete, brick-concrete and wood, which represents a percentage change of life cycle energy intensity from 3.5% to 350.4%. The relative changes of life cycle energy intensity in office buildings ranges from 8.4% to 271.8%. It can be found that the operational energy intensity represents a relatively higher discrepancy among different cases. This is mainly because the quantification of operational energy intensity is simulated under a series of assumptions due to the lack of operational process-based data. By contrast, this study used field investigation data to address such weakness that can reflect the actual energy consumption behavior of occupants to a large extent. Unlike the fluctuations in operational energy consumption, most of the embodied energy intensities are in-line with the results obtained in this study. The traditional process-based method has the advantage of using detailed process data but can only be applied to a specific building. This feature weakens the model when applied to the macro-research. The MRIO analysis addresses this drawback by considering sectoral interrelationships among different regions. By combining the MRIO analysis in the embodied phase and processbased data obtained from the operation and demolition phases, the hybrid model provides insights into the life cycle energy use of a particular type of buildings at the regional level.

## 5. Discussions and policy implications

To further link the findings with the policy practice in Guangdong province, a detailed investigation of regional policy instruments on energy conservation from 2010 to 2015 has been conducted (see Fig.10). It can be found that the local government in Guangdong province took a clear stance regarding regional energy reduction by experimenting with innovative low-carbon programs. A set of regional strategies seeks to improve energy efficiency at the industrial and building levels, with the most concern being the mitigation of energy consumption in public buildings.

Despite the fact that significant progress has been made, the findings of this study indicated several possible aspects that need further enforcement in the construction field given the energy consumption features of buildings. The corresponding recommendations are provided in Table 11 through the technology, product, and management aspects at the industrial and building levels.

For technological innovations, given that the major energy consumption pattern in a building life cycle remains fossil fuel oriented, it is necessary for local government and construction department to advance carbon-clean techniques and improve the sharing of clean and renewable energy in energy-intensive sectors. More specifically, precast construction can be an efficient method to switch energyeintensive manufacturing processes into a more sustainable and green approach by providing the standard design of materials, units and components.

Fromaproductsupplyperspective,highvalueaddedproductsand energy-efficient materials should be advocated. Given that Guangdongprovinceisfullyequippedwithfacilitiesandnetworksofnatural gas and has abundant solar energy sources, photovoltaic panel and solar water heater are therefore encouraged to adopt as green products capable of gaining environmental benefits during building operation phase. Moreover, the local government should encourage developers to adopt high-performance external walls with better thermal properties, especially for office buildings. Despite the additionalenergyinputtothematerialsproductionprocess,suchachange could result in overall energy savings from a building life cycle perspective. In addition, electricity use dominates all energy patterns due to the use of air conditioning, daily lighting and appliances. Therefore, using high energy-efficient appliances and natural ventilation during the building operation stage is important.

For the management aspect, the absence of provincial leadership and the lack of sufficient local support may impede energy improvement of buildings. Therefore, the government should establish a set of norms and regulations intended to guide local constituents. According to the results, it is necessary to change the current energy-intensive structure into one that is more sustainable and clean for buildings in Guangdong province. It requires providing environment-friendly, technology innovative, and multidisciplinary solutions in the full-process assessment and management of energy reduction of buildings. In addition, a number of economy-oriented measures, including financial incentive, energy performance contracting, tiered pricing system for operational electricity use, and the air-condition temperature control system should be implemented at the building level. The results of MRIO analysis demonstrates that the major energy suppliers are not only from energy-intensive industries but also from the transportation sector. Therefore, relevant policy should encourage the selection of nearby building material suppliers to save energy from material transportation.

## 6. Conclusions

This study employed a multi-regional hybrid method to quantify the total embodied energy consumption and energy transfers from the construction industry and assess the life cycle energy use of residential and office buildings in Guangdong Province. The results show that the embodied energy consumption of the construction industry was localization dominant and fossil fuel oriented, which accounted for approximately 18.6% of the total regional energy consumption. With respect to inter-regional energy transfers, the geographical connection and resource characteristic were the two factors that influenced the cross-regional energy transmissions.

In the building level analysis, the embodied and operational phases together accounted for nearly 98% of the total energy consumption. In particular, a significant energy saving potential existed in the operational phase of office buildings. The results of uncertainty analysis indicated that the meanvalueofenergy intensities simulated by MCS was highly consistent with the deterministic results calculated by the hybrid method developed in this study. Examining the effect of sector aggregation under 30, 42, and 135-sector scenario revealed that accounting the detailed sectoral information was critical to improve the accuracy of the I-O analysis. In considering the characteristics of the geographical location and features of building life cycle energy consumption in Guangdong province, a number of recommendations are provided through the technology, product,and management aspects at the industrial and building levels. The local government and construction department can benefit from implementing such environment-friendly, technology innovative and multi-disciplinary solutions in the full-process management and improvement of energy consumption of buildings.

Acknowledgement

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Appendix I. Region division in multi-regional based inputoutput table

| | 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 |

Appendix II. Basic information of residential building

| No. | Type | Vacancy | | Gross floor | | Building | | Floor | Exterior | Exterior | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | condition [B] | | Water supply | | Elevator | | Blocks | rate (%) | area ($m^2$) | | age |
| | (W/$m^2$\$K) | | window (W/$m^2$\$K) | | | (Y/N) | | | | | |
| R1Muilti-storey | 79.3% | 280,000 | 5 | 9 | 1.3 | 2.5 | 0.6 | Split/VRV system | Pumping system | Y | 29 |
| R2 Muilti-storey/villa | 95.7% | 49,106 | 28 | 6 | 1.5 | 6.5 | 0.7 | N | Roof-tank system | Y | 7 |
| R3High rise | 75.6% | 69,579 | 6 | 33 | 1.3 | 5.5 | 0.5 | Split | Pumping system | Y | 2 |
| R4Muilti-storey | 76.2% | 180,010 | 11 | 7 | 1.5 | 5.5 | 0.6 | Split/VRV system | Pumping system | Y | 33 |
| R5 Muilti-storey/High rise | -A | 186,888 | 9 | 11 | 1.3 | 4.7 | 0.6 | Split/VRV system | Roof-tank/Pumping system | Y | 32 |
| R6 Muilti-storey/High rise | 80.6% | 103,458 | 6 | 20 | 1.3 | 2.8 | 0.5 | Central | Pumping system | Y | 7 |
| R7High rise | | 97,138 | 2 | 20 | 1.0 | 1.9 | 0.4 | Central | e | Y | 8 |
| R8High rise | 100.0% | 29,602 | 18 | 24 | 1.5 | 6.5 | 0.7 | N | Roof-tank system | Y | 2 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R9Muilti-storey | 94.3% | 64,495 | 10 | 16 | 1.5 | 4.7 | 0.5 | N | Pumping system | Y | 14 |
| R10High rise | 71.3% | 36,317 | 4 | 20 | 1.0 | 2.8 | 0.5 | Central | Pumping system | Y | 2 |
| R11villa | 91.5% | 350,000 | 25 | 3 | 1.5 | 6.5 | 0.7 | N | Roof-tank system | Y | 183 |
| R12High rise | 86.5% | 32,715 | 12 | 32 | 1.5 | 6.5 | 0.6 | N | Roof-tank system | Y | 1 |
| R13High rise | 79.9% | 21,080 | 15 | 22 | 1.5 | 6.5 | 0.6 | N | Roof-tank system | Y | 1 |
| R14High rise | 73.8% | 124,520 | 7 | 18 | 1.5 | 5.5 | 0.5 | Split/VRV system | Pumping system | Y | 17 |
| R15High rise | 75.2% | 140,000 | 4 | 20 | 1.0 | 2.0 | 0.5 | Central | Pumping system | Y | 9 |
| R16High rise | e | 161,013 | 7 | 25 | 1.3 | 2.0 | 0.5 | Central | Pumping system | Y | 14 |
| R17High rise | e | 175,663 | 8 | 25 | 1.3 | 2.0 | 0.4 | Central | Non-negative pressure system | Y | 14 |

Note: A. "-" means the data is not available by field investigation; B. SC is abbreviation of shading coefficie abbreviation of Variable Refrigerant Volume.

Appendix III. Basic Information of Office Building

| No. | Type | Rental rate (%) | Gross floor area ($m^2$) | Building age (Year) | Glass Person Density (%) (Person/$m^2$) | curtain wall | Exterior wall (W/$m^2$$K) | Exterior [B] window (W/$m^2$$K) | SC | Air condition | Lighting | V s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| O1 | Office/ commercial | 14,016 | 95.5% | 12 | Y (100%) 0.061 | | 1.5 | 3.0 | 0.25 | FCU[C] þ MAU/AHU Fluorescent system | | F s |
| O2 | Office | 20,697 | 97.0% | 1 | N | 0.081 | 1.0 | 3.5 | 0.60 | FCU þ MAU[D] | Electrical ballast | N r p s |
| O3 | Office | 118,472 | 33.0% | 4 | Y (80%) | -A | 1.0 | 3.0 | 0.25 | FCU þ MAU | Fluorescent | F c p |
| O4 | Office | 12,115 | 92.1% | 25 | N | 0.052 | 1.5 | 5.0 | 0.45 | FCU þ MAU | Fluorescent | F s |
| O5 | Office/ commercial | 16,000 | 100.0% | 20 | Y (33%) | 0.038 | 1.5 | 3.5 | 0.36 | FCU þ MAU | Fluorescent | N V s |
| O6 | Office | 7791 | 86.1% | 28 | N | 0.042 | 1.5 | 6.5 | 0.70 | FCU | Fluorescent | N v s |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| O7 | Office | 46,953 | 100.0% | 9 | N | e | 1.2 | 3.5 | 0.54 | AHU system | Fluorescent | F c p |
| O8 | Office | 15,000 | 98.7% | 16 | Y | e | 1.2 | 5.0 | 0.40 | FCU þ | Fluorescent | F |
| O9 | Office | 17,204 | 99.5% | 25 | (12%)<br>e | e | 1.5 | 6.5 | 0.65 | MAU FCU | Fluorescent | s M v s |
| O10 | Office | 9101 | 96.5% | 18 | Y (40%) | e | 1.5 | 3.0 | 0.36 | AHU system | Fluorescent | F s |
| O11 | Office | 19,072 | 100.0% | 3 | N | e | 1.0 | 4.7 | 0.45 | e | Fluorescent | N r p s |
| O12 | Office | 40,447 | 97.3% | 2 | Y (50%) | 0.062 | 1.0 | 3.0 | 0.33 | AHU system | Fluorescent | F c p |
| O13 | Office | 17,845 | 93.9% | 26 | N | 0.06 | 1.5 | 3.5 | 0.54 | FCU þ | Fluorescent | F |
| O14 | Office/hotel/ commercial | 87,192 | 94.6% | 14 | Y | 0.32 | 1.3 | 3.5 | 0.40 | MAU FCU þ MAU/AHU system | Fluorescent | s F s |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| O15 | Office | 9380 | 100.0% | 6 | N | 0.047 | 1.2 | 5.0 | 0.54 | e | Fluorescent F s |
| O16 | Office | 8522 | 100.0% | 18 | Y (50%) | 0.072 | 1.5 | 4.7 | 0.33 | AHU system | Fluorescent |
| O17 | Office | 84,950 | 100.0% | 4 | Y (10%) | e | 1.0 | 5.0 | 0.54 | FCU þ MAU | Fluorescent/ LED water supply |

Note: A. "-" means the data is not available by field investigation; B. SC is abbreviation of shading coeffi abbreviation of fan coil units; D. MAU is the abbreviation of make-up air unit; AHU is the abbreviation of air

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