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Life-cycle CO_2 Emissions and Their Driving Factors in Construction Sector in China

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Abstract: As the construction sector is a major energy consumer and thus a significant contributor of CO_2 emissions in China, it is important to consider carbon reduction in this industry. This study analyzed six life-cycle stages and calculated the life-cycle CO_2 emissions of the construction sector in 30 Chinese provincial jurisdictions to understand the disparity among them. Results show that building materials production was the key stage for carbon reduction in the construction sector, followed by the building operation stage. External variables, e.g., economic growth, industrial structure, urbanization, price fluctuation, and marketization, were significantly correlated with the emission intensity of the construction sector. Specifically, economic growth exhibited an inverted U-shaped relation with CO_2 emissions per capita and per area during the period examined. Secondary industry and land urbanization were negatively correlated with CO_2 emission intensity indicators from the construction sector, whereas tertiary industry and urbanization were positively correlated. Price indices and marketization had negative effects on CO_2 emission intensity. The policy implications of our findings are that cleaner technologies should be encouraged for cement providers, and green purchasing rules for the construction sector should also be established. Pricing tools (e.g., resource taxes) could help to adjust the demand for raw materials and energy.

Keywords: life-cycle; CO_2 emission; construction sector; multi-regression; influencing factor

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1 Introduction

Global climate change is recognized as one of the toughest challenges facing society in the 21st century. In addition to natural processes, intensive economic activity has greatly escalated climate change due to greenhouse gas emissions resulting from fossil fuel combustion. China, as the world's biggest developing country and largest carbon emitter, has pledged to lower CO_2 emissions per gross domestic product (GDP) by 60%–65% from 2005 levels by 2030 (National Development and Reform Commission, 2015). According to The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC., 2014), the construction sector accounts for about 32% of total energy consumption worldwide and is therefore responsible for a large share of the global CO_2 emissions. From a life cycle perspective, the production of building materials (e.g., cement and steel) discharges huge volumes of CO_2 as a result of fuel combustion and the operation of industrial processes (Shan et al., 2017). Carbon emissions resulting from embedded energy consumption are also generated during the extraction and transportation of building materials as well as the construction, operation, and demolition of buildings (Cheng et al., 2015; Zhang and Wang, 2016b). However, traditional production-based accounting methods only incorporate the construction phase when accounting for the energy consumption and

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carbon emissions of the construction sector. This approach obviously obscures the full picture. Thus, a holistic approach is required.

A life-cycle analysis (LCA) is often adopted as an effective approach to facilitating CO_2 emission accounting. This method, which offers a 'cradle to cradle' perspective on consumable products or services, has been extensively applied at various levels (Castelo Branco et al., 2013; Ren et al., 2016; Robertson, 2016; Zhou et al., 2016). For example, Feiz used LCA together with key performance indicators to assess the overall performance of the cement industry, including carbon emissions (Feiz et al., 2015). LCA has also been applied to explore a range of construction-related topics, among which individual buildings, structures, and materials are of interest. For example, Yan et al. (2010) discovered that the embodied GHG (greenhouse gas) emissions of building materials were the major emission source of a building, while Bin and Parker (2012) reached the same conclusion by examining the REEP (Residential Energy Efficiency Project) House, a century-old single detached house located in downtown Kitchener, Canada. The embodied carbon in modern construction methods was compared with that of traditional methods by Monahan and Powell (2011) using LCA, who found a 34% reduction in embodied carbon if modern methods were adopted. LCA was also applied in a study of CO_2 emissions from detached, semi-detached, and terraced houses in the UK (Cuéllar-Franca and Azapagic, 2012). Only a very limited number of studies has considered the construction sector from a macro perspective. Zhang et al. proposed a three-stage life cycle accounting approach to examine the construction sector in China and found that the construction stage made up over 60% of the total energy consumption of the sector (Zhang and Wang, 2016a). Previous investigations of the factors influencing carbon emissions have considered carbon intensity (Lu et al., 2016; Du et al., 2017), energy intensity (Lin and Liu, 2015), and energy efficiency (Liu and Lin, 2017), which are direct factors that are specific to each individual industry, whereas the external socioeconomic environment has rarely been discussed (Tang et al., 2012). To summarize, while many examinations of specific buildings and materials have used the LCA approach, much less attention has been given to larger scale (i.e., regional or national) analyses. The few macro studies that have been conducted did not examine regional discrepancies and socioeconomic factors, resulting in a noticeable research gap that needs to be addressed to facilitate effective policy making.

This study aims to investigate the CO_2 emissions from the construction sector in 30 provincial jurisdictions in China and the socioeconomic factors that influence the emissions. Three indices, i.e., gross emission, emission per area (EPA), and emission per capita (EPC), were analyzed at the provincial level. Furthermore, external environmental variables (i.e., the influencing factors) were considered based on previous research and our assumptions, trying to understand the reason for disparities among emissions in each province. Empirically, we used multiple regression, spatial autocorrelation, and panel regression analyses to evaluate the relations between socioeconomic factors and CO_2 emissions from the construction sector. Policy suggestions were proposed after an in-depth discussion of the implications of the findings. This study makes a significant contribution to CO_2 emission reduction initiatives by: 1) geographically and temporally accounting for CO_2 emissions from the construction sector in China and 2) exploring the socioeconomic factors that cause those discrepancies.

2 Materials and Methods

2.1 Study area

This study focuses on 30 provincial administrations in China; it does not consider Tibet, Hongkong, Macao, and Taiwan because limited data were available for the calculation of CO_2 emissions from their construction sectors. The provinces or municipalities investigated were located in mainland China, with a diverse range of geographical conditions, various states of environmental quality, and multiple different economies; of course in different patterns of the development of the construction sector. Viewed from the perspective of the construction sector, the value added by the sector has increased over time in most provinces or municipalities, as shown in Fig. 1a. The construction area, e.g., the floor space of completed buildings (Fig. 1b), and the population (Fig. 1c) that drive the sector varied among the 30 provinces or municipalities. Due to these differences, when considering the importance of emissions from the sector, we focused on those emissions from the construction sector that were strongly related to the economic conditions of each province.

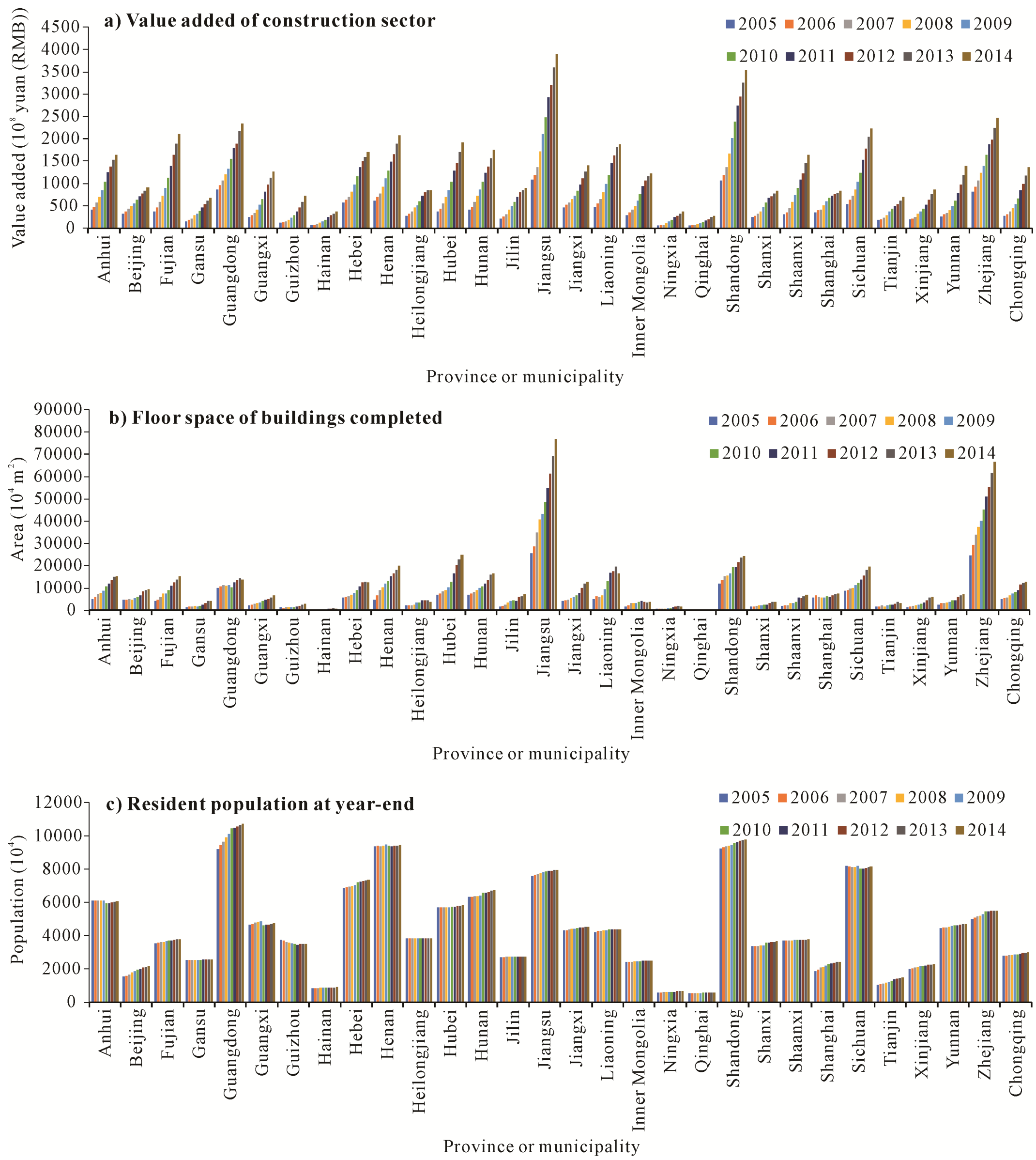

Fig. 1 Differences in construction activities and population among 30 provinces or municipalities. Data source: National Bureau of Statistics of China (2006–2015)

2.2 Life-cycle accounting for the construction sector

Six life-cycle stages of the construction sector were investigated: materials production, materials transportation, construction, operation, demolition, and waste disposal. Given that, in China, a negligible fraction (< 1%) of construction waste is reused (Wang, 2014), the waste-recovery stage was excluded in this study. The total emission was equal to the sum of emissions from all six stages:

$$Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 \quad (1)$$

where Q is the total emissions from the construction sector, Q_1 is the emissions from the materials production stage, Q_2 is the emissions from the materials transportation stage, Q_3 is the emissions from the construction stage, Q_4 is the emissions from the operation stage, Q_5 is the emissions from the demolition stage, and Q_6 is the emissions from the waste disposal stage.

For each stage of the construction sector, the total CO_2 emissions can be calculated as follows:

$$E = \sum AD \times EF \quad (2)$$

where E is the total CO_2 emission (t). AD is activity data, and EF is the emission factor (volume of emission per unit activity). The specific definitions of *AD* and *EF* varied in the different stages. In the materials production stage, *AD* is the quantity of a certain material, and *EF* is the CO_2 emissions factor for the production of that material. In the materials transportation stage, *AD* is the quantity of a material multiplied by the distance it is transported, and *EF* is the emissions factor for a specific mode of transportation. In the building construction, operation, and demolition stages, *AD* is the amount of energy consumed during the various activities in each stage, and *EF* is the emission factor for a specific energy source such as coal, oil, or gas. The unit for *AD* is the t or m^3 of energy consumption (for non-gas and gas energy types, respectively), and the unit for *EF* is ton per t/t or t/m^3 based on the specific energy type. In the final stage, construction and demolition waste was assumed to be transported to landfills by trucks travelling an average distance of 20 km (Li, 2009), and the emissions were calculated by the method used in the second stage.

2.3 Econometric model for influencing factors of construction emissions

Regressions were used to empirically reveal the factors influencing CO_2 emissions from the construction sector. The socioeconomic factors were income level, industrial structure, construction development, urbanization rate, price, market, and globalization. The relations of CO_2 emissions with these factors can be described as follows:

$$\begin{aligned}\ln Q = C + \beta_1 \ln GDP + \beta_2 \ln IS + \beta_3 \ln Cons + \\ \beta_4 \ln Urb + \beta_5 \ln Price + \beta_6 \ln Mkt + \\ \beta_7 \ln Glb + \varepsilon_{it}\end{aligned} \tag{3}$$

where Q is the quantity of CO_2 emissions; *IS*, *Cons*, *Urb*, *Mkt* and *Glb* stand for industrial structure, construction development, urbanization rate, market and globalization, respectively; β is the regression coefficient of each variable, and ε_{it} is a random error term derived from the individual *i* and time *t* effects. In this study, we collected data for the period from 2005 to 2014 for 30 provinces or municipalities for which the panel regressions were able to reveal the influence of both the time-series and the individual province. A cointegration test and causality relationship test were conducted before the regressions, i.e., a multiple regression (ordinary least square, OLS) and panel regressions (fixed-effect model, FEM; random-effect model, REM), respectively.

With the emissions and socioeconomic data for the 30 provinces or municipalities, the potential existence of spatial autocorrelation was investigated. Global Moran's *I* index was calculated as Equation (4):

$$\text{Moran's } I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(y_i - \bar{y})(y_j - \bar{y})}{(\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij})\sum_{j=1}^{n}(y_j - \bar{y})^2} \tag{4}$$

In this equation, y_i and y_j represent the attributes of provinces or municipalities *i* and *j*, respectively, *n* is the number of provinces or municipalities, and W_{ij} represents the spatial weighting matrix describing the spatial relations between regions, ranging from 0 (for nonadjacent provinces or municipalities) to 1 (for adjacent provinces or municipalities). The Moran's *I* value range is [–1, 1]. The closer it is to 1, the greater is the clustering trend, and the closer it is to –1, the greater is the dispersion effect. A value of 0 represents no spatial dependence. However, the Moran's *I* value makes sense only when it is statistically significant; non-significant values cannot show reliable spatial relations.

2.4 Data

Only the major construction materials, such as steel, timber, cement, glass, and aluminum, were taken into account due to data availability. Emissions factors for the different fuel types were collected from the literature (Hong, 2004; Zhao et al., 2004; Yan and Yang, 2007; Wang, 2009; Luo et al., 2011; Gao, 2012; Qi et al., 2014). Data for building material quantity, transport distance, and the construction area were obtained from the China Statistical Yearbook (2006–2015). Energy consumption data for the building construction and operation stages were obtained from the China Energy Statistical Yearbook (2006–2015). The socioeconomic data used in the regressions, also obtained from the China Statistical Yearbook (2006–2015), included GDP, added value of the real estate industry, added value of industry, gross product of construction, added value of construction, residential population at the end of the year, GDP per capita, added value of accommodations and catering, added value of secondary industries, added value of tertiary industries, land urbanization rate, population urbanization rate, industrial producer price index, energy price index, state-owned investment in fixed assets, and foreign direct investment (FDI).

3 Results

3.1 CO_2 emissions from construction sector

The CO_2 emission indicators for the construction sector, i.e., gross emission, EPC, and EPA, showed rising trends during 2005–2014 in most provinces or municipalities. However, different patterns were found when the three indicators were examined separately.

Fig. 2a shows the total CO_2 emission from the construction sector and the average annual growth rate for the 30 Chinese provincial jurisdictions from 2005 to 2014. The emissions in most provinces or municipalities increased over the study period. The fact that 23 of the 30 provinces or municipalities had growth rates over 10% was reflected in the fact that CO_2 emissions from the construction sector in most provinces or municipalities were rapidly increasing. In comparison, Beijing and Shanghai, the two megacities whose emissions had been constant over time, had much lower emission growth rates (1.72% and 0.59%, respectively). The CO_2 EPA from the construction sector is defined as total emissions divided by the area of land under construction. A continuous increase in the EPA was apparent across the whole country, with an average annual growth rate of 6.64%. At the provincial level, Fig. 2b shows that the EPA increased in 28 provinces or municipalities during the period studied. Beijing and Shanghai were the only two jurisdictions with a continuous decrease, with average annual growth rates of –0.96% and –3.28%, respectively. The EPC of the construction sector exhibited a similar rising trend in 22 provinces or municipalities with average annual growth rates over 10%, as shown in Fig. 2c. In contrast, there was a slight decline in emissions per capita in Beijing and Shanghai during the period investigated, with average annual growth rates of –2.01% and –2.16%, respectively.

As can be seen, in the three subgraphs where the provinces or municipalities are shown in the same order, similarities are apparent, as are discrepancies. Hainan had the highest average annual growth rates for all three emission indicators, while Shanghai and Beijing had the lowest growth rates. In contrast, Figs. 2b and 2c reveal different patterns. For example, Qinghai and Tianjin had EPC and EPA values significantly larger than the national averages. Such provincial discrepancies imply that, in addition to population and area, emissions might be affected by other factors.

3.2 Contribution of life-cycle processes

The processes that contributed most to these large discrepancies were examined. From a life-cycle perspective, the contributions of the six stages of the construction sector to the total CO_2 emissions are shown in Fig. 3. During the period investigated, the share of emissions from the building materials production stage increased from 62.30% to 70.43%. The building operation stage had the second largest share of emissions, accounting for approximately 30% of total emissions, although this decreased by 8.25% during the period investigated. Interestingly, the construction stage, which is the only stage that traditional production-based carbon accounting methods take into account, accounted for a negligible fraction (< 2%) of total emissions. In other words, approximately 98% of the CO_2 emissions from the construction sector, and its consequent responsibility, have been 'secretly' shifted to other sectors. These results are in line with previous studies (Chen et al., 2017; Wang et al., 2017). In China, production of the raw materials used in construction, especially cement, steel, and glass, is highly energy intensive and therefore contain significant embedded emissions. With the production of these materials and other products largely driven by demand from the construction sector, the materials production stage has become the overwhelmingly dominant stage in terms of CO_2 emissions; however, this is unfortunately neglected by production-based accounting methods. As is obvious in Fig. 3, the building operation stage was a major contributor that should be taken into account when devising mitigation policies. Even when combined, the emission contributions of the other stages were much less significant at the national scale.

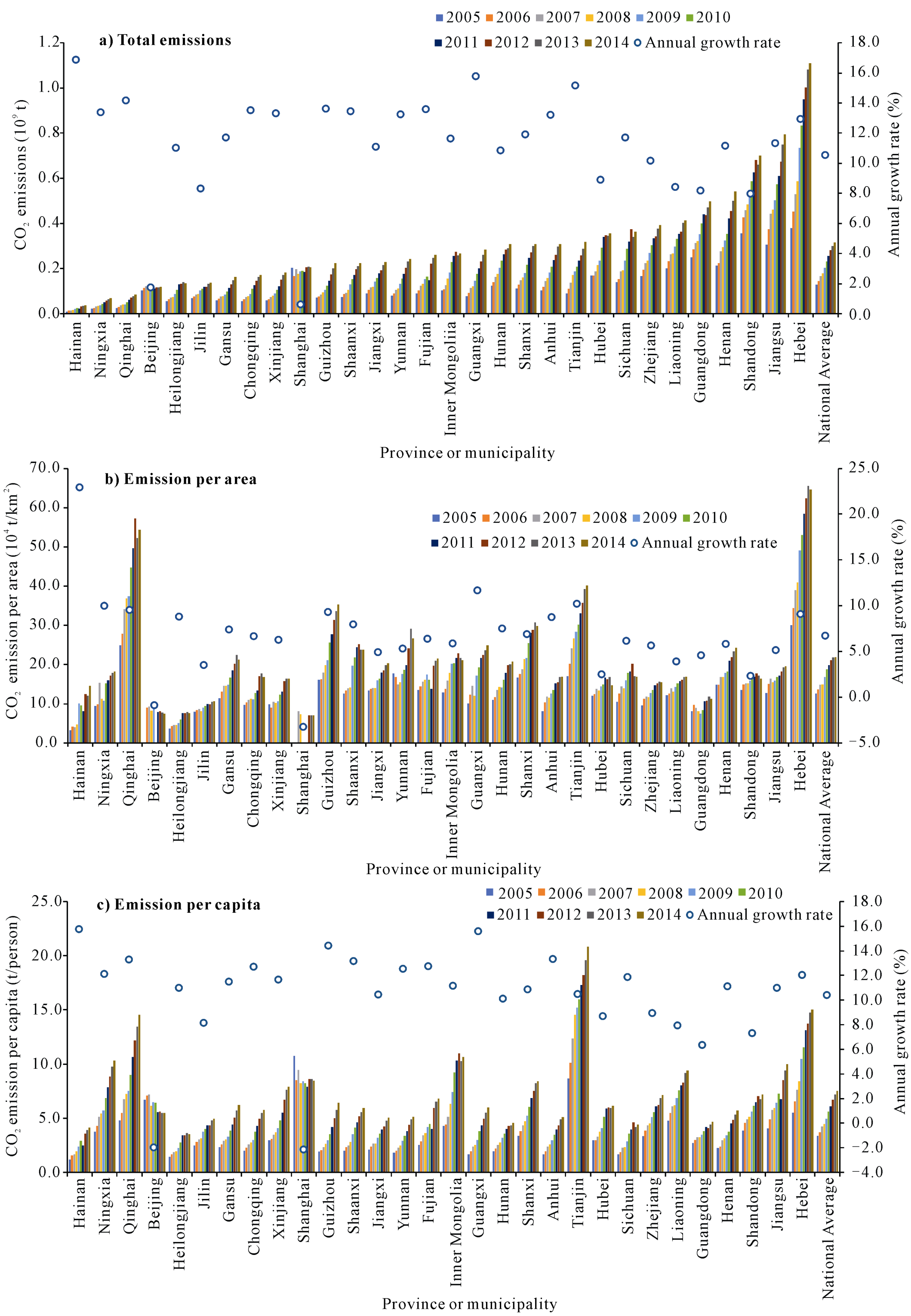

Fig. 2 CO_2 emission trends from the construction sector of provinces in China from 2005 to 2014

The emission contributions at the provincial level were also investigated, and significant differences were discovered among provinces or municipalities. Fig. 4 shows the share of emissions from each life-cycle stage in each province. Specifically, the share of emissions from the building materials production stage ranged from 10.8% (Beijing) to 86.0% (Hebei), which partially explains why the emissions in Fig. 2 have such large

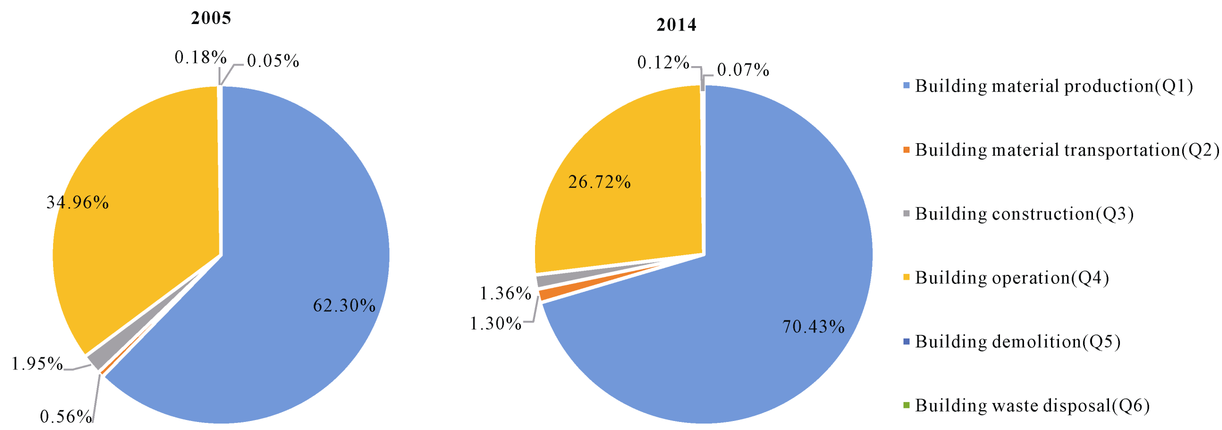

Fig. 3 Composition of CO_2 emission from each stage of Chinese construction sector at national level in 2005 and 2014

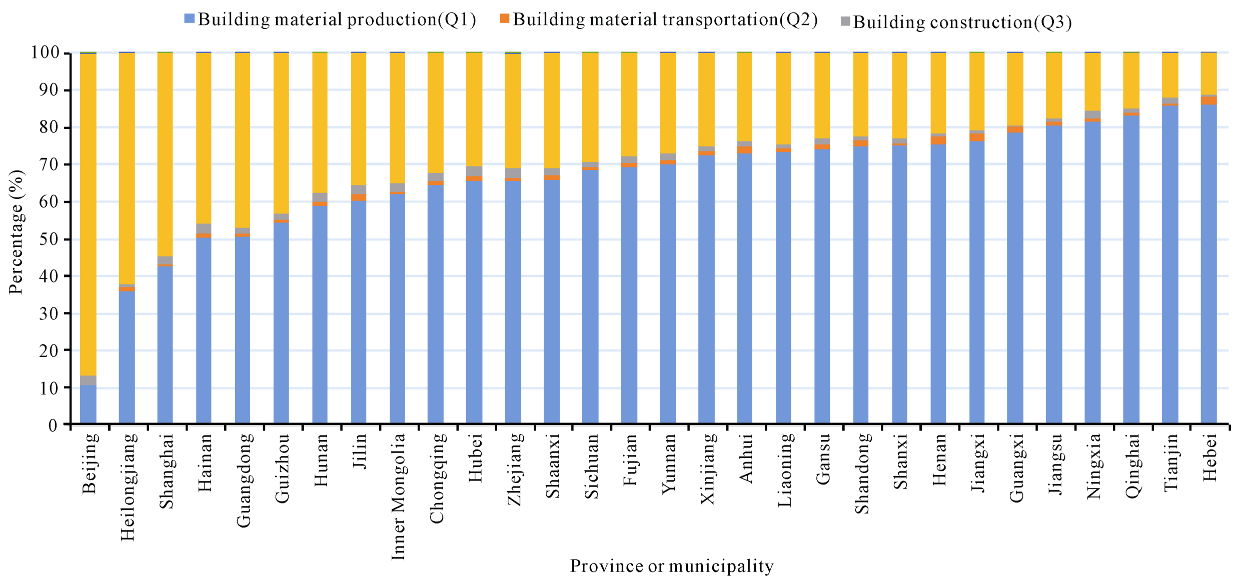

Fig. 4 Composition of CO_2 emission from each stage at the provincial level in China

variances. In general, the greater the role of the building materials production stage is in the construction industry within a province, the larger its CO_2 emission would be. Therefore, the extent of the building materials production within a province and any corresponding energy efficiency might significantly affect the emission performance of a province. For example, in Beijing, the building operation stage was a major source of CO_2 emission. With effective energy-saving technologies and policies, the energy intensity of daily operation could be maintained at a stable and relatively low level (Voigt et al., 2014), which was the case in Beijing. Therefore, the high share and low energy intensity of the building operation stage explains the low emissions of the construction sector in Beijing. In contract, in Hebei, the building materials production stage was responsible for most of the total emissions, and energy efficiency was relatively low in Hebei (Zhang et al., 2015). Thus, it is not surprising that Hebei had such large CO_2 emissions. However, this was a common issue shared by other provinces or municipalities where large amounts of raw materials were produced, intensifying the CO_2 emissions of the construction sector.

4 Socio-economic Factors Influencing CO_2 Emissions

4.1 General hypotheses

As one part of an economic network, the external environment has an impact on the emission performance of the construction sector. For example, socioeconomic factors could affect the demand for materials, technological improvements, and commercial strategies in the construction sector, thereby influencing its CO_2 emissions. Because population and construction area are most likely to affect the intensity of construction activities, EPA and EPC (excluding the impact of population and area) are the most suitable indicators for assessing carbon emissions.

Economic growth is associated with environmental impacts, with the relation often described by an environmental Kuznets curve (EKC). The EKC suggests a possible inverted U-shaped relation between the emission of pollutants and per capita income (Dinda, 2004). According to the theory, economic growth initially stimulates emissions, until a turning point is reached, after which the trend reverses and emissions decrease as a more developed economy is attained. A diminishing marginal potential to emit CO_2 has been reported as GDP per capita rises (Holtz-Eakin and Selden, 1995). Thus, it is assumed that CO_2 emissions from the construction sector follow a similar pattern, with an inverted U-shaped relation with income. In the early stages of economic growth, there is a high demand for buildings, leading to prosperity in the construction sector, with a resultant large amount of undesirable CO_2 emissions. However, such a pattern is reversed when the building market is saturated and the need for new buildings stabilizes. The scale of the construction sector reaches a plateau as the economy develops. At that point, higher energy efficiency and technological improvements help lower the level of CO_2 emissions, possibly leading to a decline in emissions and an increase in gross income.

The industrial structure of an economy can affect the CO_2 emissions of the construction sector. Secondary industries require buildings with a smaller volume than tertiary industries do, while occupying the same land area. Although tertiary industry is usually less energy dependent, it is often located in downtown areas where there are many construction projects. Large buildings are heavy emitters for two main reasons: 1) the large number of materials required to build them and 2) the large energy consumption resulting from their long hours of operation. The prosperity of other construction-related industries might also boost CO_2 emissions from the construction sector. Exemplifying such industries, the real estate industry indirectly creates a very large demand for buildings to sell, driving up CO_2 emissions from the construction sector in certain areas, which may increase overall CO_2 emissions. However, this is not always the case. In China, areas with highly developed real estate markets, e.g., Beijing and Shanghai, often benefit from the application of advanced technology due to high standards regarding cost control and environmental requirements. Therefore, regions with a well-developed real estate industry are likely to exhibit a complex pattern of CO_2 emissions from the construction sector.

Urbanization may significantly affect CO_2 emissions from the construction sector. With the rapid urbanization in China and the higher building density in urban than in rural areas, the total CO_2 emissions from the construction sector are driven by the demand for large construction projects, such as gigantic skyscrapers in urban areas, which require a tremendous amount of raw materials and energy in both the construction and operation stages. A province with a high urbanization rate is likely to have a larger building load; thus, there will be more CO_2 emissions from the construction sector.

Price fluctuations and construction market conditions are also likely to influence the industry and its CO_2 emissions. Taking the cost of building materials as an example, during periods when the costs are high, the use of building materials will become more efficient, leading to curtailed CO_2 emissions. Similarly, a rise in fuel prices will help reduce CO_2 emissions at every stage due to the reduced demand for energy. Theoretically, non-state-owned enterprises are much more sensitive to price fluctuations than are their state-owned competitors (Greer and Doellgast, 2016). Non-state-owned businesses can respond more quickly to market environment changes and adopt advanced technology to survive, reducing CO_2 emissions as a side benefit. In contrast, state-owned companies are much less sensitive to price changes because they are highly dependent on regulations and policies.

Globalization can also play a role in CO_2 emissions from industries. FDI has a complex effect on the environmental performance of many businesses (Yan and An, 2017), including the construction sector. FDI boosts economic growth as well as construction demand, but it also improves energy efficiency during building operation (Pazienza, 2015). Therefore, the net effect remains uncertain and requires further exploration.

4.2 Empirical analysis

Based on the above hypotheses, several models were developed to examine the effects of each factor and check for spatial autocorrelation. The variables used in these models are defined in Table 1, along with their expected relations to EPA and EPC.

EPA and EPC were used as dependent variables. Accordingly, GDP per area and GDP per capita were used to describe the effect of provincial economic development. The added value (shown as GDP%) of the secondary and tertiary industries reflected the economic structure in the different regions. Real estate and construction activities are intuitively related to the life-cycle CO_2 emissions of buildings. Therefore, the contribution of their added value in terms of GDP were also taken into consideration. The effects of both the land urbanization rate and population urbanization rate on CO_2 emissions were considered. The industrial producer price index and energy price index are associated with changes in the cost of both building materials and fuel, with the construction sector sensitive to both. Finally, the percentage of non-state-owned investment in fixed assets and the percentage of FDI within GDP indicated the levels of marketization and globalization.

Multiple-regression models were used to estimate the impact of the above variables on the construction sector. The results of the OLS model, FEM, and REM are shown in Table 2. In the three models, $(\mathrm{LogGDPPA})^2$ was significantly negatively correlated with EPA, reflecting an inverted-U EKC relation between emissions from the construction sector and economic development. This suggests that EPA had already passed the turning point and would decline with further economic growth. EPA exhibited a negative relation with the share of secondary industries. This discovery was in line with our earlier assumption that industrial land had lower construction intensity than did commercial and residential land and emitted less CO_2, leading to lower CO_2 emissions per building area. Other explanatory variables performed differently in the three models. Because the data used contained spatio-temporal information, a panel regression was preferred over the OLS model to

Table 1 Influential factor definitions and their expected relations with EPA (emission per area) and EPC (emission per capita)

Variables	Definitions	Expected relation with EPA	Expected relation with EPC
LogEPA	Log of EPA (EPA: quantity of CO_2 emission per area from construction sector)	/	/
LogEPC	Log of EPC (EPC: quantity of CO_2 emission per capita from construction sector)	/	/
$(\mathrm{LogGDPPA})^2$	Square of Log (GDPPA: GDP per area)	–	/
$(\mathrm{LogGDPPC})^2$	Square of GDPPC (GDPPC: GDP per capita)	/	–
LogP2I	Log of P2I (P2I: percentage of added value from secondary industries in GDP)	–	–
LogP3I	Log of P3I (P3I: percentage of added value from tertiary industries in GDP)	–	?
LogPRE	Log of PRE (PRE: percentage of added value from real estate industry in GDP)	?	?
LogPC	Log of PC (PC: percentage of added value of construction industry in GDP)	+	+
LogPUR	Log of PUR (PUR: population urbanization rate)	+	+
LogLUR	Log of LUR (LUR: land urbanization rate)	?	–
LogIPPI	Log of IPPI (IPPI: industrial producer price index)	–	–
LogEPI	Log of EPI (EPI: energy price index)	–	–
LogMK	Log of MK (MK: marketization, measured by percentage of non-state-owned investment in fixed assets)	–	–
LogGL	Log of GL (GL: globalization, measured by percentage of FDI in GDP)	?	?

Notes: EPA: emission per area; EPC: emission per capita. FDI: foreign direct investment. Signs are used to denote the expected relation. '/' denotes not applicable, '–', '+', and '? ' denotes negative, positive, and uncertain relation, respectively.

Table 2 Model results of EPA (emission per area) using OLS (ordinary largest square method), FEM (fixed effect model) and REM (random effect model)

Variable	OLS	FEM	REM
Constant	–8.710***	0.768***	1.897*
LogGDPPA	–0.032	–0.026*	0.630***
(LogGDPPA)^2	–0.017	–0.769*	–0.051***
LogP2I	–0.770**	–1.176***	–0.572^
LogP3I	–1.371***	0.117	–0.938**
LogPRE	0.464***	–0.101	0.200**
LogPC	–0.541***	0.765**	0.112
LogPUR	–0.002	0.281*	0.578*
LogLUR	–0.001	–0.057	0.086
LogIPPI	0.606**	–0.427*	–0.026
LogEPI	1.311***	–0.183^	0.039
LogMK	–0.146	–0.019	–0.019
LogGL	0.065	0.768***	–0.035
Adjusted R^2	0.384	0.669	0.635
F-statistic	16.419	53.364	44.049

Notes: $P < 0.10$, ^; $P < 0.05$, *; $P < 0.01$, **; $P < 0.001$, ***.

estimate the influence. A Hausman test suggested that the FEM was the ideal approach to examine the relations of EPA with the explanatory variables.

The FEM revealed that 9 of the 12 variables were significantly related to EPA. Of the nine variables, LogGDPPA, (LogGDPPA)^2, LogP2I, LogIPPI, and LogEPI were negatively correlated with EPA, while LogP3I, LogPC, LogPUR, and LogGL were positively correlated. As discussed above, when GDP per area reaches a certain level, environmental concerns become prominent, provoking capital and resource inflows to curtail CO_2 emissions by measures such as the construction of low-carbon buildings. In addition, the intensified development of secondary industries (e.g., circular economy industrial parks) contributed to carbon reduction in both the raw materials production and building operation stages. Consistent with our hypothesis, price indices had a negative impact on EPA, suggesting that price can effectively help control emissions in the construction sector. Specifically, the energy price can influence CO_2 emissions from the construction sector in two ways. First, high fuel prices could be applied to the raw materials market via material production, indirectly reducing emissions by discouraging material consumption. Second, higher energy prices can directly lower energy consumption as well as CO_2 emissions in the building operation stage. The share of tertiary industry had a positive correlation with EPA. When industry booms, dense groupings of commercial buildings are constructed and huge amounts of electricity and fossil fuels are needed to operate them. Also in line with our hypothesis, the percentage of value added in the construction sector and the population urbanization rate were both positively related to EPA. Empirically, globalization contributes positively to CO_2 emissions, possibly because the increase in emissions driven by FDI outweighs the decrease brought about by the improvements in energy efficiency.

Three variables in the FEM had no significant impact: LogPRE, LogLUR, and LogMK. The three models showed inconsistent effects of the percentage of real estate value added on the dependent variables, suggesting complex relations. The land urbanization rate did not influence EPA, possibly because adopting EPA as a dependent variable already eliminated the impact of land urbanization. Marketization had a negative impact on the three models, possibly supporting the assumption that a higher marketization rate tended to be associated with less CO_2 emitted from the construction sector. However, the fact that this negative relation was not significant indicated that non-state-owned businesses did not perform significantly better than their state-owned competitors.

A panel regression was also used to investigate the relationship between the EPC of the construction sector and economic factors, as shown in Table 3. A Hausman test suggested that the FEM generated the best estimation. Similar results were found with the EPA regressions for

Table 3 Model results of EPC (emission per capita) using OLS (ordinary largest square method), FEM (fixed effect model) and REM (random effect model)

Variable	OLS	FEM	REM
Constant	–17.220*	0.790	–3.40
LogGDPPC	2.192	–0.006	–0.148
(LogGDPPC)^2	–0.123$^{\wedge}$	–0.515$^{\wedge}$	0.035
LogP2I	0.640**	–0.5664$^{\wedge}$	–0.343
LogP3I	1.134**	–0.010	–0.410
LogPRE	0.515***	–0.596***	0.034
LogPC	–0.403***	0.692*	–0.171*
LogPUR	–0.134	–0.015	0.003
LogLUR	–0.014	–0.462*	–0.003
LogIPPI	0.483*	0.154	–0.086
LogEPI	1.578***	–0.140	0.362$^{\wedge}$
LogMK	0.647*	–0.087**	0.134
LogGL	–0.090	0.790	–0.054
Adjusted R^2	0.411	0.838	0.803
F-statistic	18.405	132.406	102.244

Notes: $P < 0.10$, $^{\wedge}$; $P < 0.05$, *; $P < 0.01$, **; $P < 0.001$, ***.

(LogGDPPC)^2, LogP2I, LogP3I, LogPC, LogPUR, LogMK, and LogGL. The LogLUR regression results agreed with our assumptions, while the LogIPPI and LogEPI results did not. The real estate industry has a complicated impact on the construction sector because its high added value is often embedded with high energy efficiency in building operation, which consumers greatly value. Thus, it often helps to lower the energy intensity and EPC; thus, LogPRE was negatively, but not significantly, correlated with EPC. However, the land urbanization rate was found to be negatively correlated with EPC. In highly land-urbanized and densely populated areas like Beijing and Shanghai, energy efficiency is high, leading to low EPC values in all stages of the construction sector. The price indices of industrial products and energy were not significantly correlated with EPC, implying that using price as a tool is not sufficient to control end users' building needs.

The results of the Moran's *I* test are shown in Fig. 5. The EPC had a significant clustering trend ($P < 0.10$, meaning significant clustering) in 2104, indicating a strong spatial correlation among provinces or municipalities. This result means that areas with high EPC were located close to each other, as were those with low EPC. However, in other years, there was no significant spatial autocorrelation in emissions ($P > 0.10$). Therefore, further spatial analyses were not conducted in this study.

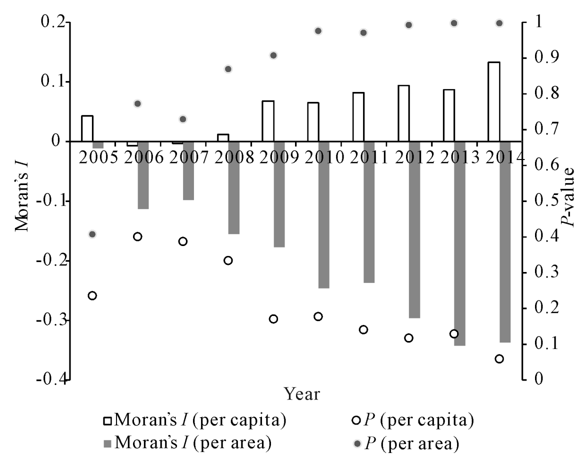

Fig. 5 Moran's *I* of the residuals estimated by OLS (ordinary largest square method) multi-regression

5 Conclusions

As a consequence of the diverse range of socioeconomic situations, CO_2 emissions from the construction sector during the period of 2005–2014 differed among the Chinese provinces or municipalities investigated. In 23 of the 30 provinces or municipalities studied, total CO_2 emissions were found to have increased at an annual rate of over 10%, and EPA and EPC exhibited similar trends in most provinces or municipalities. The contributions of the different stages of the construction industry to overall CO_2 emissions also varied among provinces or municipalities.

The building materials production stage was recognized as the most important contributor, accounting for over 60% of emissions on average, followed by the building operation stage, which accounted for over 25% of emissions on average. Provincial CO_2 emissions were correlated with economic factors; however, no spatial correlation was found, except for EPA in 2014. External economic and environmental factors had an impact on the emission performance of the construction sector. Empirically, an inverted U-shaped EKC was established between emission intensity and GDP growth. The industrial structure affected emissions from the construction sector; as an example, the share of secondary industry negatively affected emissions. Moreover, urbanization, price, and marketization were also found to be driving factors influencing CO_2 emissions.

This study will facilitate better policy making, as policy implications can be drawn from our findings. First, indirect CO_2 emissions from raw materials should be controlled. To be specific, cleaner technologies should be encouraged for raw materials providers, especially for cement and steel producers, and green purchasing rules for the construction sector should also be established to improve CO_2 emissions. Second, pricing tools (e.g., resource taxes) could help to adjust the demand for raw materials and energy, thereby reducing EPA. In the long run, it is necessary to develop low-carbon lifestyles and workstyles to reduce emissions in the operating stage. In particular, high-rise buildings that are designed to save energy may effectively reduce CO_2 emissions in tertiary industries. The industrial structure also influences emissions from the construction sector, including the proportions of secondary industry, tertiary industry, and the construction and real estate industry. Therefore, land use and energy use regulations should be imposed on these industries. With ongoing urbanization, the reduction of emissions from the construction sector requires better coordination between population and land. There is a need to reduce the energy intensity of construction projects intended to meet the rising demand of the urban population. Emissions could also be reduced by other policies, such as regulating the emission performance of FDI, which is related to the impacts of global markets on emissions from the construction sector.

The lack of detailed transportation and recycling data has made it difficult to obtain an accurate estimation of the emissions from the transportation stage. Because transportation only accounts for a small share of the total emissions, an approach based on estimations was adopted as a reasonable alternative. Many issues, such as the detailed emission profile of each stage and their regional discrepancies, remain unresolved and need to be addressed in future studies.

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