Analyzing the influence factors of the carbon emissions from China’s building and construction industry from 2000-2015

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Abstract

China has been the largest contributor to global carbon emissions since 2008, with its building and construction industry considered as one of the most significant sources. However, few studies have been conducted on analyzing the influencing factors of the carbon emissions following a life cycle perspective. This study aims to evaluate the carbon emissions of this industry from a life cycle perspective, including the extraction, manufacturing, construction and construction-related transportation, and building operation, using Logarithmic Mean Divisia Index. The key findings are: 1) the extraction and manufacturing of raw materials, and building operation are the two biggest contributors to the life cycle carbon emissions of the building and construction industry, accounting for 58% and 40% respectively; 2) the most effective strategies to reduce carbon emissions in the construction stage from 2000 to 2015 are to improve energy efficiency and lower emission factor; and 3) the most effective strategies to reduce carbon emissions in the building operation stage from 2000 to 2015 are to increase development density, improve emission factor, energy structure and industry structure. This study provides useful scientific evidence for policy makers to establish appropriate emission targets and relevant reduction strategies that are relevant to China’s building and construction industry.

Keywords: Carbon emissions; Sustainability; Logarithmic Mean Divisia Index; Decomposition; Carbon policy.

1. Introduction

Climate change has been recognized as a global environmental impact that needs to be appropriately addressed. It is widely believed that human activities can lead to an increase in carbon emissions. According to the American Chemical Society (2017), global CO_2 concentration is currently at 408.8 parts per million. The concentration level is 46% more than the average CO_2 concentration in the past two centuries (approximately 280ppm). The building and construction industry, including the extraction of raw materials, construction and building operation, is considered as one of the largest emitters of global carbon emissions (Wu et al., 2017a; Wang et al., 2017). According to Monahan and Powell (2011), energy use in buildings contributes to 25% of global carbon emissions. In addition, the cement sector alone accounts for almost 5% of global carbon emissions (Worrell et al., 2001). The building and construction industry therefore faces increasing pressure to manage its carbon emissions level (Li et al., 2017a).

China has been the largest carbon dioxide emitter since 2008 (Zhang and Da, 2015; Zhao et al., 2014). According to Zhang and Da (2015), a total amount of 9.21 billion ton of carbon emissions was generated by China in 2012, accounting for almost 27% of the world's total carbon emissions. From 1990-2010, China's carbon emission value has increased by 174% and the value has doubled from 2001-2010 alone (Michaelowa and Michaelowa, 2015). As such, the Chinese government has committed heavily to reduce its carbon emissions. For example, domestically, China has implemented its 12th five year plan (2011-2015) and aims to reduce the emission intensity by 17% (Lu et al., 2013; Li et al., 2017b). The 13th five year plan (2016-2020) aims to achieve a further reduction of emission intensity by 18%, which is slightly stronger than the target of the 12th five year plan. Globally, before the Copenhagen Climate Change Summit, China has announced that it aims to achieve a reduction of emission intensity by 40-45% in 2020 (based on the 2005 value) (Lu et al., 2013). The building and construction industry is one of the largest contributors to China's carbon emissions. The Greenhouse Gas (GHG) Emissions of China's buildings are almost equal to the total emission of Middle East, or two times that of Africa (Song et al., 2018). This industry includes contractors and builders that are primarily engaged in the construction, maintaining and repairing residential, industrial, commercial and other buildings (U.S. Census Bureau, 2017). This industry excludes heavy and civil engineering construction. Although construction activities alone contribute a small percentage of direct carbon emissions, building operation and the extraction of raw construction materials are energy intensive (Song et al., 2017). As Hammond and Norman (2012) pointed out, the analysis of past trend of carbon emissions is useful because it can help decision makers understand the current situation and establish feasible and effective emission reduction targets.

A few studies have been conducted to analyze the past trend of carbon emissions from various industry sectors, such as manufacturing (Ren et al., 2014) and energy-related industries (Ouyang and Lin, 2015). Similarly, since 2010, the emissions from China's building and construction industry have been investigated by studies such as Lu et al. (2016) and Hong et al. (2016). Even though these studies provide useful insights into understanding the contributing factors of the carbon emissions from China's building and construction industry, they have several key limitations. A complete construction life cycle includes the extraction and manufacturing of raw materials, transportation, on-site construction, building operation, and end-of-life treatments. As such, understanding the influence factors of the carbon emissions from the building and construction industry following a life cycle perspective is useful for establishing emission reduction strategies. Only recent studies have just started investigating the emissions from a life cycle perspective (Zhang and Wang, 2016). In addition, some important sources of carbon emissions, such as the use of aluminum and glass, was excluded from previous studies (e.g. Lu et al., 2016). Aluminum production has a much higher emission factor when compared to cement production (Gao et al., 2009). The exclusion of these materials can significantly affect the accuracy of the carbon analysis and subsequent decision making related to emission reduction. Furthermore, significant process improvement has been achieved in China’s coal-fired electricity power plants where the average coal usage is reduced from 415g standard coal equivalent (sce) per kwh to 319 g sce per kwh, which is a 18.75% decrease. Overlooking these improvements may lead to an overestimation of the carbon emissions from the China’s building and construction industry, leading to inaccurate policy suggestions. To summarize, there is an urgent need to conduct an accurate lifecycle investigation of the carbon emissions from China’s building and construction industry considering the recent developments in China, to inform the policymaking of reducing emissions from the building and construction industry.

To respond to the above significant gaps of knowledge, this study aims to: 1) evaluate the carbon emissions from China’s building and construction industry from 2000-2015 based on a life cycle perspective; 2) identify the influencing factors which contribute to the change of carbon emissions and quantify the contributions from 2000-2015; and 3) provide policy implications related to emission reduction in the building and construction industry. It is expected that this systematic study on carbon emissions from China’s building and construction industry could inform building and construction researchers, industry practitioners and policy makers in not only China, but also other countries that face emission reduction challenges similar with China.

The structure of the study is as follows. Section 2 provides a literature review of the influencing factors of industrial carbon emissions and the commonly adopted decomposition methods. Section 3 provides detailed mathematics models for calculating the carbon emissions from the building and construction industry and the decomposition model for analyzing the contribution of each influencing factor. Section 4 discusses the results of the study, including the estimated emissions and the contribution of each influencing factor. Section 5 discusses the implication of this study for policy making and Section 6 concludes the research work.

2. Literature review

2.1. Influencing factors of industrial carbon emissions

The building and construction industry, in terms of the extraction of raw materials, on-site construction activities and building operations, has been considered as one of the largest sources of carbon emissions (Gan et al., 2018). The cement sector alone accounts for 5% of global carbon emissions (Worrell et al., 2001). China' building and construction industry consumes 70% of its annual cement production and 25% of its annual steel production (Shi et al., 2017; Wu et al., 2017b). In 2011, the energy consumption in China's steel industry was around 600 million tone sce (standard coal equivalent), which is approximately two times of the total primary energy consumption of the UK (BP, 2013). Energy consumption of the China's building and construction industry is quite complex as well, indicated by Hong et al. (2016) who analyzed the carbon emissions from China's building and construction industry and indicated that China could be divided into seven areas based on construction energy intensity. Given the significant impact and complexity of the building and construction industry, various studies have been conducted to investigate the influencing factors that can affect the emissions level of the building and construction industry in order to establish effective emission reduction strategies. For example, Lu et al. (2016) analyzed the influencing factors of the carbon emissions from China's construction activities, including the use of construction materials and on-site construction activities. The influencing factors include emission factor, energy structure, energy intensity, unit cost, construction automation level, and machine efficiency (Lu et al., 2016). Similarly, Lin and Liu (2015) calculated the carbon emissions from transportation and construction activities, as well as on-site offices and analyzed the contribution of influencing factors, including emission factor, structure effect, intensity effect, profit effect and activity effect. Wang and Feng (2018) explored the driving forces of energy-related CO_2 emissions in China's building and construction industry, discovering that industrial activity and output technology change are significant influencing factors, but factors affecting emissions of China’s building and construction industry vary in difference provinces. Chen et al. (2019) investigated the carbon emissions difference between China and USA in their building and construction industry, and discovered that total final demand effect contributed most to narrowing the difference, while the production structure effect was a main driver enlarging the difference. These studies focus mainly on on-site construction activities and relevant transportation activities.

In addition, there are some studies which focus on the decomposition analysis of the energy and carbon emissions from building operation through residential and commercial energy consumption. For example, Nie and Kemp (2014) analyzed the residential energy consumption of China from 2002-2010 and investigated the impact of four influencing factors related to urbanization, including population, floor space, energy mix and appliances. Similarly, Yuan et al. (2015) conducted a regional analysis of the carbon emissions of residential indirect carbon emissions and investigated the contribution of two major factors, including urbanization and consumption factors (such as consumption ratio and structure). Given the importance of electricity, optimization algorithms have also been developed for power systems to minimize the total cost while satisfying other constraints (Ghorbani et al., 2017). Table 1 summarizes the influencing factors that are commonly adopted to analyze the changes of carbon emissions in the building and construction industry over a time period.

Table 1. The influencing factors of carbon emissions from the building and construction industry

Studies	**Influencing factors**	**Life cycle stages**
Lu et al. (2016)	EF, ES, EI, UC, CA, ME, M	Material consumption and on-site construction activities
Lin and Liu (2015)	EF, ES, EI, UC, AE	On-site construction activities and on-site offices
Nie and Kemp (2014)	Population, floor space, ES, appliances	Residential building operation

Xu and Ang (2014)	Population, energy price, energy efficiency, climate, life-style and structure	Residential building operation
Yuan et al. (2015)	Population, EI, consumption factors, urbanization effect	Residential building operation
Notes: EF = Emission Factor, which can be represented by carbon emissions per unit of energy consumption; ES = Energy Structure, which can be represented by the proportion of different energy sources; EI = Energy Intensity, which is related to the energy consumption per unit of output; UC = Unit Cost, which can be represented by the value per unit of output; CA = Construction Automation, which can be represented by construction area per unit of machinery energy consumption; ME = Machinery efficiency, which is related to the efficiency of machinery in handling construction materials; M = Material usage; AE = Activity effect, which can be represented by floor area under construction.		

2.2. Decomposition methods

Two decomposition methods, which are structural decomposition method (SDA) and index decomposition analysis (IDA), are commonly adopted when analyzing the changes in energy consumption and CO_2 emission caused by different influencing factors. SDA is employed primarily by researchers who prefer to use the input-output model, which is extended to help uncover changes in energy consumption or CO_2 emissions in the economy. On the other hand, IDA is used primarily by researchers who wish to better understand the influencing drivers of energy consumption and CO_2 emissions in a specific sector, such as the manufacturing industry or the building and construction industry.

Both decomposition methods can be used to analyze the contribution of influencing factors to the changes of carbon emissions in the building and construction industry. For example, Shi et al. (2017) used SDA, which is based on a formulated input-output model, to analyze the contribution of influencing factors to the changes of carbon emissions in China’s building and construction industry from 1995 to 2009. Total final demand effect and energy intensity effect were found to have the most significant impact on the carbon emissions changes. Similarly, Hong et al. (2017) applied SDA to quantify the effects of driving factors causing energy increase in the building and construction industry of China from 1990 to 2012. The results show that the increasing demand and reduction in energy intensity have significant impact on the carbon emissions level. In addition, energy consumption, CO_2 emission, and influencing factors of the indirect CO_2 emissions from the residential sector of China from 2000 to 2010 were examined using the Input-Output model (Zhang et al., 2017).

Compared to SDA, IDA has an advantage of relatively low data requirement and is flexible in terms of the analysis period (Cellura et al., 2012; Liu et al., 2016). As the aggregate data of each industrial sector is usually provided by different countries' bureau of statistics, IDA has been largely adopted in many studies. One of the most commonly adopted IDA method is Logarithmic Mean Divisa Index (LMDI), which has distinct advantages of no unexplained residual and full resolution (Ang, 2004; Ang, 2005). Lu et al. (2016) decomposed the carbon emissions into seven factors and investigated their corresponding impacts by using LMDI. China's building and construction industry is found to contribute 3.4% to the country's total emissions from 1994 to 2012. In addition, LMDI has also been used to investigate the carbon mitigation potential in China's building and construction industry (Lin and Liu, 2015). Lin and Liu (2015) found that the CO_2 level was increasing rapidly and energy intensity was the major contributor to CO_2 mitigation. Other than the construction stage, building operation, in terms of residential energy consumption, which is one of the largest sources of energy use and CO_2 emissions, has also been studied by different researchers using LDMI. For example, Zhao et al. (2012) decomposed residential energy consumption (REC) from 1998 to 2007 in China, and the results showed that there has been a structure change towards cleaner energy, i.e. a change of consumption mode. Nie and Kemp (2014) used LMDI-based decomposition analysis to analyze five residential energy-related activities: space cooling, heating, electric appliances, cooking, and lighting, in China from 2002 to 2010. Because of the advantages of LMDI in terms of data availability, data processing and analysis period and the demonstrated applicability of LMDI in analyzing the influencing factors of carbon emissions of the building and construction industry, this method was adopted in this paper.

The contribution of this study is at three levels. This study aims to evaluate the influence factors of carbon emissions from China's building and construction industry after the completion of the 12th five-year plan (2011-2015). Given the ambitious reduction target of 17% for the 13th five-year plan, it is necessary to investigate the influence factors that have demonstrated success in reducing emissions in the previous five-year plan so as to guide future decision making. In addition, along with previous studies which have evaluated the carbon emissions from the building and construction industry from a life cycle perspective (e.g. Zhang and Wang, 2016), it is also important to analyze the influence factors that affect the carbon emissions. Improvements should also be made to increase the accuracy of the calculation. For example, steel production methods, including Basic Oxygen Furnaces (BOF) and Electric Arc Furnaces (EAF) have significantly different emission factors. They should be considered separately in the calculation process. Both coal and electricity are used for steam and heat consumption in China and the energy consumption of both sources should be considered.

3. Research method and data

In this paper, the system boundary of the estimation includes three main stages, which are extraction and manufacturing of raw materials, construction and construction related transportation and building operation. It should be noted that the complete lifecycle of the industry should also include demolition, waste disposal, reuse or recycling (Zhang and Wang, 2016). However, as the energy consumption of these stages are not reported, it would not be feasible to conduct the decomposition process to analyze the influence factors of the change of carbon emissions. In addition, the contribution of demolition, waste disposal, waste reuse and recycling is relatively small, as can be seen from Zhang and Wang (2016), Wang (2014) and Huang et al., (2018). These stages are therefore excluded from this study.

3.1. Mathematical formulation of annual construction emissions

The mathematical representations of the construction emissions from the extraction and manufacturing of raw materials, construction and construction-related transportation, as well as building operation are shown in the following sections. It should be noted that although end-of-life treatment of buildings, including recycling and reuse, is an essential stage of the life cycle, it is not included in this study due to its high uncertainty and the availability of data. It should be noted that all values are reported in metric ton unless stated otherwise.

3.1.1. Extraction and manufacturing of raw materials

Five categories of construction materials, including cement, steel, timber, glass and aluminum, are included in this study. The annual consumption of these five categories of construction materials is sourced from the China Statistical Yearbook on Construction from 2000-2016. The overall carbon emissions values from the extraction of raw materials are calculated by Eq. (1) and the carbon emissions values from the extraction of cement, steel, timber, glass and aluminum are calculated by Eq. (2) to Eq. (6) respectively.

$$CO_{2,t,extraction} = CO_{2,t,cement} + CO_{2,t,steel} + CO_{2,t,timber} + CO_{2,t,glass} + CO_{2,t,aluminum} \quad \text{Eq. (1)}$$

$$CO_{2,t,cement} = EF_{clinker} \times M_{t,cement} \times O \times 44/12 \quad \text{Eq. (2)}$$

$$CO_{2,t,steel} = BOF_t \times EF_{BOF} + EAF_t \times EF_{EAF} + OHF_t \times EF_{OHF} \quad \text{Eq. (3)}$$

$$CO_{2,t,timber} = M_{t,timber} \times EF_{timber} = M_{t,timber} \times \frac{E_{timber} \times 2.6308}{P_{timber}} \quad \text{Eq. (4)}$$

$$CO_{2,t,glass} = M_{t,glass} \times EF_{glass} \times (1 - CR) \quad \text{Eq. (5)}$$

$$CO_{2,t,aluminum} = M_{t,aluminum} \times EF_{aluminum} \quad \text{Eq. (6)}$$

Where:

$EF_{clinker}$ is the emission factor (reported in net carbon content per ton of cement) of clinker and is 0.074 ton C/ ton, as reported by Liu et al. (2015).

$M_{t,cement}$, BOF_t, EAF_t, OHF_t, $M_{t,timber}$, $M_{t,glass}$, $M_{t,aluminum}$ refer to the annual consumption of cement, steel, timber, glass and aluminum of year t (reported in ton). A weighting is applied to the annual consumption of construction materials because the original consumption includes civil construction, building construction and building decorations. From 2000 to 2015, building construction occupies around 94.1% to 96.2% of the overall constructed floor area.

O refers to the oxidization rate and is assumed to be 99% for the cement industry, as reported by Liu et al. (2015).

EF_{BOF}, EF_{EAF} and EF_{OHF} refer to the emission factors of steel production from Basic Oxygen Furnaces (BOF), Electric Arc Furnaces (EAF) and Open Hearth Furnaces (OHF) and are 1.46 and 0.07, and 1.72 ton CO_2/ton respectively, as suggested by IPCC (2006). China does not have steel produced from Open Hearth Furnaces (OHF) since 2006.

EF_{timber} refers to the emission factor of timber production and is calculated by the energy consumption of processing and manufacturing wood products. E_{timber} refers to the total energy consumption of the timber industry. According to Sun et al. (2016), the emission coefficient per standard coal equivalent unit is 2.6308 tCO_2/t. P_{timber} refers to the production volume of timber (m^3).

EF_{glass} refers to the emission factor of glass production and is 0.2 ton CO_2/ton, according to IPCC (2006). CR refers to the cullet ratio and is assumed to be 0.4 according to Liu et al. (2014).

$EF_{aluminum}$ refers to the emission factor of primary aluminum production and is 18.18 ton CO_2/ton, according to Gao et al. (2009).

3.1.2. Construction and construction-related transportation

The China Statistical Yearbook reports the energy consumption of the building and construction industry, including coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas and electricity consumption. The reported consumption is related to construction activities, construction related transportation and the building energy consumption of construction companies. According to the China Association of Building Energy Efficiency (2016), 5% of the reported consumption is related to on-site buildings' energy consumption and is therefore excluded from this stage. In addition, the reported consumption also includes civil engineering activities. The proportion of civil engineering activities is also calculated using the completed square metres of civil engineering and building activities. Such proportion is excluded from consumption data. The carbon emissions generated from construction activities and construction related transportation (hereinafter referred to as the construction stage) can be calculated by:

$$CO_{2,construction} = E_{i,construction} \times EF_i \times V_i \times 95\% \times \frac{A_b}{A_c} \qquad \text{Eq. (7)}$$

Where:

$E_{i,construction}$ is the energy consumption from energy source i.

EF_i is the emission factor of energy combustion from energy source j, reported in calorific values in IPCC (2006).

V_i is the Chinese specific low-calorific value of energy source j, reported in the *National Standard GB/T 2589-2008: General Rules for Comprehensive Energy Consumption Calculation.*

A_b is the total floor area of completed building projects and A_c is the total floor area of all completed projects, including both civil and building projects. Such data is available in the China Statistical Yearbook on Construction.

3.1.3. Building operation

Building operation refers to the daily use of completed buildings. Modelling the energy consumption and carbon emissions from the building operation is complicated due to the multiple types of buildings involved, including residential, retail, industrial, construction and others. According to the National Bureau of Statistics (2017), five sources of energy consumption are related to building operation, including industry, construction, wholesale, retail trades, hotel and catering services, residential building and others. According to the China Association of Building Energy Efficiency (2016), these sources of energy consumption includes diesel and gasoline consumption, which are predominately used for transportation and should be excluded. As such, strategies are established to estimate the building operation energy from the following five industries:

- Industry. 5% of the energy consumption from the industry sector is related to building operation, including on-site offices and accommodation (China Association of Building Energy Efficiency, 2016).
- Construction. 5% of the energy consumption from the construction sector is related to building operation, including on-site construction offices and accommodation (China Association of Building Energy Efficiency, 2016).
- Wholesale, retail trades, hotel and catering services. 35% of diesel and 95% of gasoline consumption are predominately used for transportation. Relevant diesel and gasoline consumption should be excluded to calculate the building energy consumption in this sector.
- Residential buildings. Similar to the wholesale sector, relevant diesel and gasoline consumption should be excluded.
- Others. Similar to the residential consumption sector, relevant diesel and gasoline consumption should be excluded.

- Steam and heat consumption. According to China Association of Building Energy Efficiency (2016), a coefficient of 2.5 is applied to the aggregated steam and heat consumption from residential, wholesale and others to obtain the overall steam and heat consumption of the whole building sector.

Following the calculation method proposed in the China Association of Building Energy Efficiency (2016), the following equation was used to calculate the carbon emissions from building energy consumption:

$$CO_{2,operation} = E_{j,industry} \times EF_j \times 5\% + E_{j,construction} \times EF_j \times 5\% + \left(E_{j,wholesale} - 95\% \times E_{gasoline,wholesale} - 35\% \times E_{diesel,wholesale}\right) \times EF_j + \left(E_{j,residential} - 100\% \times E_{gasoline,residential} - 95\% \times E_{diesel,residential}\right) \times EF_j + \left(E_{j,others} - 95\% \times E_{gasoline,others} - 95\% \times E_{diesel,others}\right) \times EF_j + 2.5 \times (S_{residential} + S_{wholesale} + S_{others}) \times EF_j \qquad \text{Eq.(8)}$$

Where:

$S_{residential}$, $S_{wholesale}$ and S_{others} represents the energy consumption of steam usage.

3.2. Mathematical formulation of the decomposition model

The LMDI method has been commonly adopted to analyze the contribution of influencing factors to the overall carbon emissions. Three decomposition models were developed separately for the extraction and use of raw materials (E), construction stage (C), and building operation (O). The detailed decomposition models are explained as follows in the order of complexity. The decomposition model for the construction stage, including construction and construction-related transportation, can be represented by Eq. (9).

$$CO_{2,C} = \sum_i CO_{2,C} = \sum_i \frac{CO_{2,C,i}}{E_{C,i}} \times \frac{E_{C,i}}{E_C} \times \frac{E_C}{P_C} \times \frac{P_C}{A_b} \times A_b = \sum_i EF_i \times ES \times EE \times UC \times A_b \qquad \text{Eq. (9)}$$

where:

P_c is the value of completed building projects (i.e. civil construction is excluded); $E_{c,i}$ is the energy consumption of source i; A_b is the total floor area of completed building projects; EF_i is the emission factors of energy source i; ES is the energy structure of the construction stage; EE is the energy efficiency of the construction stage, represented by the average energy consumption per unit of value added; UC is the unit cost, represented by the value added per unit of constructed floor area.

Consequently, the change of carbon emissions in the construction stage can be decomposed into the five factors of EF_i, ES, EE, UC and A, using the Eq. (10) – Eq. (15).

$$\Delta CO_{2,C} = \Delta CO_{2,C,EF} + \Delta CO_{2,C,ES} + \Delta CO_{2,C,EE} + \Delta CO_{2,C,UC} + \Delta CO_{2,C,A_b} \qquad \text{Eq.(10)}$$

$$\Delta CO_{2,C,EF} = \sum_{i=1}^{9} L\left(CO_{2,C,i}^{T}, CO_{2,C,i}^{0}\right) ln\frac{EF_i^T}{EF_i^0} = \sum_{i=1}^{9} \frac{CO_{2,C,i}^{T} - CO_{2,C,i}^{0}}{\ln CO_{2,C,i}^{T} - \ln CO_{2,C,i}^{0}}\ ln\frac{EF_i^T}{EF_i^0} \qquad \text{Eq.(11)}$$

$$\Delta CO_{2,C,ES} = \sum_{i=1}^{9} L\left(CO_{2,C.i}^{T}, CO_{2,C,i}^{0}\right) ln\frac{ES_i^T}{ES_i^0} = \sum_{i=1}^{9} \frac{CO_{2,C,i}^{T} - CO_{2,C,i}^{0}}{\ln CO_{2,C,i}^{T} - \ln CO_{2,C,i}^{0}}\ ln\frac{ES_i^T}{ES_i^0} \qquad \text{Eq.(12)}$$

$$\Delta CO_{2,C,EE} = \sum_{i=1}^{9} L\left(CO_{2,C,i}^{T}, CO_{2,C,i}^{0}\right) ln\frac{EE^T}{EE^0} = \sum_{i=1}^{9} \frac{CO_{2,C,i}^{T} - CO_{2,C,i}^{0}}{\ln CO_{2,C,i}^{T} - \ln CO_{2,C,i}^{0}}\ ln\frac{EE^T}{EE^0} \qquad \text{Eq.(13)}$$

$$\Delta CO_{2,C,UC} = \sum_{i=1}^{9} L\left(CO_{2,C,i}^{T}, CO_{2,C,i}^{0}\right) ln\frac{UC^T}{UC^0} = \sum_{i=1}^{9} \frac{CO_{2,C,i}^{T} - CO_{2,C,i}^{0}}{\ln CO_{2,C,i}^{T} - \ln CO_{2,C,i}^{0}}\ ln\frac{UC^T}{UC^0} \qquad \text{Eq.(14)}$$

$$\Delta CO_{2,C,A_b} = \sum_{i=1}^{9} L\left(CO_{2,C,i}^{T}, CO_{2,C,i}^{0}\right) ln\frac{EE^T}{EE^0} = \sum_{i=1}^{9} \frac{CO_{2,C,i}^{T} - CO_{2,C,i}^{0}}{\ln CO_{2,C,i}^{T} - \ln CO_{2,C,i}^{0}}\ ln\frac{A_b^T}{A_b^0} \qquad \text{Eq.(15)}$$

Similarly, the decomposition model for building operation can be represented by Eq.(16).

$$CO_{2,O} = \sum_{ij} CO_{2,O,ij} = \sum_{ij} \frac{CO_{2,O,ij}}{E_{O,ij}} \times \frac{E_{O,ij}}{E_{O,i}} \times \frac{E_{O.i}}{E_O} \times \frac{E_O}{A'} \times \frac{A'}{P'} \times \frac{P'}{IN} \times IN = \sum_i EF_i \times IS \times ES \times EA \times FS \times IC \times IN \qquad \text{Eq.(16)}$$

Where:

EF refers to the emission factor; IS refers to the industry structure; ES refers to the energy structure; EA refers to the energy demand from appliance, represented by energy consumption per square meter (Nie and Kemp, 2014); FS refers to the floor space effect, which is represented by floor space per capita; IC refers to the infrastructure capacity, represented by population per km road (a proxy indicator for urban density); IN refers to infrastructure development and road length is used as a proxy indicator; A' is the total floor area of all buildings (in use), available in the research report of China's construction and building energy consumption (Energy Foundation, 2016) ; and P' is the population in China. It should be noted that the calculation of the total floor area of all buildings (in use) includes the use of a comprehensive research method of calculating residential floor areas and industrial floor areas, by considering newly constructed floor areas and demolished floor areas.

Correspondingly, the change of carbon emissions in building operation stage can be decomposed into the seven factors of EF_i, IS, ES, EA, FS, IC and IN, following a similar method for the construction stage.

Another decomposition model is developed for the extraction and use of raw materials, i.e. Eq.(17).

$$CO_{2,E} = \sum_i CO_{2,E,i} = \sum_i \frac{CO_{2,E,i}}{CO_{2,E}} \times \frac{CO_{2,E}}{A_b} \times A_b = \sum_i MS_i \times EE \times A_b \qquad \text{Eq. (17)}$$

Where:

$CO_{2,\,E}$ refers to the carbon emissions from the extraction and use of raw materials; i refers to the five types of raw materials; A_b is the total floor area of completed building projects; MS is the material structure in the building and construction industry; EE refers to the environmental efficiency, represented by carbon emissions per unit floor area.

4. Results

4.1.The life cycle carbon emissions of China's building and construction industry

Figure 1, Figure 2 and Figure 3 show the life cycle carbon emissions of China's building and construction industry from the three stages: extraction and manufacturing of raw materials, transportation and construction, as well as building operation.

As can be seen from Figure 1, the annual CO_2 of the building and construction industry due to the extraction and manufacturing of raw materials in 2015 has increased by almost 10 times over the past 15 years. The annual CO_2 related to raw materials is 2.60 billion ton in 2015 and 0.28 billion ton in 2000. While the annual CO_2 related to raw materials has been generally increasing, it has declined from 2012-2013 and from 2014-2015. Steel, aluminum and cement represent the top three types of construction materials in terms of their contributions towards CO_2. Their contributions are relatively stable since 2011, valued at 36.86%, 32.98% and 24.63% respectively from 2011-2015. In addition, the contributions of timber and glass are relatively limited, valued at 5.46% and 0.06% respectively.

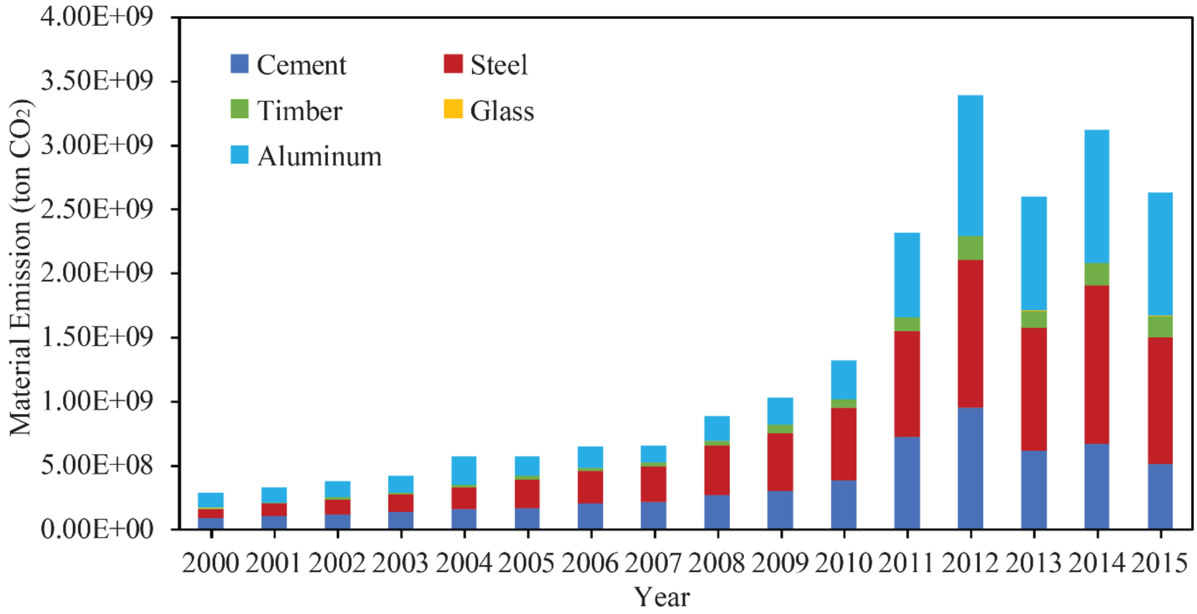


Figure 1. Annual carbon emissions due to the extraction and manufacturing of raw materials

Figure 2 shows the carbon emissions from the construction stage, and a comparison of the emissions with that from raw materials consumption. The amount of CO_2 from the construction stage has an overall upward trend from 31.97 million ton in 2000 to 81.59 million ton in 2010. In 2011, it declines to 74.07 million ton and has been gradually increasing to 83.19 million ton in 2015. A very interesting finding is that although the amount of carbon emissions from the construction stage is relatively stable since 2010 (from 81.58 million ton in 2010 to 83.19 million ton in 2015), the amount of carbon emissions from raw materials consumption increases significantly from 1.32 billion ton to 2.63 billion ton over the same time period. The increase is caused by the significant increase in emissions related to aluminum and steel usage, which have increased by 0.66 billion ton and 0.43 billion ton respectively. There has been a significant problem of production overcapacity in the steel and aluminum industry since 2006 (State Council of China, 2006). The Chinese government has therefore been promoting the use of steel structure and light-weight aluminum formwork in the building and construction industry through a series of guiding policies and regulations, such as *Accelerating the restructuring of the sectors with production capacity redundancy* (State Council of China, 2006) and *Guiding opinions on resolving serious production overcapacity conflicts* (State Council of China, 2013). Such promotion has been used to address production overcapacity over the past few years and has caused a significant increase in carbon emissions related to raw materials consumption.

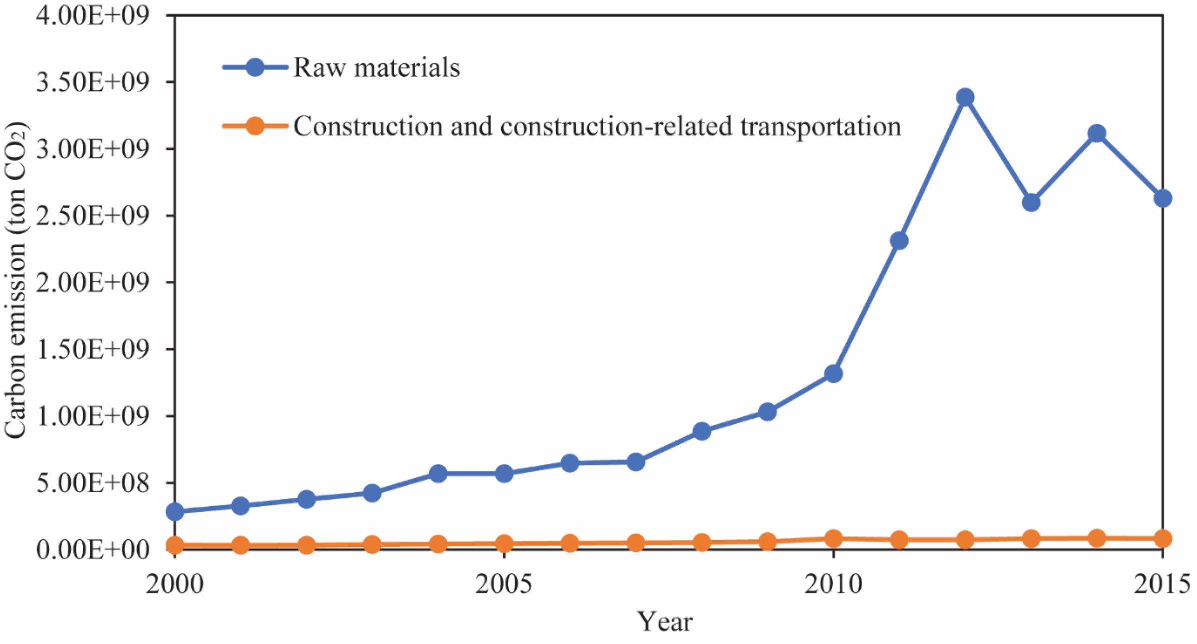


Figure 2. Annual carbon emissions from construction and construction-related transportation

Building operation was the single largest contributor to the annual carbon emissions of China's building and construction industry till 2010. As shown in Figure 3, a general upward trend is spotted with the annual carbon emissions from building operation increased from 0.68 billion ton to 2.05 billion ton, which is a 206% increase. As can be seen from Figure 3, the contribution of building operation to the annual carbon emissions of the building and construction industry is relatively stable since 2011 at approximately 40%. Compared to building operation, the extraction and manufacturing of raw materials account for approximately 58% and the construction stage only accounts for around 2% of the annual carbon emissions.

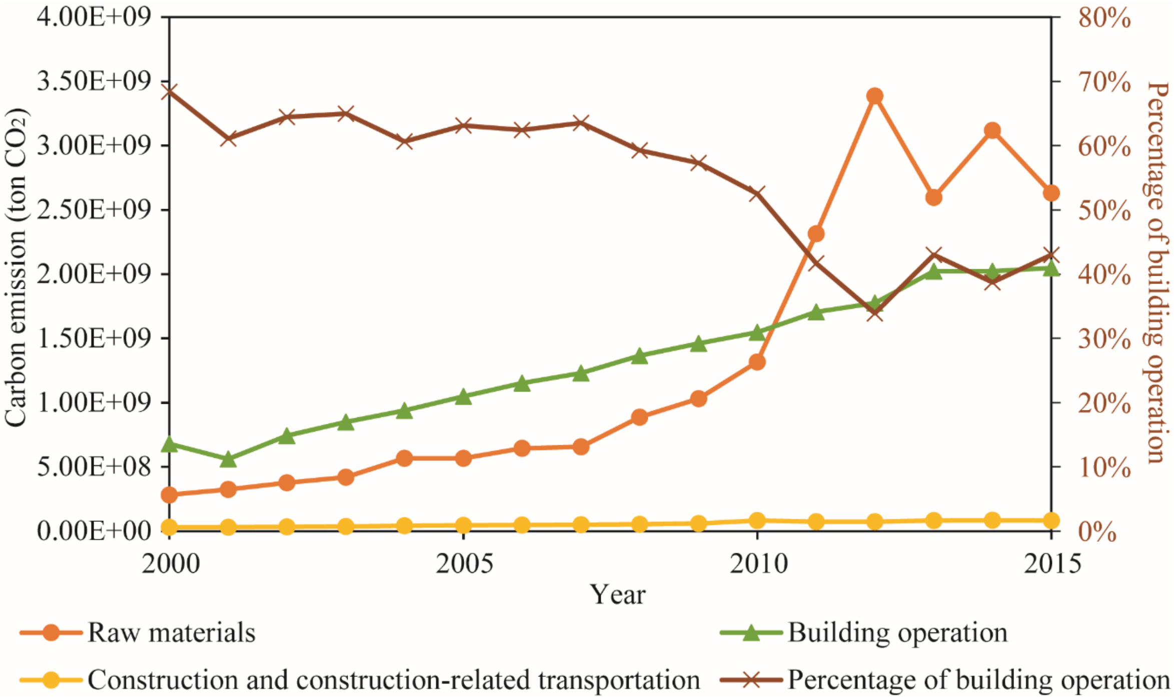


Figure 3. Annual carbon emissions from building operation

4.2.Decomposition analysis of the extraction and use of raw materials

The decomposition analysis of the emissions from the extraction and use of raw materials is shown in Table 2 and Figure 4. The overall change of emissions from 2000 to 2015 is 2.37 billion ton CO_2. The contribution of material structure in such change is negligible, with a small contribution of 3.11 million ton CO_2. On the other hand, the total constructed floor area plays an important role in the increase of carbon emissions, contributing 1.81 billion ton CO_2 from 2000 to 2015, demonstrating the impact of rapid urbanization of China on the environment. In addition, environmental efficiency (in terms of carbon emissions per unit floor area) contributes to the increase of 5.55 billion ton CO_2. This presents an interesting finding that is worthwhile for further investigation. Despite the extensive studies on green materials, e.g. green concrete (Crossin, 2015), to help reduce emissions from the building and construction industry, the impact of green materials is minimal in this period. This can be caused by the relatively stable market share of cement (25%) in the building and construction industry where steel and aluminum are also heavily used and the embodied emissions of these two types of materials may not be significantly reduced.

Table 2. The decomposition results of the emissions from the extraction and use of raw materials

Year	Change of emissions (million ton CO_2)			
	MS	**EE**	**Ab**	**Total**
2000-2001	0.03	-13.09	55.66	42.60
2001-2002	0.08	9.76	40.62	50.46
2002-2003	0.04	-1.37	46.67	45.34
2003-2004	0.31	68.37	78.07	146.74
2004-2005	-0.01	-50.95	50.12	-0.84
2005-2006	0.05	2.10	76.54	78.69
2006-2007	0.01	-69.74	79.26	9.54
2007-2008	0.06	162.54	67.53	230.14
2008-2009	0.30	56.68	88.91	145.89
2009-2010	-0.11	144.68	140.76	285.34
2010-2011	2.25	788.16	206.31	996.73
2011-2012	0.96	672.90	400.10	1073.96
2012-2013	-0.81	-1128.51	339.31	-790.01
2013-2014	0.24	373.10	147.12	520.46
2014-2015	-0.29	-458.88	-2.84	-462.01
2000-2015	3.11	555.75	1814.16	2373.02

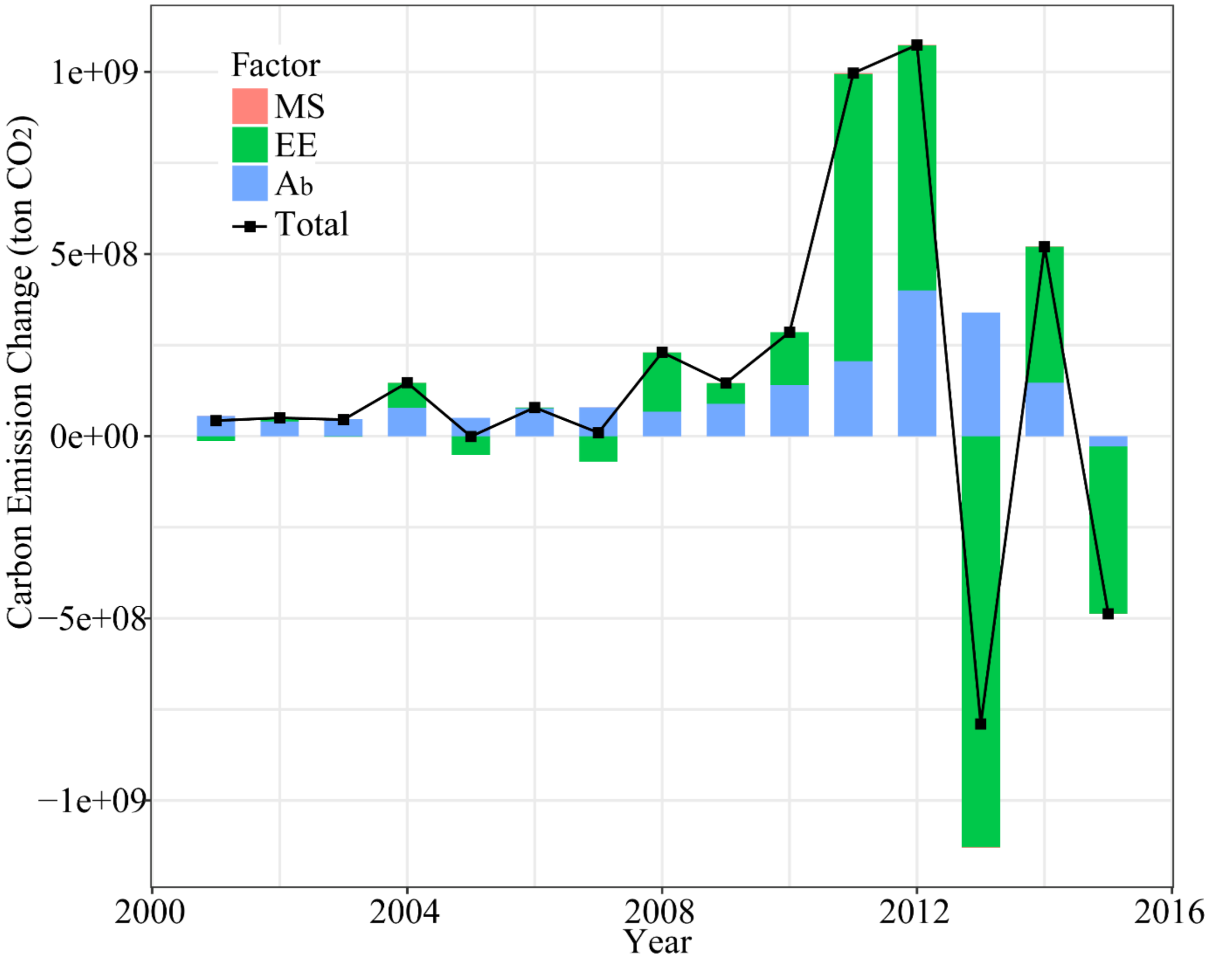


Figure 4. Decomposition of the CO2 emissions of extraction and use of raw materials in China's building and construction industry

4.3.Decomposition analysis of the construction stage

4.2.1. General decomposition results

The decomposition analysis of the emissions from the construction stage is shown in Table 3. The overall change of emissions from 2000 to 2015 is 51.17 million ton CO_2. Energy structure, energy efficiency, unit cost and constructed floor area have caused changes of -1.50, -57.60, 28.20 and 85.76 million ton CO_2 respective. The contribution of emission factor to the construction stage is a reduction of 3.70 million ton CO_2. It seems that the most effective strategies that have been adopted to reduce CO_2 emissions in these stages are improved energy structure. In addition, unit cost and constructed floor area contribute positively to the annual CO_2 emissions of these stages.

Table 3. The decomposition results of the emissions from material consumption, construction and transportation

Year	**Change of emissions (million ton CO_2)**					
	EF	**ES**	**EE**	**UC**	**Ab**	**Total**
2000-2001	-0.33	0.06	-6.41	0.25	5.80	-0.63
2001-2002	0.13	-0.03	7.52	-8.58	3.79	2.84
2002-2003	0.31	-0.12	-4.04	2.94	4.18	3.28
2003-2004	-0.22	-0.17	-2.09	0.45	6.26	4.23
2004-2005	0.07	-0.14	-4.13	3.10	3.80	2.70
2005-2006	0.19	-0.27	-3.95	2.63	5.86	4.45
2006-2007	0.10	-0.21	-5.90	2.36	6.07	2.43
2007-2008	-0.63	-0.27	-6.15	3.87	4.56	1.39
2008-2009	0.09	-0.23	-4.68	5.37	5.16	5.72
2009-2010	-0.65	-0.61	10.75	5.34	8.33	23.16
2010-2011	0.96	0.61	-22.89	4.72	9.07	-7.52
2011-2012	-1.48	-0.19	-14.60	5.60	10.52	-0.14
2012-2013	-0.08	-0.03	6.67	-7.38	8.89	8.07
2013-2014	-1.28	0.21	-3.62	2.77	4.29	2.37
2014-2015	-0.90	-0.11	-4.10	4.76	-0.83	-1.18
2000-2015	-3.70	-1.50	-57.60	28.20	85.76	51.17

Figure 5 shows the contribution of the five factors to the overall CO_2 emissions at a yearly basis. Two notable observations can be identified from Figure 5. Two factors, including unit cost and constructed floor area contribute positively to the carbon emissions level of the construction stage and have consistent patterns. On the other hand, although energy structure and energy efficiency have aggregated negative effect on the carbon emission level, the contribution from 2000 to 2015 is not consistent.

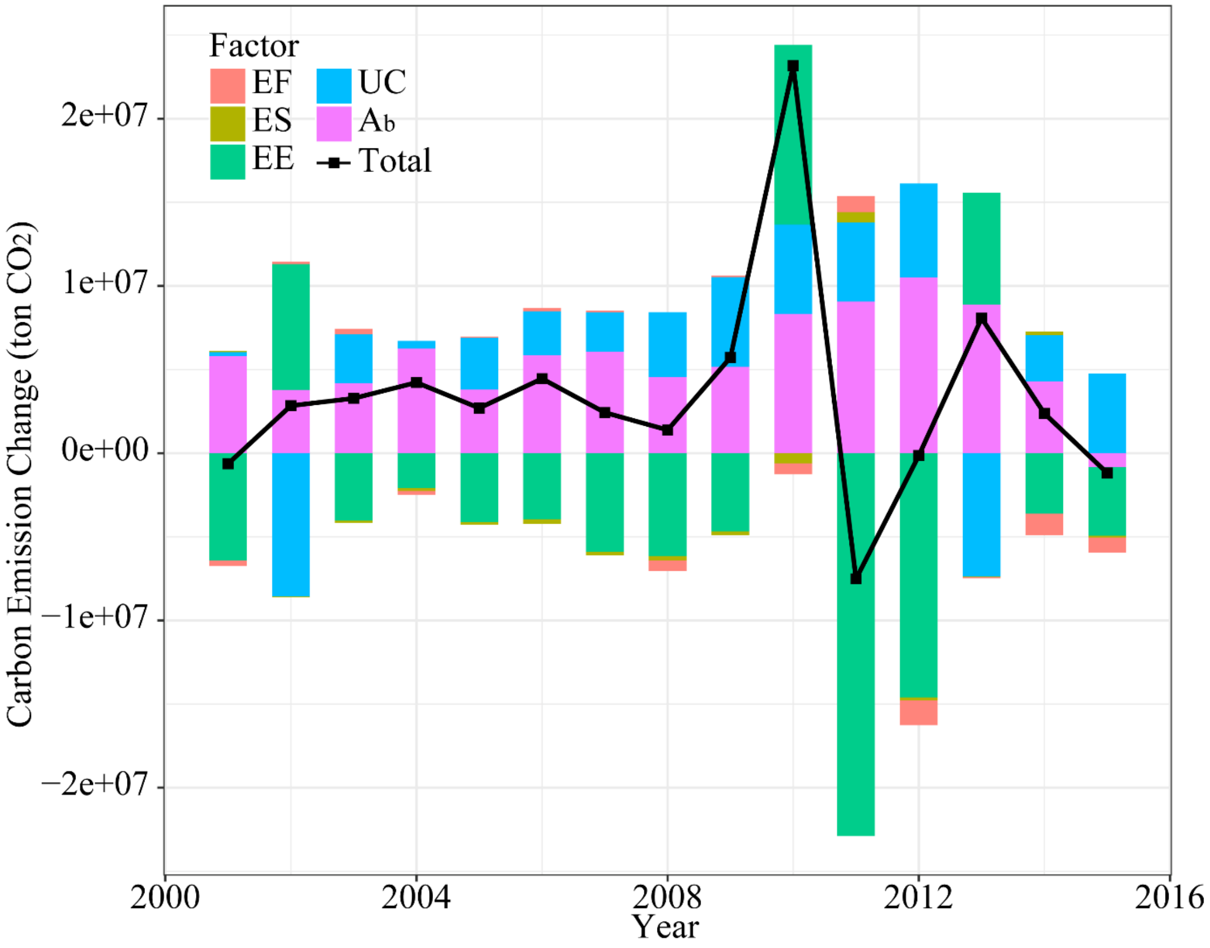


Figure 5. Decomposition of the CO_2 emissions of the construction stage of China's building and construction industry from 2000 to 2015

4.2.2. Positive factors

Unit cost is commonly used as an indicator to assess people's living standard (Lu et al., 2016). Higher unit cost commonly indicates higher living standard. The unit cost (in terms of value added) increases from 1073.1 yuan/m^2 to 1595.7 yuan/m^2. The upward trend is fairly consistent.

Constructed floor area can be used as an indicator for assessing the expansion of construction activities. The constructed floor area is increasing from 2000 to 2015, although at varied speed, as shown in Figure 6. In the early years (2000-2007), a higher weighted increase (around 14.2%) is identified. The increase rate is slowed down to around 9.2% and 9.7% in 2008 and 2009 respective, due to the global financial crisis. In recent years, a relatively low increase (5.3% in

2014) or even decrease (-0.1% in 2015) are identified, reducing the contribution of constructed floor area to the carbon emissions level.

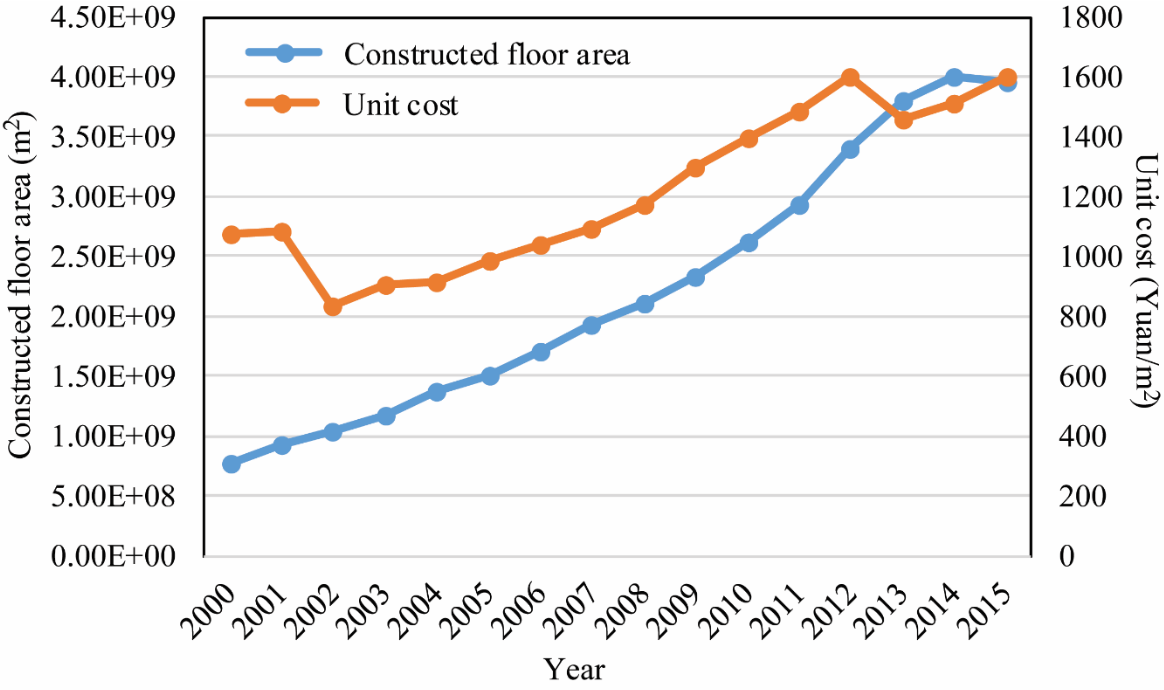


Figure 6. Unit cost and constructed floor area from 2000-2015.

4.2.3. Negative factors

Two factors, which are energy structure and energy efficiency, have negative effect on the overall carbon emissions level.

Figure 7 shows the energy structure of manufacturing raw materials, construction and transportation. The aggregated effect of energy structure on the carbon emission level is -1.50 million ton CO_2. This decrease is caused by the relatively stable usage of coal and the significance increase in electricity usage. The transformation of heavy reliance on coal usage has been the targets for China's 10th, 11th and 12th five-year plans (Hu, 2016). Therefore, the coal usage in the construction stage has only increased from 4.91 million ton to 7.85 million ton; a 60% increase. On the other hand, electricity usage in construction stage has increased significantly from 14.1 billion KWh to 62.5 billion KWh; a 343% increase. In addition, the average energy consumption per valued added from 2000 to 2015 is reduced significantly from

15.9 to 5.9 g sce/yuan, which is equivalent to a 63% reduction. This indicates a significant improvement of energy efficiency over the past 15 years.

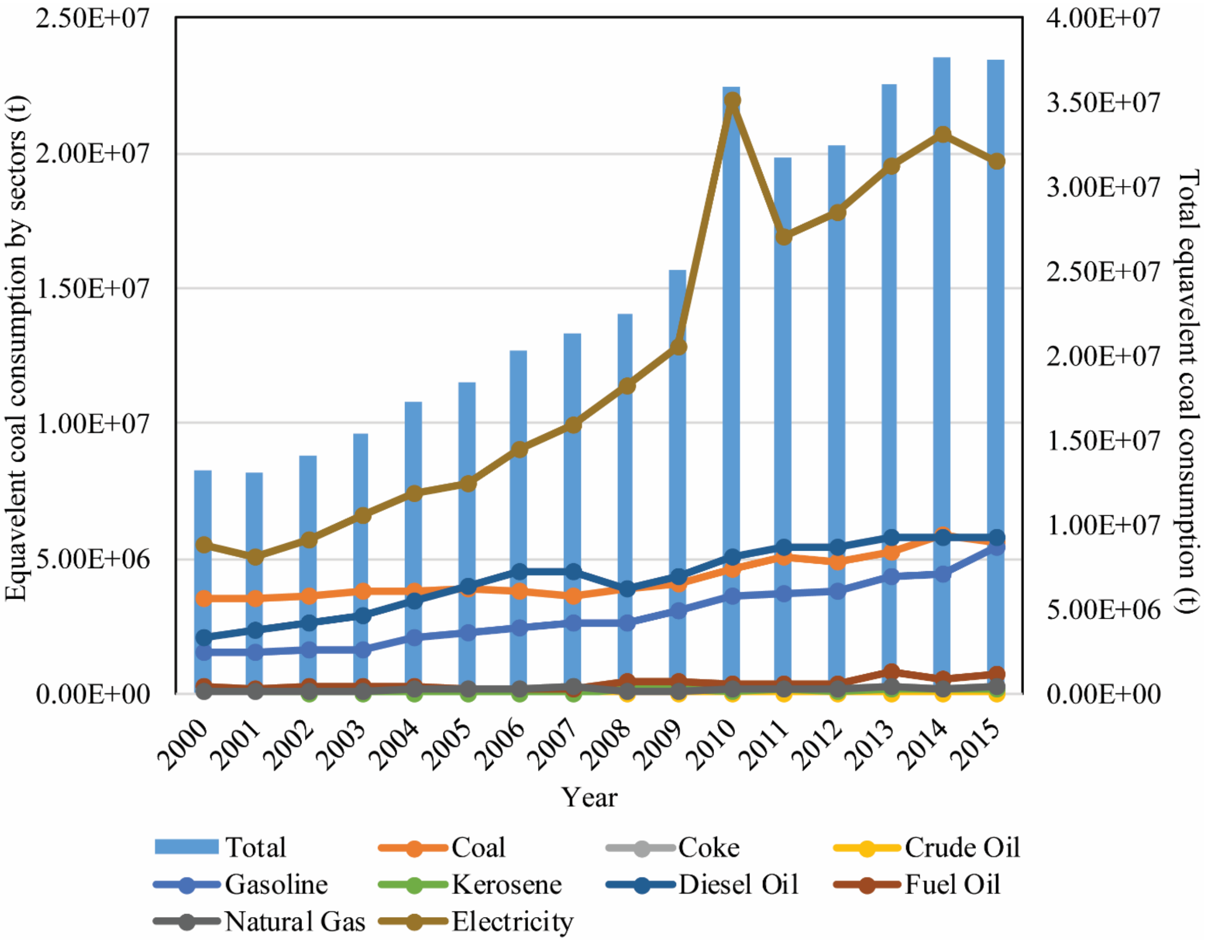


Figure 7. The energy structure of the construction stage of China's building and construction industry from 2000 to 2015

4.4.Decomposition analysis of building operation

4.4.1. General decomposition results

The decomposition analysis of the emissions from building operation is shown in Table 4. Figure 8 shows the contribution of the seven factors to the overall CO_2 emissions at a yearly basis. The overall change of emissions from 2000 to 2015 is 1.63 billion ton CO_2. The seven factors, including EF, IS, ES, EA, FS, IC and IN have caused changes of -89.10, -1.82, -37.43, 605.62, 1035.67, -1341.87 and 1462.82 million ton CO_2 respective. It seems that the most effective strategy that has been adopted to reduce CO_2 emissions in the building operation stage is infrastructure capacity, which is represented by population per kilometer of road and can be used as an indicator of urban development density (Ji et al., 2014). The biggest contributors of carbon emissions in the building operation stage include infrastructure development, a proxy development for urbanization, as well as floor space effect and energy demand from appliance. It should be noted that the sharp increase in 2005 from infrastructure development is caused by the significant increase of road length from 1.87 million kms in 2004 to 3.35 million kms in 2005.

Table 4. The decomposition results of the emissions from building operation

Year	**Change of emissions (million ton CO_2)**							
	EF	**IS**	**ES**	**EA**	**FS**	**IC**	**IN**	**Total**
2000-2001	-8.17	-8.30	-16.83	-134.02	42.30	-126.69	131.59	-120.14
2001-2002	3.57	8.23	14.69	119.39	44.68	-23.66	28.22	195.13
2002-2003	8.18	0.04	1.05	96.11	22.31	-17.09	22.78	133.38
2003-2004	-5.85	-2.43	-1.69	97.62	22.56	-27.93	34.35	116.64
2004-2005	1.86	0.06	1.45	65.70	68.52	-673.56	680.77	144.80
2005-2006	5.35	0.02	-3.85	88.34	31.65	-36.01	43.01	128.51
2006-2007	2.84	0.00	-5.27	29.85	50.40	-43.43	50.97	85.36
2007-2008	-16.78	0.13	0.08	82.31	74.80	-53.15	61.25	148.64
2008-2009	2.36	0.01	-4.17	45.21	59.83	-49.71	57.22	110.75
2009-2010	-12.98	0.01	-9.31	37.82	60.54	-56.74	65.98	85.32
2010-2011	18.42	0.02	-5.42	26.16	118.41	-35.82	45.66	167.43
2011-2012	-34.37	0.01	-5.73	29.26	101.44	-54.52	63.51	99.61
2012-2013	-1.79	0.37	10.59	106.41	133.14	-50.92	60.65	258.45
2013-2014	-29.94	0.00	-6.92	-89.90	136.13	-45.11	57.15	21.41
2014-2015	-21.80	0.01	-6.11	5.37	68.96	-47.52	59.71	58.62

2000-2015	-89.10	-1.82	-37.43	605.62	1035.67	-1341.87	1462.82	1633.89

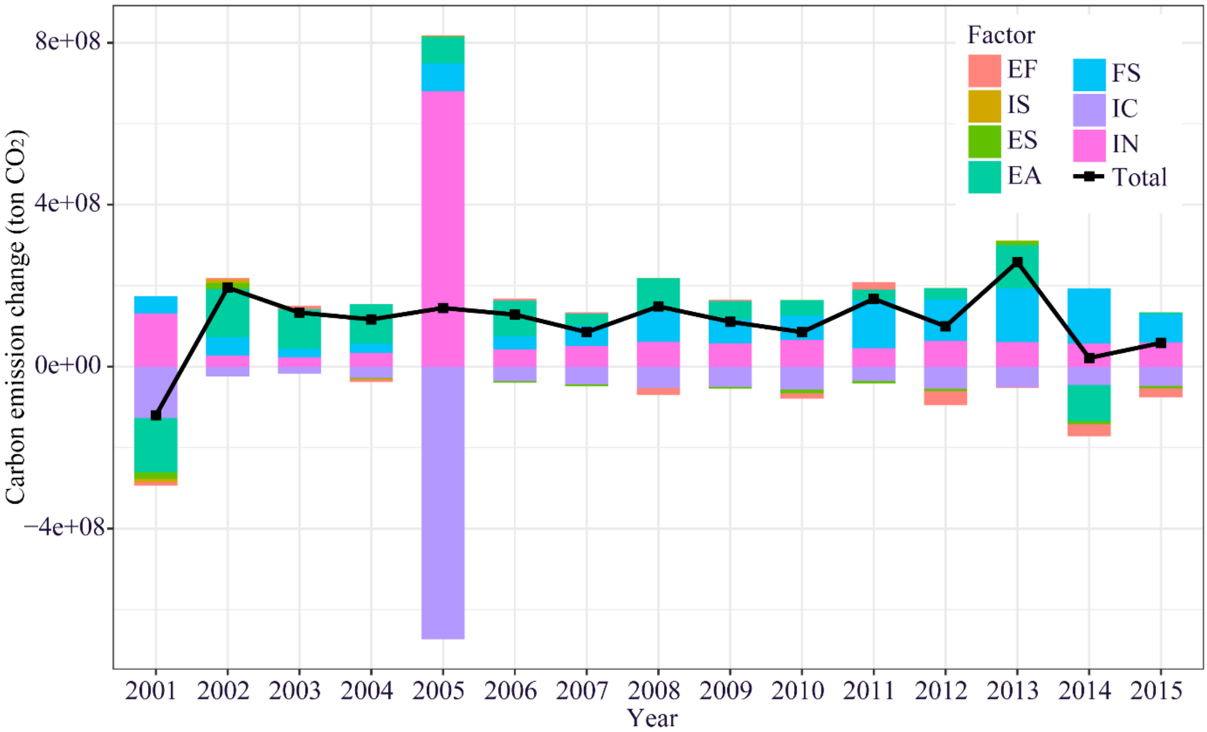


Figure 8. Decomposition of the CO_2 emissions of the building operation phase

4.3.2. Positive factors

The most important factors that contribute positively to the carbon emissions level are urban development, floor space effect, and energy demand from appliance effect, contributing 1462.82, 1035.67, and 605.62 million ton CO_2 respectively.

The rapid urban development of China causes a significant increase of carbon emissions from 2000-2015. Road length, which is commonly used as a proxy indicator for infrastructure development and urbanization, is increasing at an average rate of 14.15% every year (Dickerson, 2013). From 2010, the rate of increase is relatively stable at around 3%. According to Zhang and Lin (2012), urbanization has a positive impact on energy consumption and carbon emissions, which explains its significant contribution on carbon emissions.

In accordance with Nie and Kemp (2014), floor space effect, represented by square meter per capita is one of the significant contributing factors to residential energy consumption. The indicator is commonly used to represent the residents' living circumstances. As can be seen from Table 3, the factor has been the largest contributor to carbon emissions since 2011. This is consistent with Nie and Kemp (2014) who found that floor space effect has been the largest contributor to carbon emissions from 2007-2010. The results show that the living circumstance of residents in China has been consistently improving. The other indicator that represents the living circumstance of residents, i.e. energy demand from appliance, has also been improving, causing a significant increase in carbon emissions. The performance of these two indicators from 2000 to 2015 are shown in Figure 9. The floor space effect indicator has risen from 23.45 to 45.70 m^2 per capita. Similarly, the energy demand from appliance indicator has risen from 10.67 to 16.85 kg sce per m^2.

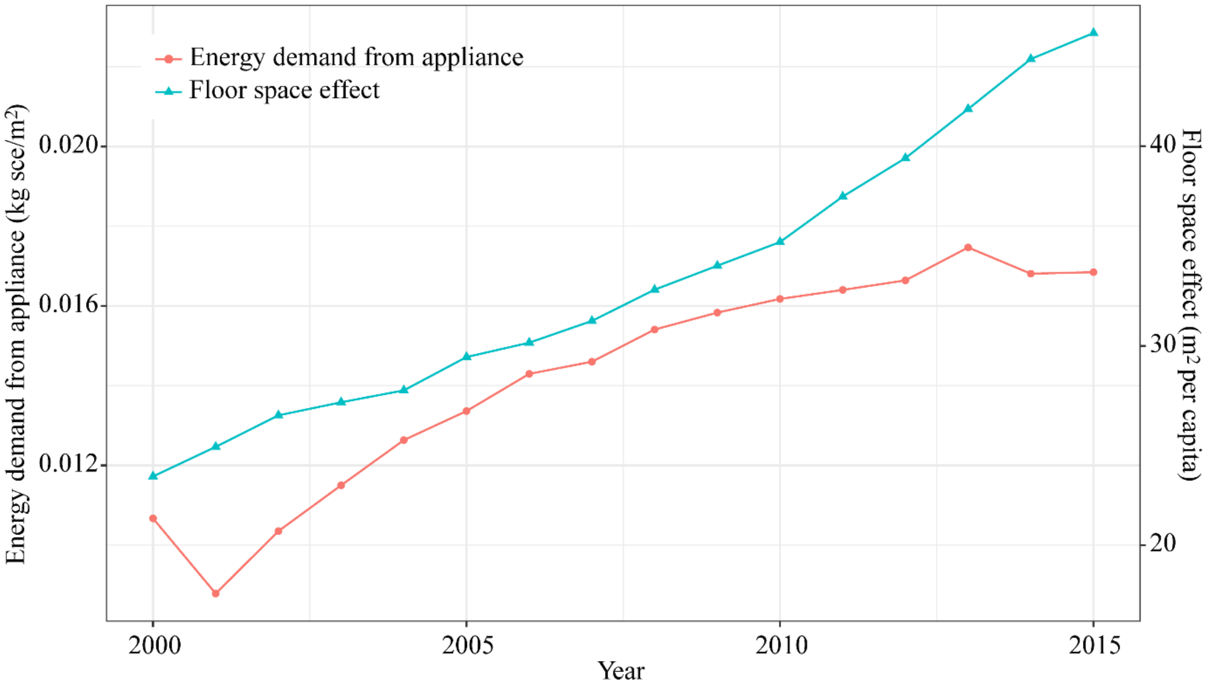


Figure 9. The performance of EA and FS from 2000 to 2015

4.3.3. Negative factors

Four factors are found to contribute negatively to the carbon emissions level from the building operational stage in China. Infrastructure capacity, emission factor, energy structure and industry structure contribute -1341.87, -89.10, -37.43 and -1.82 million ton CO_2 from 2001 to 2015. Infrastructure capacity, a proxy indicator for urban development density, is the most significant one. This finding is in accordance with Norman et al. (2006), who investigated the energy and GHG performance of both low-density and high-density development in Toronto in 1996 and found that low-density development is more energy and GHG intensive when compared with high-density development.

In addition, in accordance with previous studies (e.g. Zhang and Guo, 2013; Donglan et al., 2010), the contribution of emission factor is relatively considerable, valued at 89.10 million ton CO_2, mainly caused by the less use of energy in electricity production. This is caused by two reasons. The percentage of coal-fired electricity generation in China is gradually decreasing from 82.33% in 2000 to 74.24% in 2005, as shown in Table 5. In addition, the standard coal consumption for producing 1 kwh electricity is reduced from 392 g sce to 315 g sce. These two factors lead to the limited decrease of carbon emissions.

Table 5. The percentage of four types of power generation

Year	Thermal	Hydro	Wind	Nuclear	Average energy consumption for thermal power (g sce/kwh)
2015	74.24%	19.59%	3.22%	2.96%	315
2014	75.93%	18.93%	2.78%	2.36%	319
2013	78.36%	16.98%	2.61%	2.06%	321
2012	78.51%	17.59%	1.94%	1.96%	325
2011	81.75%	14.91%	1.50%	1.84%	329
2010	79.85%	17.31%	1.07%	1.77%	333
2009	81.31%	16.78%	0.00%	1.91%	340
2008	81.02%	16.99%	0.00%	1.99%	345
2007	83.26%	14.84%	0.00%	1.90%	356
2006	82.85%	15.24%	0.00%	1.92%	367
2005	81.98%	15.90%	0.00%	2.13%	370
2004	81.63%	16.07%	0.00%	2.29%	376
2003	82.86%	14.87%	0.00%	2.27%	380
2002	80.91%	17.55%	0.00%	1.53%	383

2001	79.96%	18.85%	0.00%	1.19%	385
2000	82.33%	16.43%	0.00%	1.24%	392

One interesting finding is that energy structure has led to lower than expected carbon reduction in the building operation stage, especially given its significant total emissions. Figure 10 shows the energy structure in the building operation stage from 2000 to 2015 and the significant increase in coal usage from 2000 to 2015 explains the lower than expected carbon reduction from energy structure.

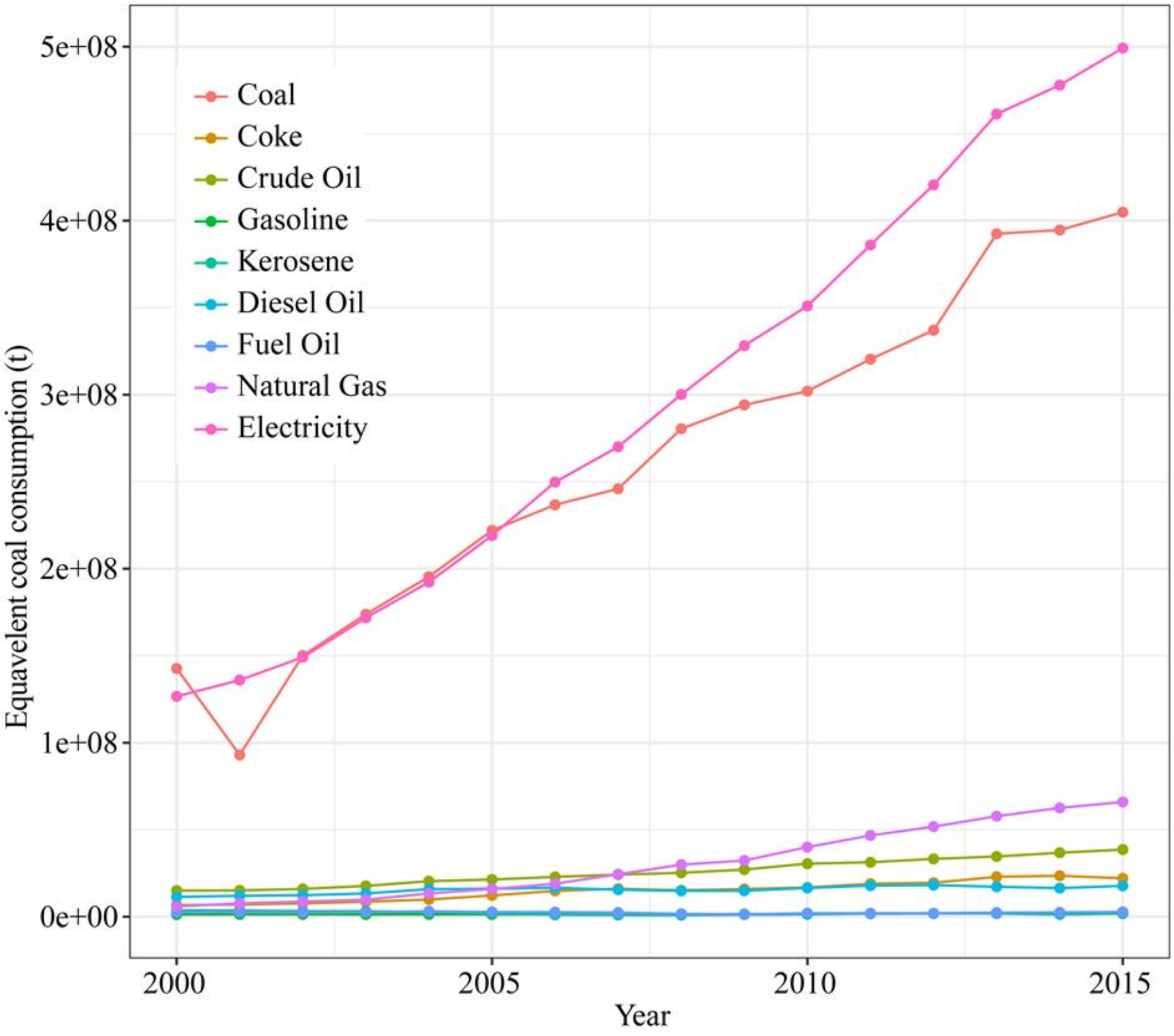


Figure 10. The energy structure of building operation from 2000-2015

In addition, the change of industry structure, i.e. the composition of building energy consumption from various building types and sources, has been observed. Figure 11 shows the composition of energy consumption from the six sources. The share of residential energy consumption has been decreasing from 40.70% in 2000 to 33.44% in 2015 while the shares of other building types, including industrial buildings, construction buildings, retails buildings and others have been stable. Heat and steam consumption, as a source of building operational energy, has increased from 11.41% to 14.19%. According to International Energy Agency (2014), the energy intensity of north urban heating in China is lower than commercial buildings from 2006 and has been decreasing since then. The energy intensity of urban heating is approximately 16 kg sce/m^2. Comparatively, the energy intensity of residential and retail buildings is approximately 46 and 72 kg sce/m^2 respectively (Pérez-Lombard, 2008).

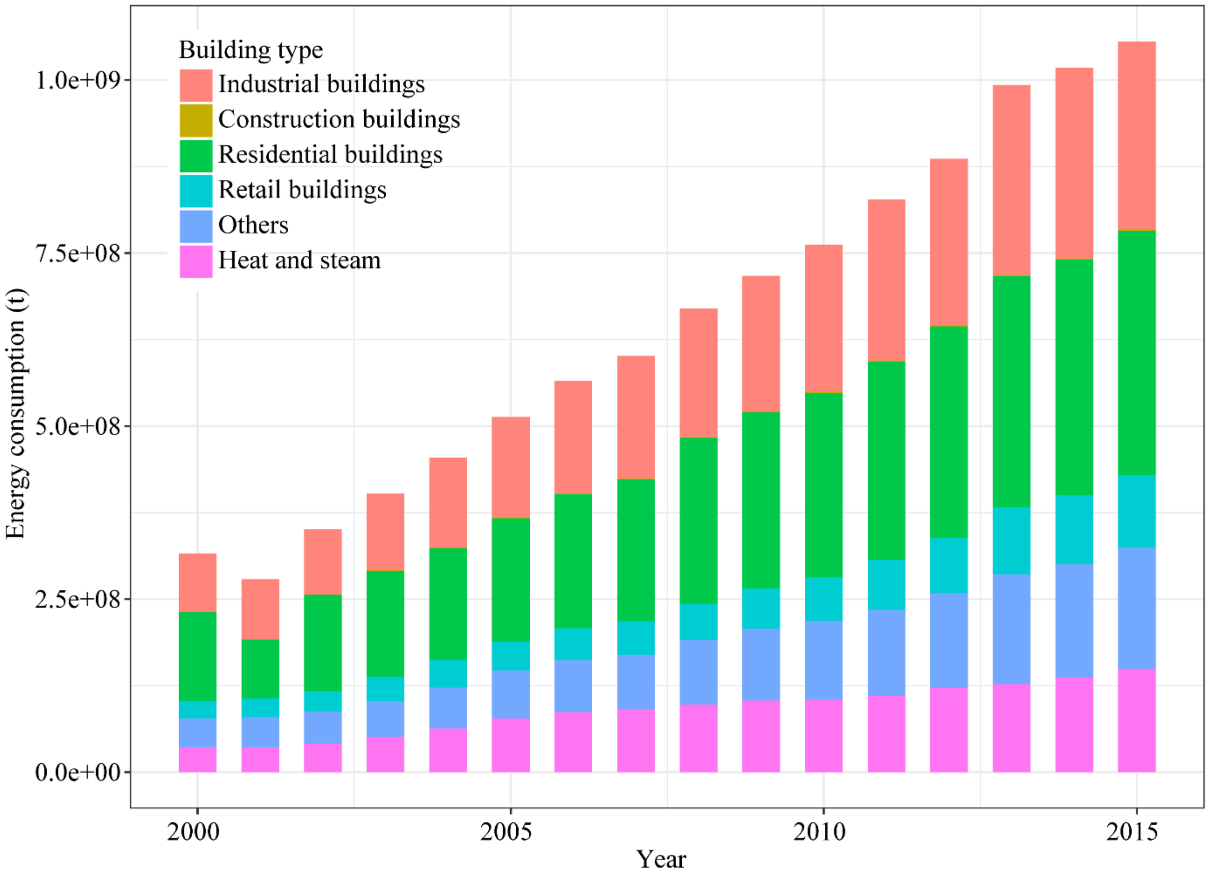


Figure 11. The composition of energy consumption from various building types and sources

5. Discussions

5.1. Influence factors

Compared with previous studies on the estimation and analysis of the carbon emissions of China's building and construction industry, it is found that building operation has a higher impact. Zhang and Wang (2016) found that building operation accounts for approximately 24% of the overall carbon emissions from the industry. The reason is that steam and heat consumption represents a significant portion of the energy consumption of buildings in winter and the energy sources of steam and heat consumption include both coal usage and electricity consumption. In addition, construction and industry onsite offices and accommodations are also classified as buildings which were not included in previous estimation. By doing so, the contribution of building operation is estimated to increase to 40%.

The empirical results also reveal a few interesting findings. The most significant contributing factor to the life-cycle carbon emissions of China's building and construction industry is the rapid urbanization effect. This is in accordance with previous studies, such as Chang (2010), who argued that economic growth will increase energy consumption and carbon emissions. In the extraction and use of raw materials, urbanization, represented by the total constructed floor area of buildings, is the most significant contributing factor, valued at 1.8 billion ton CO_2. In the construction stage, urbanization is also the most significant contributing factor, which is valued at 91.62 million ton CO_2. The value is more than all other carbon reduction effort, including changing energy structure towards a clean one and improving energy efficiency. Similarly, rapid urbanization, is the largest contributing factor to carbon emissions from building operation and is valued at 1.46 billion ton CO_2. With a predicted annual urbanization rate of 1.46% from 2015 to 2030, it is extremely difficult to achieve the mitigation target from this perspective (Sun et al., 2017).

The change of energy structure has been clearly observed in both the construction stage and the building operation stage. According to Xu et al. (2014), coal remains to account for almost 70% of the energy consumption. In order to reduce carbon emissions, effort has to be made in changing the energy structure, especially in the building operation stage, which accounts for 40% of the whole industry's emissions. However, from 2000 to 2015, the use of coal in the construction stage increases by 60%. At the same time, the use of coal in the building operation stage has increased from 199.74 million ton to 566.82 million ton, which is a 184% increase. Consequently, although effort has been made to change to energy structure towards a sustainable one, minimal reduction is observed in the construction stage (1.50 million ton CO_2) and the building operation stage (37.43 million ton CO_2). The finding clearly indicates that coal usage has a dominant effect in determining the energy structure of China, which is in accordance with Xu et al. (2014) and effort can be made to replace coal usage with clean energy, such as natural gas, to considerably help reduce carbon emissions in both the construction and building operation stages. By excluding civil engineering activities, the contribution of energy structure to carbon reduction is relatively small when compared to previous studies, such as Lu et al. (2016) who found that energy structure contributes to approximately 3.5 million ton CO_2 reduction from 2000 – 2012.

The empirical results also show that the living condition is improving in China and the rising living circumstance leads to an increase in carbon emissions in the building operation phase. The energy demand from appliance factor, represented by energy consumption per square meter, is increasing steadily from 5kg sce/m^2 to 35 kg sce/m^2. In addition, the floor space effect, represented by square meter per capita, increases from 23.45m^2 per person to 45.70m^2 per person. As better living standards is one of the main targets in the new 13th five year plan (2016-2020) (National Development and Reform Commission, 2016), it may be difficult to achieve reduced carbon emissions from this perspective.

5.2.Policy implications

The strategies that have demonstrated their effectiveness in reducing carbon emissions in the building and construction industry from 2000 to 2015 are therefore ranked as follows:

1. Increased development density (in the building operation stage), valued at 1341.87 million ton CO_2;
2. Lower emission factors (in the building operation stage), valued at 89.10 million ton CO_2;
3. Better energy efficiency (in the construction stage), valued at 57.60 million ton CO_2;
4. Improved energy structure (in the building operation stage), valued at 37.43 million ton CO_2;
5. Lower emissions factors (in the construction stage), valued at 3.7 million ton CO_2;
6. Changed industry structure (in the building operation stage), valued at 1.82 million ton CO_2.
7. Improved energy structure (in the construction stage), valued at 1.5 million ton CO_2.

In building operation, which is the single largest contributor to carbon emissions, it is found that the contribution of energy structure is relatively limited due to the large amount of coal usage before 2013 (Nie and Kemp, 2014). According to Qi et al. (2016), it is found that China has reached its peak coal consumption in 2014 and as coal consumption is limited, energy structure will play a positive role in reducing carbon emissions. In addition, according to Norman et al. (2006), low-density suburban development is more energy intensive (at an approximate scale of 2.0-2.5) than high-density development on a per capita basis. This study also shows that, development density (using infrastructure capacity as a proxy indicator) is the single most important strategy to reduce carbon emissions in the building operation stage, which provides useful policy implications for establishing emission reduction strategies.

6. Conclusions

As the largest carbon dioxide emitter, China has considerable responsibility in reducing its emissions gradually. The main contribution of this study is to evaluate the carbon emissions of the building and construction industry from a life cycle perspective. Using the Logarithmic

Mean Divisia Index method, the changes of carbon emission in the stage of material extraction and usage are decomposed into three factors, including material structure, environmental efficiency and constructed floor area. All three factors contribute positively to the carbon emissions level. Similarly, the reduction in the construction stage are decomposed into five factors, which are emission factor, energy structure, energy efficiency, unit cost effect and constructed floor area. In these five factors, constructed floor area and unit cost effect contribute positively to the carbon emissions level, and energy efficiency has demonstrated their effectiveness in reducing carbon emissions. In addition, the changes of carbon emissions in the building operation stage are decomposed into seven factors, which are emission factor, industry structure, energy structure, energy demand from appliance, floor space effect, infrastructure capacity (a proxy indicator for development density) and infrastructure development (a proxy indicator for urbanization). In these seven factors, infrastructure capacity, emission factor, energy structure and industry structure have been effective to reduce the carbon emissions in the building operation stage. On the other hand, infrastructure development, floor space effect and energy demand from appliance contribute positively to the carbon emissions level. From the life cycle perspective, the most effective strategies that have been adopted to achieve carbon reduction in China’s building and construction industry are increased development density, better emission factors, better energy efficiency in the construction stage and improved energy structure.

This study faces several limitations. For simplicity, a number of proxy indicators are used. However, development density and urbanization are complicated and future studies are recommended to develop comprehensive models for these two indicators. Although the contribution of demolition, waste disposal, reuse and recycling is relatively limited, these stages should be included in future studies, as they are integral parts of the building life cycle.

In addition, the model for calculating the energy consumption from various building types can be improved if more accurate data can be obtained.

Acknowledgements

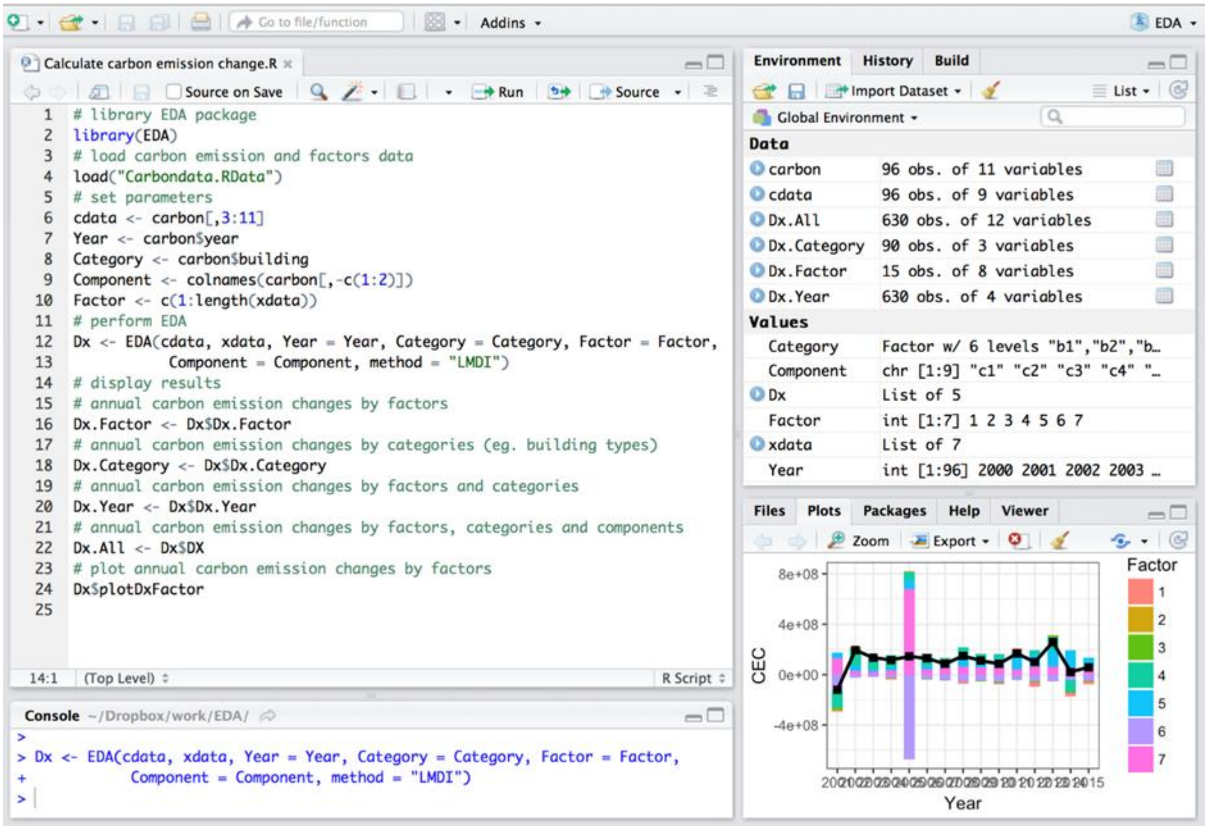
The funding information is excluded at this stage to ensure blind review. It will be added at a later stage.

Supplementary material

From this study, an Energy Decomposition Analysis (EDA) R package is developed for energy decomposition analysis and to conveniently calculate carbon emission changes using different methods. The EDA R package is available on the Comprehensive R Archive Network (CRAN) (https://CRAN.R-project.org/package=EDA). The EDA R package provides five methods for energy decomposition analysis and carbon emission changes calculation, including LMDI and four other classical methods, including Laspeyres (Marlay, 1984), Paasche (Paasche, 1874), Marshall-Edgeworth (Marshall, 1887; Edgeworth, 1925), and Walsh (1921). It also provides an exemplar dataset, so that users can convert their own data to the same format and easily utilize the package (see Figure 12). Once the data is prepared, users can perform EDA function using the following code:

```
Dx <- EDA(cdata, xdata, Year = Year, Category = Category, Factor = Factor, Component = Component, method = "LMDI")
```

The EDA R package provides abundant calculation results and their visualizations, including carbon emission changes by factors, by categories, by both factors and categories, and by factors, categories and energy consumption components. The results also include the figure of carbon emission changes by factors, which is usually regarded as the primary outcome of carbon decomposition analysis by researchers.



```r
# library EDA package
library(EDA)
# load carbon emission and factors data
load("Carbondata.RData")
# set parameters
cdata <- carbon[,3:11]
Year <- carbon$year
Category <- carbon$building
Component <- colnames(carbon[,-c(1:2)])
Factor <- c(1:length(xdata))
# perform EDA
Dx <- EDA(cdata, xdata, Year = Year, Category = Category, Factor = Factor,
           Component = Component, method = "LMDI")
# display results
# annual carbon emission changes by factors
Dx.Factor <- Dx$Dx.Factor
# annual carbon emission changes by categories (eg. building types)
Dx.Category <- Dx$Dx.Category
# annual carbon emission changes by factors and categories
Dx.Year <- Dx$Dx.Year
# annual carbon emission changes by factors, categories and components
Dx.All <- Dx$DX
# plot annual carbon emission changes by factors
Dx$plotDxFactor
```

```
14:1    (Top Level)                                    R Script
```

```
Data
carbon        96 obs. of 11 variables
cdata         96 obs. of 9 variables
Dx.All        630 obs. of 12 variables
Dx.Category   90 obs. of 3 variables
Dx.Factor     15 obs. of 8 variables
Dx.Year       630 obs. of 4 variables
Values
Category      Factor w/ 6 levels "b1","b2","b…
Component     chr [1:9] "c1" "c2" "c3" "c4" "…
Dx            List of 5
Factor        int [1:7] 1 2 3 4 5 6 7
xdata         List of 7
Year          int [1:96] 2000 2001 2002 2003 …
```

```
Console ~/Dropbox/work/EDA/
>
> Dx <- EDA(cdata, xdata, Year = Year, Category = Category, Factor = Factor,
+            Component = Component, method = "LMDI")
>
```

Figure 12. Interface and primary codes of carbon emission change calculation using the EDA R package

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