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Spatiotemporal characteristics and mechanisms of embodied carbon emissions in the construction industry: Evidence from China's municipalities directly under the central government

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Abstract

Using comprehensive industrial linkage analysis and quantitative structural decomposition analysis based on the multi-regional input-output model, this study systematically explores the intrinsic characteristics and driving determinants of, and variations in the consumption-based embodied carbon emissions (CBEC) significantly generated by the urban construction industry. The results show that: (1) Gross fixed capital formation and consumption by urban residents lead to obvious CBEC heterogeneity; (2) Construction industry's gross fixed capital formation drives the CBEC of the Production and Supply of Electric Power and Hot Water, Smelting and Pressing of Metals, and Nonmetal Mineral Products; (3) The CBEC shows significant dynamic spatiotemporal changes; (4) The emissions intensity effect and input-output structure effect are considered to be the key impetuses for increasing and decreasing the CBEC, respectively. Our study enhances understanding of spatiotemporal

characteristics and multi-factor mechanisms of carbon emissions in construction, aids carbon peak and neutrality efforts, and guides urban environmental and energy planning.

Keywords: Embodied carbon emissions, Construction energy industry, Industrial linkage analysis, Multi-regional input-output model, Structural decomposition analysis

1 Introduction

Humans are facing increasingly enormous challenges from environmental pollution, such as climate change and the destruction of the ozone layer. These are closely related to carbon dioxide emissions. According to the World Bank, globally, carbon emissions increased from a total of 20.6 million Kt in 1990 to 34.3 million Kt in 2019, with an average annual growth rate of 1.77%[1]. In 2015, the Paris Agreement was signed with the aim of limiting increases in global average temperatures to less than 2 degrees Celsius compared to pre-industrial times. Many countries around the world are actively adopting carbon reduction measures to reduce the impact of greenhouse effects and striving to achieve green and sustainable economic development. Many countries are actively adopting carbon reduction measures to reduce the impact of greenhouse effects and striving to achieve green and sustainable economic development. However, with the continuous acceleration of global urbanization, over 75% of total global carbon emissions are closely related to urbanization development,[2] and urban carbon emission reduction has become a serious challenge in achieving carbon neutrality in the future.

As the largest developing country, China needs to take the initiative in shouldering the burden of reducing carbon emissions in the field of industrial low-carbon transition.

Thus, China has set a target of achieving carbon peak by 2030 and carbon neutrality by 2060. However, due to differences in structure and the proportion of energy consumption between different industrial sectors, there are significant sectoral variations in terms of carbon emissions reduction strategies. The construction industry is a typical energy-intensive industry, and is also one of the main carbon emissions producing industries in China.[3] As Fig1 shows, the amount of carbon emissions generated by the construction industry (S24) from a production perspective is much less than other industries, but the carbon emissions resulting from its consumption side is the highest of all the industrial sectors. In addition, due to the close relationship between the construction industry and urbanization development. The construction industry provides infrastructure and public services for cities, and the development of cities provides a vast market and development opportunities for the construction industry. Thus, the amount of carbon emissions driven by construction industry in Chinese cities is a major concern, which provides the motivation for our study, which aims to clarify the characteristics and determinants of embodied carbon emissions generated by the construction industry.

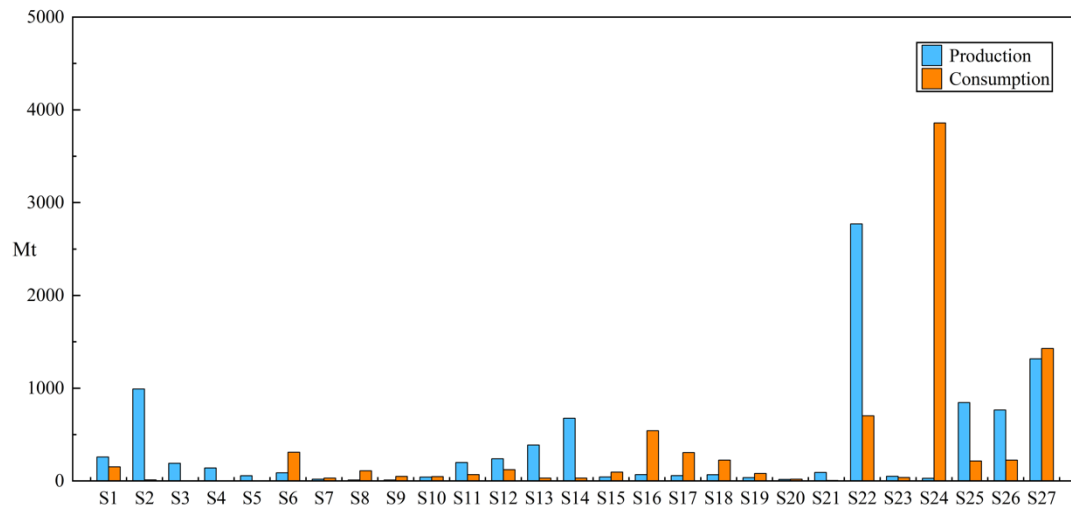


Fig1 Comparison of carbon emissions generated by the production and consumption sides of various industries in China.

With regard to the research topic, previous studies have attempted to describe and analyse the embodied carbon emissions produced by various industries. These studies have focused on the following issues: (1) Correlation analysis of carbon emissions between different industries based on the input-output model; (2) Calculating the total carbon emissions generated from a production perspective; and (3) Selecting relevant socio-economic indicators with which to analyse the mechanisms behind carbon emissions. However, the following shortcomings have been identified in relation to existing studies: first, from the perspective of scale, most previous studies have focused on the side-effects of production at the national or supranational level, but rarely have they analysed the consumption side at the subnational level. Second, few studies have investigated spatiotemporal changes and linkages between and within carbon emissions generating industries in different spaces. Third, although a socio-economic perspective can help to explain the mechanisms behind carbon emissions generation to some extent,

a static method of analysis cannot explain dynamic structural changes in these mechanisms.

In order to address the aforementioned issues, this study aims to investigate the dynamic spatiotemporal linkages and analyse the mechanisms involved in generating carbon emissions in the construction industry at the subnational level. Taking the four municipalities directly under China's central government as case studies, the study aims to fulfil the following research objectives: (1) Calculate the total amount of carbon emissions generated by the production and consumption sides of the construction industry across time and space simultaneously; (2) Identify the role played by the construction industry in the four cities, using different industrial carbon emissions systems, with regard to other provinces; (3) Map the dynamic spatiotemporal path of carbon emissions transfer from these four cities to other provinces; (4) Construct a carbon emissions generating mechanism for the construction industry in the four cities from a dynamic structural perspective. Thus, our study can contribute to current knowledge in the following ways: Firstly, with regard to scale: on a horizontal scale, the study focuses on both the production and consumption sides of the process; on a vertical scale, the sub-national level is taken into consideration in the spatial-temporal patterns and carbon emissions mechanism analyses. Second, with regard to industry level differences, we not only focus on the spatial heterogeneity and linkages between carbon emissions generation within the same industry, but also explore those between different industrial sectors. Third, from a structural perspective, we construct indicators for analysing the mechanisms behind carbon emissions generation, using the latest

spatiotemporal carbon emissions data available. Fig2 shows the rationale behind the research gaps, and the aims and objectives, as well as the contributions made by the study.

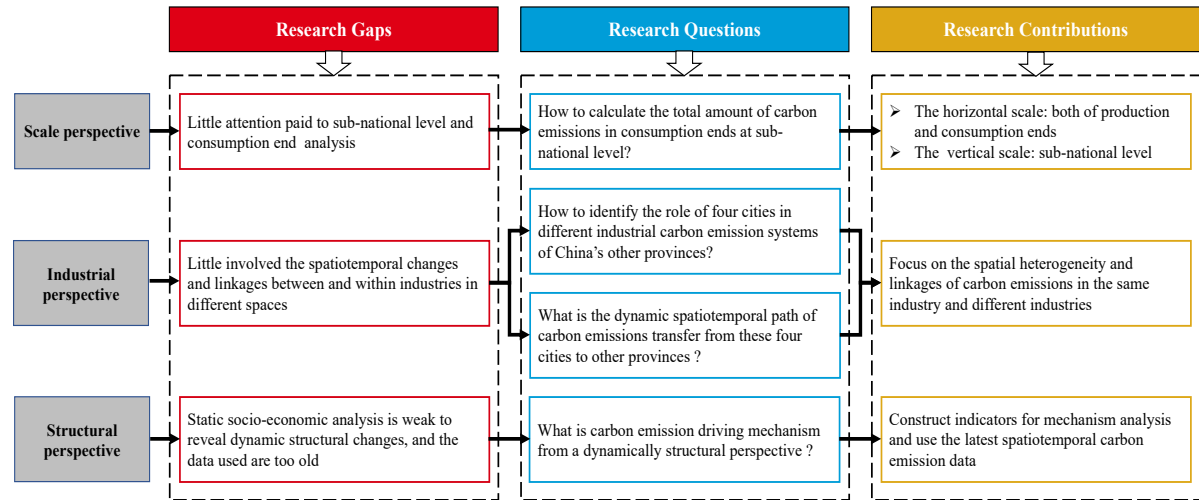


Fig2 The rationale for the study

2 Literature review

2.1 Rationale for urban industrial linkages and consumption-based embodied carbon emissions (CBEC)

Due to the combination of industrialisation, urbanisation and modernisation, CO₂ emissions generated at the city level have become not only one of the main contributors to climate change, but also a key cause of poor health. Thus, significant efforts have been made to reduce urban CO₂ emissions, such as designing calculation methods [4], factor analysis [5], forecasting modelling,[6] and the development of control technologies and strategies.[7] These methods all indicate that there is a close relationship between urban CO₂ emissions and the inter-linkages between intra-regional and inter-regional industries.

Therefore, there is a need to comprehensively calculate the amount of urban CO₂

emissions produced. This figure should include emissions produced both within and outside of the city boundaries. For example, emissions might occur within the wider urban boundary area, but they could be generated from inside the urban core. In addition to the territorial accounting perspective, the urban carbon footprint has also been suggested as a complementary, consumption-based approach to calculating CO₂ emissions. It facilitates the identification and quantification of economic (sectoral) and spatial interconnections within the supply chain of key economic sectors, defined as those where investment is likely to maximise both economic growth and carbon mitigation.

Most studies of the construction industry focus on accounting for the total amount of carbon emissions produced,[8] analysing the intensity and spatial and temporal evolution of carbon emissions,[9] and exploring the drivers of carbon emissions from the construction industry.[10] The findings suggest that the amount of CBEC generated by the construction industry is huge. However, these studies have tended to account for the amount of embodied carbon emissions from the construction industry within an existing space. Rarely has the embodied carbon emissions footprint of the construction industry been calculated and compared between different cities and provinces. Although some scholars believe that carbon emissions reduction needs to be achieved through industrial upgrading and industrial restructuring, [11]there is huge heterogeneity in the emissions reduction effect resulting from industrial upgrading, which is closely related to regional economic development.[12] At the same time, industrial restructuring can also cause the spatial transfer of carbon emissions within

the original region.[13] Therefore, this suggests a need to focus on the CBEC flows from the construction industry between cities, and their temporal and spatial variations. With regard to the temporal and spatial variations in CBEC flows from the construction industry between regions, the main focus has been on the impact of stages of urban development, and economic, and population growth on carbon emissions. These studies have identified some of the driving mechanisms of carbon emissions. However, few studies have analysed the influence of economic structural transformation on variations in carbon emissions from the construction industry.

2.2 Evolution of mechanisms for measuring CBEC: methods and indicators

An approach that has been widely employed to estimate the amount of embodied carbon emissions for different industrial sectors is the input-output (IO) model, developed by Leontief (1941). Carbon footprints based on IO models have already been estimated for several cities, globally. However, only a handful of studies have directly calculated local sectoral carbon intensities [14]. The majority of existing studies have instead assumed that local sectoral carbon intensities are the same as national sectoral intensities. This assumption can be seen in both single region IO models[15] and multi-region models.[16] Other studies have attempted to calculate sectoral carbon intensities at the urban level by combining downscaled national input-output data with process-based data. While this approach has improved the data quality, so far, no sub-national multi-region input-output (MRIO) model with nested city-scale tables has been developed and applied to in an existing economic sector.

Within the framework of IO analysis, the classical multiplier method and the

hypothetical extraction method (HEM) are two widely accepted methods used to describe inter-sectoral relationships and identify key industrial sectors. Based on these two methods, Miller and Blair (2009) deduced that two types of economic effects exerted by one particular sector on other sectors can be measured: backward linkages (BLs), based on the Leontief inverse as suggested by Rasmussen (1956); and forward linkages (FLs), based on the Ghosh inverse.[17] Increasingly, as a result of growing concerns about how CO₂ emissions can be mitigated, inter-sectoral linkage analysis is being used to investigate carbon emissions. In addition, analysing the inter-sectoral linkages between cities, adjacent areas and national economies can facilitate a deeper understanding of urban carbon transformations.

Some studies have found that energy-related industrial sectors such as construction, electricity and heat production and supply, and transport are the main carbon emission producing sectors.[18] Other studies have also shown that, as a result of rapid urbanisation, the construction industry has become the main producer of carbon emissions, which has attracted attention from researchers, both domestically and abroad.[19] However, most studies have tended to compare the linkages between carbon emissions generated by different industries, rather than conducting a more detailed analysis of industrial carbon emissions linkages within the construction industry. China's four municipalities - Beijing, Tianjin, Shanghai and Chongqing - have developed a stable service-oriented economic structure[7] and experienced significant urban population growth[5], as a result of continuing urban expansion and the associated growing demand for construction.[20] The effects of these changes have

heightened the need to reduce energy consumption and mitigate climate change. Consequently, it is crucial to investigate the amount of CO₂ emissions driven by final demand from China's municipalities. Therefore, our study explores the temporal and spatial variations in CBEC from the construction industry in China's municipalities and their determinants, in order to put countermeasures in place and suggest ways reducing the amount of carbon emissions produced by the construction industry at the urban level from a supply chain perspective.

3 Methods and data

3.1. Research framework

Fig3 depicts the research framework. Firstly, the CBEC calculation of the four municipalities directly under the central government in China needs to integrate input-output tables data, carbon emission data, and socio-economic data at different time scales. Using the Multi-regional input-output (MRIO) model, the CBEC of the four cities is calculated and their final demand types for CBEC are analyzed. Secondly, by constructing Industrial linkages and transfer models, the driving role of the construction industry is clarified on the CBEC of the four cities and the industry linkages effects are analyzed between the construction industry and other industries. Thirdly, by exploring the characteristics of the spatial-temporal distribution of the CBEC in the four cities, the reasons why the construction industry drives the spatial transfer of CBEC is further analyzed. Finally, Structural decomposition analysis (SDA) model is also used to delve into the determinants of the CBEC of the construction industry in the four cities at different time periods. Through the integration of important findings from research, this

study elaborates on the characteristics and variations of the CBEC in urban construction industry, and proposed policy recommendations from both a holistic and individual perspective.

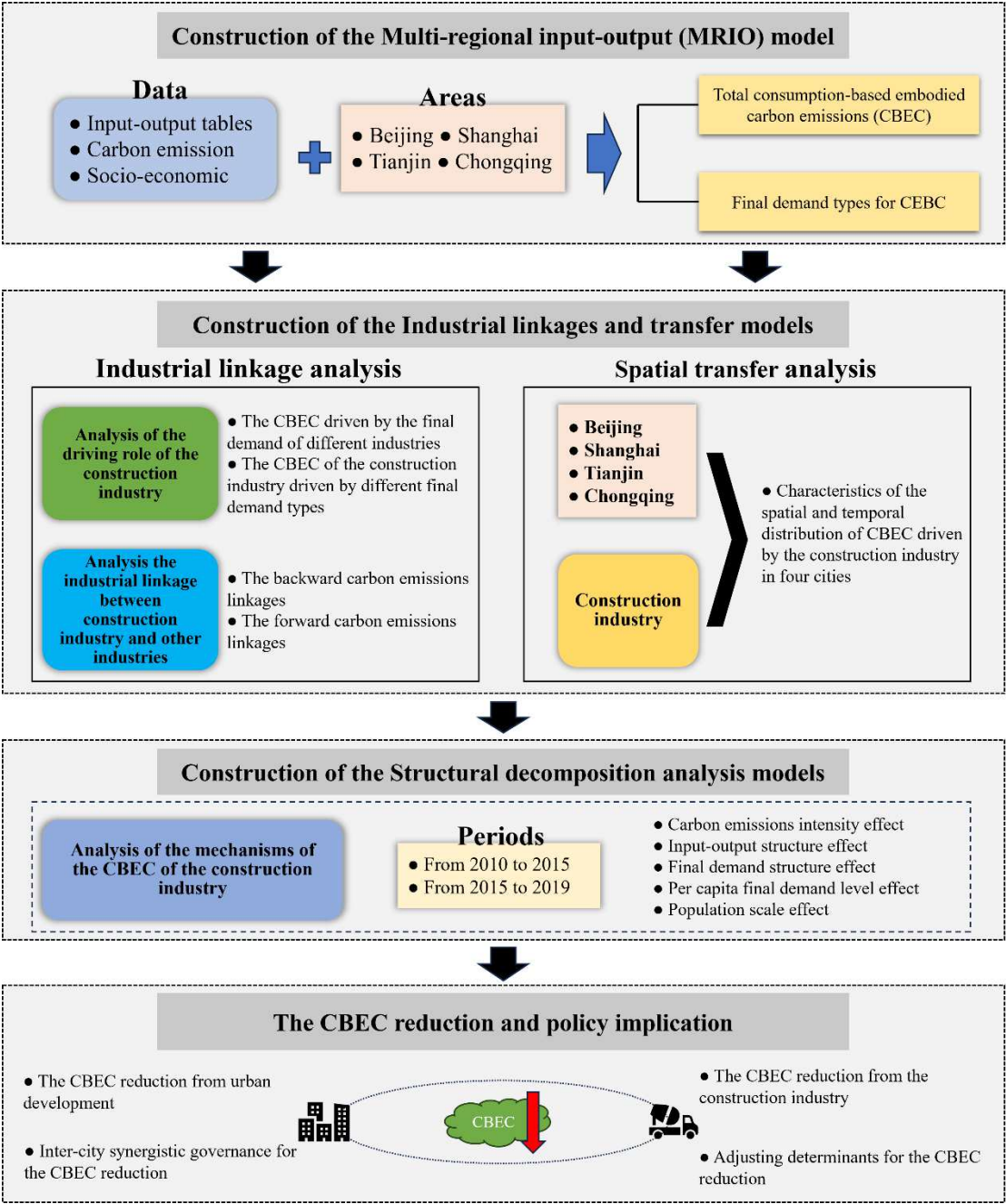


Fig3. Research framework

3.2 Research area

As centres of human socio-economic activity, cities encompass a vast range of

production activities, consumption activities, and creative activities, involving the exchange of all kinds of materials and energy. In order to improve the decision-making speed of urban economic construction, the Chinese government has established four municipalities directly under the central government (Beijing, Shanghai, Tianjin and Chongqing), thus increasing the autonomy of cities (Fig4a). They have played a radiating role in the process of economic development and have contributed to the formation of three major economic circles: the Bohai Rim Economic Circle, the Yangtze River Delta Economic Circle, and the Chongqing West Economic Corridor. Thus, they play a central role in regional economic growth. With regards to carbon emissions, the total amount produced by these four cities, from a consumption perspective, is 805.8Mt, which accounts for 9.27% of China's total carbon emissions. Therefore, it is important to examine carbon emission generation from the consumption side of industries in these four municipalities (Fig4b).

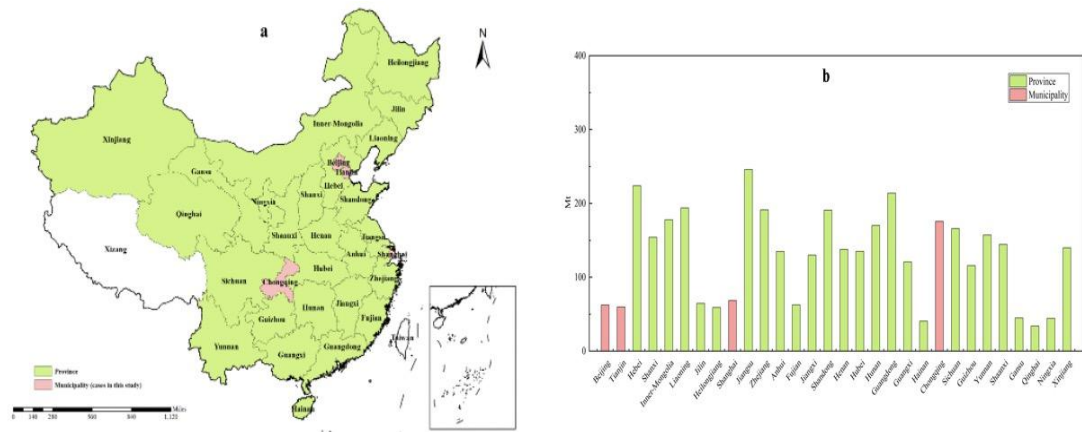


Fig4. a. Location of the case study areas; b. Comparison of carbon emissions produced by the consumption side of the construction industry between provinces and cities

3.3 Data sources

The following data were required in order to construct the model: first, Chinese MRIO

tables for 2010, 2015, and 2017 were used to create the input-output model, including trading data from 30 provincial administrative regions. Because the official data for the 2019 MRIO table had not been released, the latest available data from 2017 was used instead. These tables are available from the Carbon Emission Accounts & Database for Emerging Economies (CEADs) (https://ceads.net.cn/data/input_output_tables/). Second, CO₂ emissions inventories for Chinese provinces for the years 2010, 2015 and 2019 were used to build the CBEC model based on the MRIO. These data are also available from the Carbon Emission Accounts and Database for Emerging Economies (CEADs) (<https://www.ceads.net/data/province/>). Third, population data and GDP data for Chinese provinces and cities up to 2010, 2015 and 2019, respectively, were used to construct the SDA model. These data are available from the National Bureau of Statistics.

3.4 Methods

3.4.1 Multi-regional input-output model (MRIO) used to calculate total carbon emissions resulting from consumption

The multi-regional input-output model was devised to measure the amount of carbon emissions generated in various cities and industries from consumption. The input-output model is a useful tool for economic analysis, which is now widely used in the fields of industrial structure analysis, energy and environmental studies, regional economic integration and coordinated development.[21] In our study, we develop the model by considering how it can be used at the sub-national level, thus highlighting the advantages it offers in evaluating regional differences in goods and services, as well as

inter-regional trade. Thus, as a top-down approach, the MRIO is applied to calculate the total embodied carbon emissions generated by the consumption end of the construction trade in the four municipalities.

First, with regard to the cities, the MRIO can be expressed as follows:

$$\begin{aligned} X_i^r &= (z_{i1}^{r1} + \dots + z_{in}^{r1}) + (z_{i1}^{r2} + \dots + z_{in}^{r2}) + \dots + (z_{i1}^{rm} + \dots + z_{in}^{rm}) + y_i^{r1} + y_i^{r2} + \dots + y_i^{rm} \\ &= \sum_s \sum_j z_{ij}^{rs} + \sum_s y_i^{rs} \quad (i, j = 1, 2, \dots, n; r, s = 1, 2, \dots, m) \end{aligned} \quad (1)$$

Where, z_{ij}^{rs} represents the input of i section in r city to j section in s city; y_i^{rs} is the final demand for city s provided by the products of sector i in city r ; X_i^r denotes the total output of sector i in city r .

$$A^{rs} = \{a_{ij}^{rs}\} = \left\{ \frac{z_{ij}^{rs}}{X_j^s} \right\} \quad (2)$$

Where, A^{rs} is the intermediate demand matrix from city r to city s , and a_{ij}^{rs} is an element of the direct input matrix as A^{rs} , denoting the amount of input from sector i in city r directly required to produce one unit of output from sector j in city s . Therefore, the total output, X is:

$$X = (I - A)^{-1}Y \quad (3)$$

Where, the direct input coefficient matrix is $A = \begin{bmatrix} A^{11} & A^{12} & \dots & A^{1n} \\ A^{21} & A^{22} & \dots & A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \dots & A^{nn} \end{bmatrix}$; $(I - A)^{-1}$ is the Leontief inverse matrix; the final demand vector Y is $\begin{bmatrix} y^1 \\ y^2 \\ \vdots \\ y^m \end{bmatrix}$ and the total output

vector X is $\begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{bmatrix}$; I is the unit matrix with $m \times m$.

Second, we added the carbon emissions data for each industrial sector in a region into the MRIO to measure the consumption-based embodied carbon emissions (CBEC) generated by each industry in the region. The direct carbon emissions coefficient of each region within an economy can be used to represent the carbon emissions caused by an increase of one unit in the total output of the region. The model can be expressed as:

$$e_i^r = \frac{d_i^r}{X_i^r} \quad (4)$$

Where, d_i^r represents the carbon emissions generated by sector i in city r ; X_i^r denotes the total output of sector i in city r ; and e_i^r denotes the direct carbon emissions coefficient of sector i in region r .

The direct carbon emissions coefficient matrix E was then combined with the MRIO model to construct the CBEC model, based on the MRIO.

$$C = E(I - A)^{-1}Y \quad (5)$$

$$= \begin{bmatrix} \hat{E}^1 & 0 & \dots & 0 \\ 0 & \hat{E}^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \hat{E}^n \end{bmatrix} \left(I - \begin{bmatrix} A^{11} & A^{12} & \dots & A^{1n} \\ A^{21} & A^{22} & \dots & A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \dots & A^{nn} \end{bmatrix} \right) \begin{bmatrix} Y^{11} & Y^{12} & \dots & Y^{1n} \\ Y^{21} & Y^{22} & \dots & Y^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Y^{n1} & Y^{n2} & \dots & Y^{nn} \end{bmatrix} \quad (6)$$

Where, C^{ij} signifies the amount of embodied carbon emissions from products produced by city i to city j ; $\hat{E}^i$ is the diagonal matrix of the direct carbon emissions coefficient of city i ; A^{ij} represents the direct input coefficient matrix of city j to city i ; Y^{ij} denotes the final demand of city j provided by the production of city i ; and I is the unit matrix with $m \times m$. Therefore, the total amount of CBEC can be expressed

284 as $\sum C^{ij}$.

285 3.4.2 Industrial linkages and transfer models

286 The MRIO model can reflect the linkages between the economic activities and
287 production processes of various industrial section.[22] These industrial linkages can be
288 categorised as backward linkages and forward linkages. Therefore, the backward
289 carbon emissions linkages and forward carbon emissions linkages were calculated
290 based on the MRIO. The embodied carbon emissions intensity matrix for each
291 industrial sector was constructed from the direct carbon emissions coefficient matrix E
292 and the Leontief inverse matrix L .

$$b = E * L \quad (7)$$

293 Where, an element b_{ij} indicates the amount of embodied carbon emissions driven by
294 an increase of one unit in sector j to sector i . The embodied carbon emissions
295 intensity matrix was used to analyse the carbon emissions linkages and transfer between
296 the various industries in the four municipalities.

297 First, we constructed the backward carbon emissions linkage and transfer model. This
298 can be regarded as the impact of adding one unit of final product to a certain sector of
299 the economy on various other industrial sectors within the economy. In this study, the
300 mean of the backward carbon emissions linkage N_j can be expressed as the average
301 pulling effect of the embodied carbon emissions on each sector when one sector
302 increases by one unit of final demand. It is represented as follows:

$$N_j = \frac{1}{n} \times \sum_{i=1}^n b_{ij} \sum_{j=1}^n b_{ij} \quad (j = 1, 2, \dots, n) \quad (8)$$

303 Where, N_j is the mean of the column summation of the embodied carbon emissions

intensity matrix; $\sum_{i=1}^n b_{ij}$ is the final demand of the embodied carbon emissions of each sector caused by each unit increase in the embodied carbon emissions in sector j . A larger N_j value means that the embodied carbon emissions of sector j have a greater pulling effect on other sectors, and vice versa.

Second, the forward carbon emissions linkage and transfer model was constructed. The forward carbon emissions linkage is generally expressed as the impact of adding one unit of final demand in each sector of the economy on an industrial sector. In this study, the forward carbon emissions linkage G_i represents the driving force of increasing demand by one unit for each sector in order to generate embodied carbon emissions in a certain sector of the economy.

$$G_i = \frac{1}{n} \times \sum_{j=1}^n \sum_{i=1}^n b_{ij} \quad (j = 1, 2, \dots, n) \quad (9)$$

Where, G_i indicates the mean of the horizontal summation of the embodied carbon emissions intensity matrix; $\sum_{j=1}^n b_{ij}$ represents the total demand for the embodied carbon emissions of sector i for each unit of embodied carbon emissions added by each industrial sector. A larger G_i value means that the driving effect of other sectors on the embodied carbon emissions of sector i is also larger, and vice versa.

3.4.3 Structural decomposition analysis (SDA)

SDA was used to assess the driving mechanisms of embodied carbon emissions. Its fundamental purpose is to decompose the changes in a dependent variable within the economic system into the sum of separate independent variables related to it. This can measure the effect of each change in an independent variable on the dependent variable.[23] SDA is currently a popular method for identifying the socio-economic

factors involved in environmental issues, especially those related to carbon emissions.[24] Thus, based on Gu's (2020) work, we decomposed the driving mechanisms into different structures, namely: the carbon emissions intensity effect (CEI); the input-output structure effect (IOS); and the final demand effect (FDE). Due to the complexity of the FDE, it was then further decomposed into three determinants: the final demand structure effect (FDS); the per capita final demand level effect (PFD); and the population scale effect (PSE), based on consumption. Therefore, the following model was constructed:

$$C = E(I - A)^{-1}Y = EIE \cdot IOSE \cdot FDSE \cdot PCFDLE \cdot PE \quad (10)$$

We took t_0 and t_1 as the base period and calculation period respectively, and quantitatively calculated the driving factors behind embodied carbon emissions during these two periods. The two-pole decomposition method proposed by Dietzenbacher and Los (1998) was used to calculate the driving force decomposition of ΔC . [25] Taking the change in emissions intensity (CEI) as an example, the results of the base period t_0 were decomposed as follows:

$$f(EIE_{t_0}) = \Delta EIE \cdot IOSE_{t_0} \cdot FDSE_{t_0} \cdot PCFDLE_{t_0} \cdot PE_{t_0} \quad (11)$$

The method used for decomposing the calculation period t_1 is similar to equation (11):

$$C = E(I - A)^{-1}Y = EIE \cdot IOSE \cdot FDSE \cdot PCFDLE \cdot PE \quad (12)$$

Equations (13) and (14) were added together to obtain the average value:

$$f(\Delta EIE) = \frac{1}{2} \left(\frac{\Delta EIE \cdot IOSE_{t_0} \cdot FDSE_{t_0} \cdot PCFDLE_{t_0} \cdot PE_{t_0}}{+ \Delta EIE \cdot IOSE_{t_1} \cdot FDSE_{t_1} \cdot PCFDLE_{t_1} \cdot PE_{t_1}} \right) \quad (13)$$

4 Results

4.1 The carbon emissions generated by the production and consumption sides in

the four cities

With regard to the municipalities, during the period 2010-2019, trade links between the four municipalities and the provinces became closer. However, there were still differences in the embodied carbon emissions resulting from consumption, because of disparities in terms of the available resources, economic development, and energy structure of each municipality.

4.1.1 The total carbon emissions generated by the production and consumption sides

The CBEC model was used to calculate the total consumption-based embodied carbon emissions and carbon emissions intensity of the four municipalities in 2010, 2015, and 2019. As Fig5 (a) shows, overall, Chongqing had the largest total CBEC, with an average of 244.65 Mt. Meanwhile, Beijing had an average total CBEC value of 196.41 Mt and the figure was similar for Shanghai at 199.49 Mt. Tianjin had the lowest total CBEC, with a mean value of 134.04 Mt. Specifically, the total CBEC generated in Beijing and Tianjin increased and subsequently decreased from 2010 to 2015, but these changes were not significant. Beijing's total CBEC increased from 187.30 Mt in 2010 to 204.42 Mt in 2015, and then decreased to 197.53 Mt in 2019. By contrast, Tianjin's total CBEC rose from 126.93 Mt in 2010 to 138.28 Mt in 2015, and subsequently decreased to 136.89 Mt in 2019. Shanghai and Chongqing followed opposite trends in terms of changes in total CBEC. Shanghai's total CBEC gradually decreased from 241.79 Mt in 2010 to 166.37 Mt in 2019, with an annual growth rate of -4.07%, while the total CBEC generated in Chongqing rose from 133.87 Mt in 2010 to 305.00 Mt in 2019, with an annual growth rate of 9.58%.

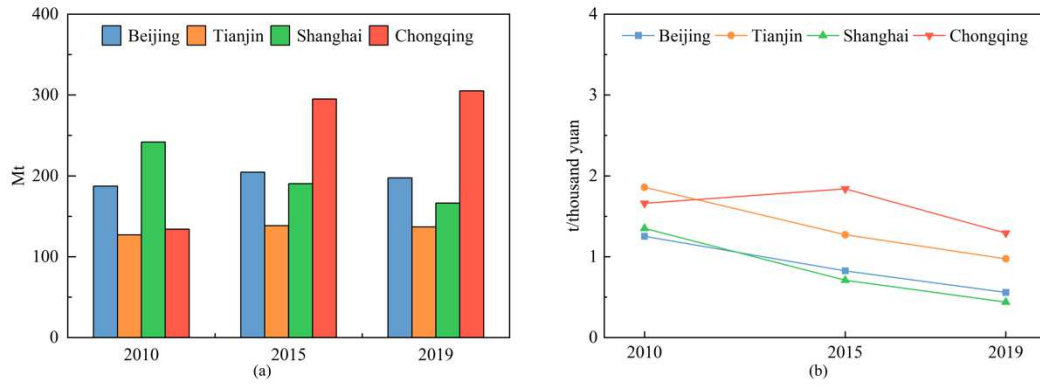


Fig5. Total embodied carbon emissions (a) and carbon emissions intensity (b) resulting from consumption for the four municipalities in 2010, 2015, and 2019

Fig5 (b) shows that Chongqing had the highest CBEC intensity, with an average of 1.60 t/thousand yuan. It was followed by Tianjin, which had an average CBEC intensity of 1.37 t/thousand yuan. However, Beijing and Shanghai had relatively low levels of CBEC intensity, at 0.88 t/thousand yuan and 0.83 t/thousand yuan respectively. During the period 2010-2019, the CBEC intensity of Beijing decreased from 1.25 t/thousand yuan to 0.56 t/thousand yuan, while that of Tianjin declined from 1.85 t/thousand yuan to 0.97 t/thousand yuan, and that of Shanghai fell from 1.34 t/thousand yuan to 0.44 t/thousand yuan. However, the change in Chongqing's CBEC intensity followed a different trend from the other three municipalities, increasing from 1.66 t/thousand yuan in 2010 to 1.84 t/thousand yuan in 2015, and then decreasing to 1.29 t/thousand yuan in 2019. Despite this, the results show a decreasing trend in the overall intensity of CBEC.

4.1.2 The carbon emissions generated by different final demand types

We then clarified the CBEC of final demand types in the municipalities. The analysis of the final demand types demonstrates the impact of the different final demands in

each municipality on the embodied carbon emissions, and further identifies the driving forces of these various types of final demand on the CBEC. Fig6 depicts the amount of CBEC in the four municipalities caused by each of the final demand types in 2015 and 2019. More than 50% of the CBEC in Beijing, Tianjin, Shanghai, and Chongqing were caused by gross fixed capital formation, which was the largest driving force of consumption-based demand in the four municipalities. The high final demand resulting from gross fixed capital formation can be explained by a combination of urbanisation and government policy, which is mainly reflected in the rapid development of the urban economy and the construction of urban infrastructure.[26] Consumption by urban residents is the second largest driving force of consumption-based demand in the four municipalities, accounting for 12% - 28% of the total CBEC. Beijing's CBEC resulting from Government consumption accounts for 14% of the total, which is approximately 2-3 times the proportion of the CBEC caused by Government consumption in Tianjin (7%), Shanghai (8%), and Chongqing (4%). The proportion of CBEC resulting from increased demand from rural residents' consumption and inventory in these four municipalities is relatively small.

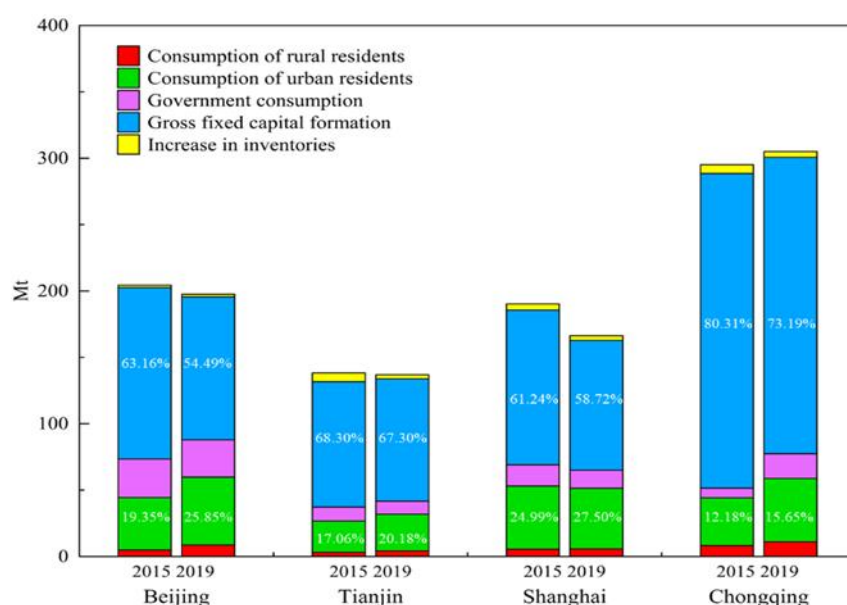


Fig6. Percentages of CBEC in the four municipalities caused by each of the final demand types in 2015 and 2019

To sum up, during the period 2010-2019, levels of CBEC in Beijing and Tianjin underwent fewer changes. Furthermore, the intensity of carbon emissions also declined because of the significant rate of economic growth. Shanghai was the only city where both the total amount and intensity of CBEC continued to decline. A possible explanation for this is the policy and governance measures implemented via the ‘Twelfth Five-Year Plan’, which aims to create a resource-saving and ecologically sound low-carbon city. Thus, there are strict rules governing energy conservation in relation to new buildings, and making existing buildings more energy efficient, as well as regulating industries closely related to construction, all of which have had an effect on reducing carbon emissions from related industries. In addition, Chongqing’s total CBEC increased significantly while there was only a limited decrease in its intensity. Chongqing has played a crucial role in regional economic growth. For example, it is an

important strategic fulcrum for the *Western Development* plan as well as an important connection point between the *Belt and Road Initiative* and the Yangtze River Economic Belt. Therefore, its permanent population continued to expand, in tandem with rapid economic development. This has led to a gradual expansion in Chongqing's demand for infrastructure, provided by the construction industry, which has indirectly resulted in a rapid increase in the overall amount of carbon emissions.

4.2 Identifying the role of the construction industry in the carbon emissions in the four cities

4.2.1 The CBEC of national industries driven by the final demand of four municipalities

This section analyses the proportion of CBEC of national industries driven by the final demand of four cities (Fig7). The CBEC driven by Beijing, Tianjin, Shanghai, and Chongqing were mainly concentrated in the following sectors: the Production and Supply of Electric Power and Hot Water (S22), Smelting and Pressing of Metals (S14), Nonmetal Mineral Products (S13), and Transport and Warehousing (S25), which accounted for an average of 50.77%, 14.35% 10.33% and 7.71%, respectively. As for construction industry (S24), the average proportion of CBEC of it driven by the final demand of Beijing was 0.62%; while the proportions for Tianjin, Shanghai, and Chongqing were 2.04%, 0.87%, and 0.72%, respectively. This means that the final demand from these three cities had more impact on the CBEC of the national construction industry (S24).

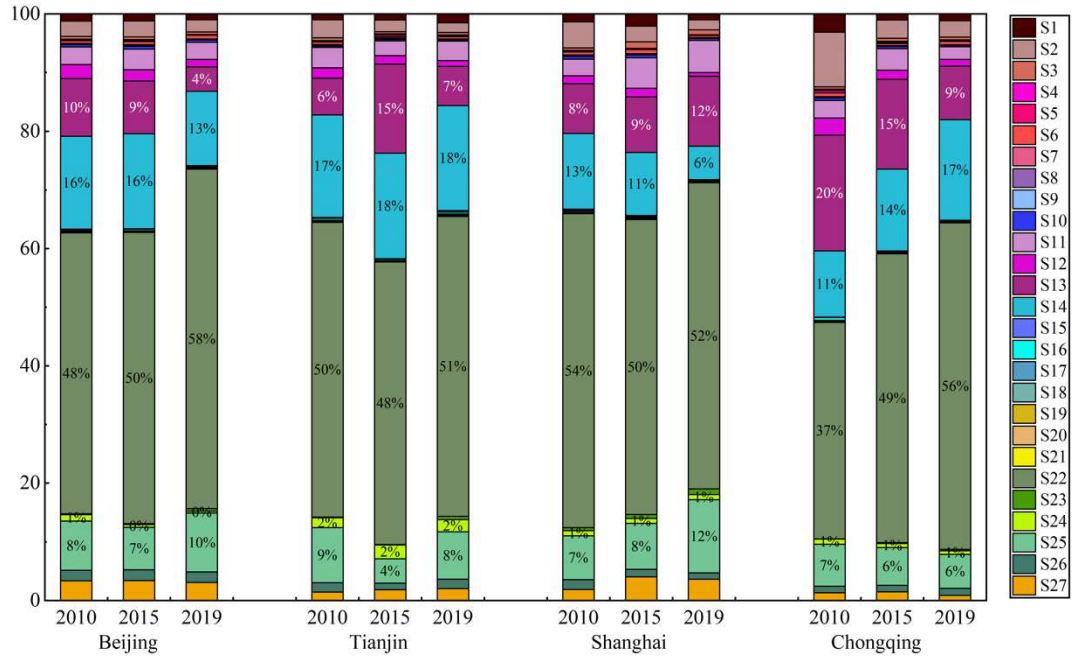


Fig7. The proportion of the CBEC of national industries driven by the final demand of four municipalities in 2010, 2015, and 2019

4.2.2 The CBEC driven by the final demand of different industries in four municipalities

Identically, Fig8 revealed the proportion of CBEC driven by different industries in the

four cities. During the period 2010-2019, there were few changes in the proportion of

the CBEC driven by industries. The industries with changes were mainly General and

Special Equipment Manufacturing (S16), Transportation Equipment (S17), the

Production and Supply of Electric Power and Hot Water (S22), Construction (S24), and

Others (S27), which contributed more than 80% of these cities' total CBEC.

Specifically, others (S27) were responsible for the largest proportion of CBEC in

Beijing, with a mean of 41.61%. The Construction industry (S24) was second, with a

mean of 34.78%. However, construction (S24) accounted for the largest proportion of

CBEC in Tianjin (45.17%), Shanghai (22.87%), and Chongqing (11.29%). It can be

seen that, the CBEC driven by the Construction industry (S24) in municipalities

increased. As Construction industry (S24) in municipalities played a increasingly important role in driving CBEC, it is necessary to analyse the construction industry (S24) deeply in this study.

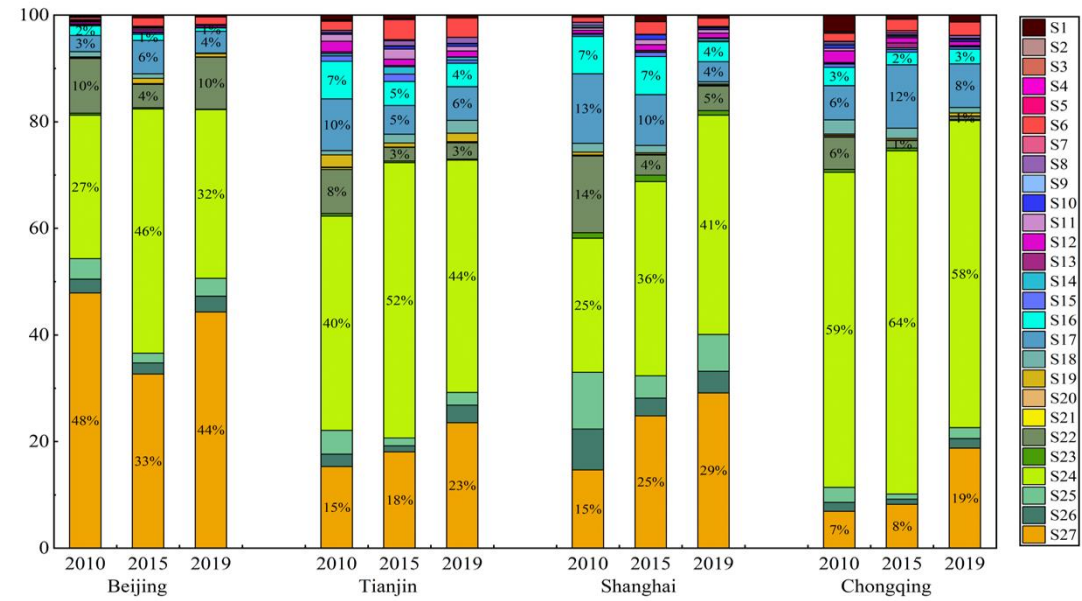


Fig8. The proportion of the CBEC driven by the final demand of different industries in four municipalities in 2010, 2015 and 2019

4.2.3 The industrial linkage analysis between construction industry and other industries

To further analyse the linkages in terms of carbon emissions between the construction industry in the four cities and other industries in other provinces in inter-provincial trade, the industrial linkage model was used to clarify the backward carbon emissions linkages and forward carbon emissions linkages. Due to the fact that the construction industry in the municipalities has the largest backward carbon emissions linkage, this study examined the upstream industries that have the largest backward carbon emissions linkages with the construction industry in the four cities (as shown in Table 1). During the period 2010-2019, the industries with the largest backward carbon

emissions linkages with Beijing's construction industry were: Nonmetal Mineral Products (S13), Smelting and Pressing of Metals (S14), and the Production and Supply of Electric Power and Hot Water (S22) in Hebei. It was found that the industrial sectors that had the largest backward carbon emissions linkages with Tianjin's construction industry were: the Production and Supply of Electric Power and Hot Water (S22) and Smelting and Pressing of Metals (S14). In the case of Shanghai's construction industry, the sectors with the largest backward carbon emissions linkages were: the Production and Supply of Electric Power and Hot Water (S22) and Smelting and Pressing of Metals (S14) in Shanghai; and Nonmetal Mineral Products (S13) in Zhejiang province. Meanwhile, the industries with the strongest backward carbon emissions linkages with Chongqing's construction industry were: Nonmetal Mineral Products (S13) and the Production and Supply of Electric Power and Hot Water (S22).

Similarly, the downstream industries with the highest forward carbon emissions linkages with the construction industry in the four cities are shown in Table 2. The industry with the largest forward carbon emissions linkage with the construction industry in the four municipalities was found to be the Construction (S24) industry itself. This indicates that the consumption demand from the construction industry had little impact on the CBEC of other downstream industries. Therefore, it is necessary to reduce the demand for high energy-consuming, carbon-intensive products from the consumption side of the construction industry and to improve the energy efficiency of buildings. To sum up, the industry with the largest carbon emissions linkage with the construction industry in the four cities was found to be the Production and Supply of

Electric Power and Hot Water (S22), which is due to the high demand for electricity and heat consumption during the construction process.[27]

4.2.4 The CBEC of the construction industry driven by different final demand types

In addition, the analysis shows how the construction industry is driven by the different types of final demand. The CBEC values of the construction industry, driven by the various types of final demand, in the four cities are shown in Table 3. More than 95% of the CBEC from the construction industry in Beijing, Tianjin, Shanghai, and Chongqing was caused by gross fixed capital formation. In addition, the increase in inventory had the effect of reducing the CBEC of the construction industry in the four cities in 2015. Thus, gross fixed capital formation is the main types of final demand that needs to be addressed in relation to the construction industry. The results also indicate that the government could introduce specific measures to reduce carbon emissions based on the gross fixed capital formation demand of the construction industry.[28]

In summary, during 2010-2019, the Construction (S24) industry was the main cause of high CBEC levels in the four cities, and gross fixed capital formation is the main source of final demand that drove these high CBEC levels in the construction industry. In addition, as the final demand in the four cities has little impact on the CBEC of the national construction industry, this study analysed the CBEC of the consumption side of the construction industry in the four cities.

4.3 The spatial transfer of embodied carbon emissions from the construction industry

This study investigated the spatial transfer of the CBEC of the construction industry in the four cities in 2010, 2015 and 2019 (Fig9). In the case of Beijing, during the period 2010-2015, its construction industry pulled more locally generated embodied carbon emissions, whereas in 2019 it pulled more embodied carbon emissions generated in other regions.

4.3.1 The embodied carbon emissions driven by the construction industry in Beijing

To be more specific, the demand from Beijing's construction industry caused the amount of local carbon emissions to increase from 50.39 Mt in 2010 to 73.41 Mt in 2015, and then to decrease to 30.19 Mt in 2019. Conversely, however, demand from Beijing's construction industry led to a significant increase in the total amount of carbon emissions in other regions, from 20.25 Mt in 2015 to 32.26 Mt in 2019. As a result of the spatial transfer of embodied carbon emissions, during the period 2010-2015, the following regions experienced significant changes in embodied carbon emissions driven by demand from Beijing's construction industry: Hebei (2.22 Mt), Tianjin (2.02 Mt), Jilin (1.85 Mt), and Inner-Mongolia (1.58 Mt). A possible explanation for this phenomenon is their geographical proximity to Beijing. These provinces are located in Northern and Northeastern China, and thus Beijing's construction industry has closer trade links with them. From 2015 to 2019, Guangdong (4.08 Mt), Henan (3.50 Mt), and Shandong (3.10 Mt) all experienced an increase in the embodied carbon emissions caused by Beijing's construction industry. On the whole, from 2010 to 2019, the demand from Beijing's construction industry had a reduced impact on local carbon emissions, while the largest proportion of embodied carbon emissions pulled by

demand from Beijing's construction industry shifted from the northern region to the central and southern coastal regions of China.

4.3.2 The embodied carbon emissions driven by the construction industry in Tianjin

Compared to other regions, Tianjin's construction industry pulls more locally generated embodied carbon emissions during the period 2010-2019. More specifically, the demand from Tianjin's construction industry caused the amount of locally generated carbon emissions to rise from 48.93 Mt in 2010 to 69.61 Mt in 2015, and then decrease to 45.80 Mt in 2019. However, the total carbon emissions generated in other regions driven by the demand from Tianjin's construction industry, dropped from 2.14 Mt in 2010 to 1.87 Mt in 2015, and then underwent a significant increase to 13.87 Mt in 2019. Therefore, during the period from 2010 to 2015, the demand from Tianjin's construction industry was responsible for an increase in the amount of local carbon emissions, while during the period from 2015 to 2019, the demand from Tianjin's construction industry resulted in an increase in carbon emissions in other regions. Regarding the transfer of embodied carbon emissions, from 2010 to 2015, the regions of Jiangsu, Liaoning, Jilin and Heilongjiang experienced significant changes in levels of embodied carbon emissions driven by demand from Tianjin's construction industry, with increases of 0.13 Mt, 0.10 Mt, 0.10 Mt, and 0.09 Mt, respectively. Similar to Beijing, from 2015 to 2019, the regions that experienced the greatest changes in embodied carbon emissions due to demand from Tianjin's construction industry were Guangdong (1.97 Mt), Henan (1.73 Mt), and Shandong (1.39 Mt), respectively. On the whole, the largest proportion of embodied carbon emissions pulled by demand from Tianjin's construction industry

shifted from the northern region to the central and southern coastal regions of China.

4.3.3 The embodied carbon emissions driven by the construction industry in Shanghai

From 2010 to 2019, the amount of embodied carbon emissions generated locally by Shanghai's construction industry was greater than the amount generated in other regions. Demand from Shanghai's construction industry caused the amount of locally generated carbon emissions to decrease from 60.19 Mt in 2010 to 49.99 Mt in 2015, and then drop further to 38.47 Mt in 2019. However, the demand from Shanghai's construction industry was responsible for a significant increase in the total carbon emissions generated in other regions, from 0.55 Mt in 2010 to 19.40 Mt in 2015, followed by a further rise to 30.00 Mt in 2019. As a coastal city in the Yangtze River Delta economic circle, Shanghai is China's economic and trading centre, and so any increase in consumer demand is more likely to cause an increase in embodied carbon emissions in other provinces and cities.[29] From the perspective of the regional transfer of carbon emissions, the regions that experienced the most significant changes in the embodied carbon emissions driven by Shanghai's construction industry from 2010 to 2015 were Hebei, Tianjin, Jilin, and Inner Mongolia, with respective increases of 2.07 Mt, 1.90 Mt, 1.76 Mt, and 1.41 Mt. However, from 2015 to 2019, the regions that experienced the most significant increases were Guangdong (3.81 Mt), Henan (3.26 Mt), and Shandong (2.90 Mt). Overall, the amount of locally generated carbon emissions from Shanghai's construction industry declined, but a shift occurred in the regions most impacted by the embodied carbon emissions driven by demand from the construction industry from the northern region to the central region and the southern

coastal areas.

4.3.4 The embodied carbon emissions driven by the construction industry in Chongqing

From 2010 to 2019, the amount of embodied carbon emissions generated by the construction industry in Chongqing itself remained higher than those of other regions.

The amount of carbon emissions generated by final demand from Chongqing's construction industry increased from 65.25 Mt in 2010 to 166.92 Mt in 2015, and subsequently decreased to 113.53 Mt in 2019. Of the four cities, Chongqing was the

one responsible for transferring the highest level of embodied carbon emissions from the consumption side of the construction industry to other provinces. The total carbon

emissions generated by Chongqing's construction industry and transferred to other areas increase from 13.88 Mt in 2010 to 23.04 Mt in 2015, and then underwent a further significant increase to 62.15 Mt in 2019. With regard to the regional transfer of carbon

emissions, the regions that experienced the most significant changes in the impact of embodied carbon emissions driven by Chongqing's construction industry from 2010 to

2015 were Jilin (1.57 Mt), Jiangsu (1.51 Mt), and Tianjin (1.43 Mt). However, from

2015 to 2019 Guangdong, Henan, and Shandong underwent the greatest changes, with respective increases in embodied carbon emissions of 8.39 Mt, 7.29 Mt, and 6.12 Mt.

Overall, a shift occurred in the regions most affected by embodied carbon emissions driven by demand from Chongqing's construction industry from the northern region to the central and southern coastal areas.

In summary, during 2010-2019, the embodied carbon emissions generated locally by the construction industry in Tianjin, Shanghai, and Chongqing was greater than that of

other regions. The same was true for Beijing from 2010 to 2015. However, the amount of embodied carbon emissions generated in other regions due to demand from Beijing's construction industry increased substantially in 2019. Furthermore, there was a downward trend in the amount of carbon emissions generated locally by the consumption side of the construction industry, while the amount of embodied carbon emissions generated in other areas gradually increased. During the period 2010-2015, the regions of Hebei, Tianjin, Inner-Mongolia and Jilin experienced the greatest changes in demand-pulled embodied carbon emissions from the construction industry in the four cities. A possible explanation is that the neighbouring regions of these cities, such as Hebei, introduced significant reform within the construction market and actively expanded trading cooperation outside the province during this period, and thus, the amount of embodied carbon emissions increased due to growing demand from the construction industry.[10] From 2015 to 2019, the consumption side of the construction industry in these four cities caused a more significant increase in the amount of embodied carbon emissions in Guangdong, Henan, and Shandong. During the past decade, the population of Guangdong, Henan, and Shandong has risen steeply, and the resultant increase in demand for housing and transportation infrastructure drove the increase in embodied carbon in these regions.

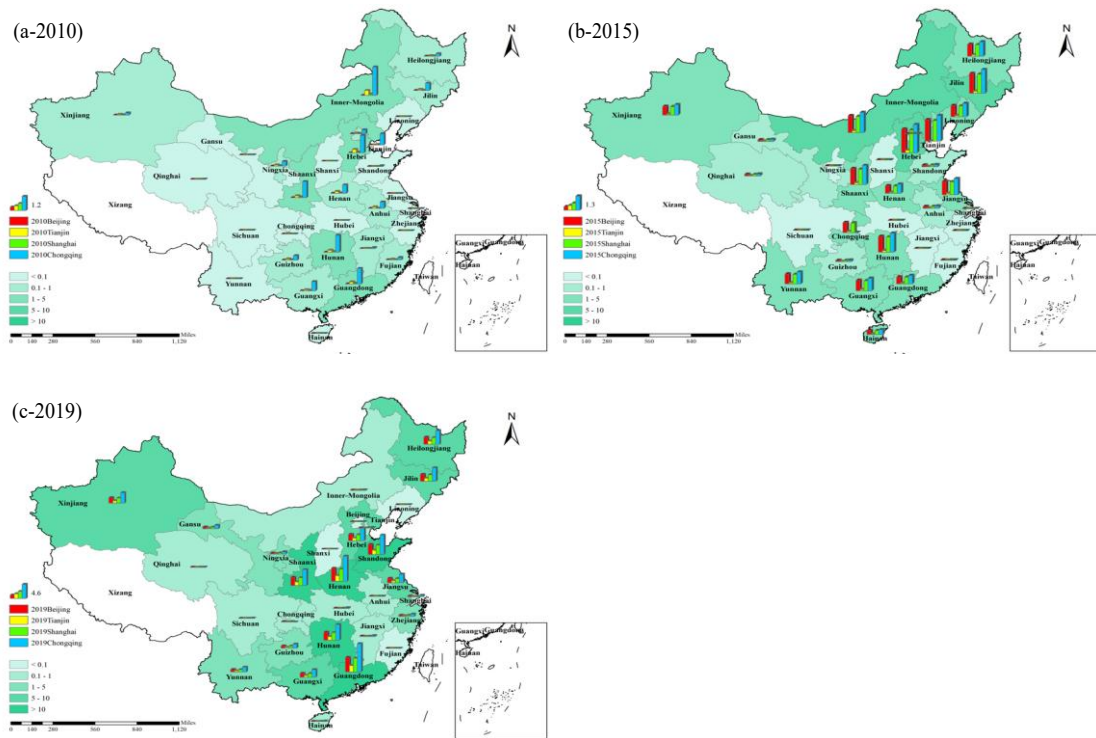


Fig9 Regional transfer of the CBEC of the construction industry in the four municipalities in 2010, 2015 and 2019 (The bar chart represents the embodied carbon emissions (Mt) generated in each region pulled by the demand from the construction industry in the four cities, and the chart underneath it represents the sum of the embodied carbon emission (Mt) generated in each region pulled by the demand from the construction industry in the four municipalities.)

4.4 The mechanisms of the CBEC of the construction industry

During the period 2010-2019, the total changes in embodied carbon emissions from the consumption side of the construction industry in all four cities showed varying degrees of reduction. In the case of Beijing, it decreased by 74.49 Mt; for Tianjin the figure was 32.22 Mt; for Shanghai it dropped by 9.57 Mt; and in Chongqing's case by 125.13 Mt. Shanghai experienced the least total change in the CBEC of the construction industry, while Chongqing's CBEC from the construction industry underwent the greatest change. To further investigate the impact of various structural factors on the reduction

of the CBEC from the construction industry in these four cities, the structural decomposition analysis model was used to identify the reasons for the different trends of the CBEC during the different periods (Fig10). The study used the five structural indicators shown in Table 4.

Carbon emissions intensity is a measure of the carbon emissions resulting from the growth of unit GDP,[30] and is a popular means of analysing the relationship between the development of the construction industry and carbon emissions.[10] As shown in Fig10, from 2010 to 2015, the carbon emissions intensity of the CBEC of the construction industry reduced in all four cities, by 17.39 Mt in Beijing, 10.98 Mt in Tianjin, 9.26 Mt in Shanghai, and 42.38 Mt in Chongqing. However, from 2015 to 2019, the carbon emission intensity effect became positive, leading to increases of 14.47 Mt in Beijing, 4.19 Mt in Tianjin, 5.93 Mt in Shanghai, and 29.03 Mt in Chongqing. These findings suggest that there is a need to further improve the efficiency of energy utilisation by the construction industry in order to reduce its carbon emissions intensity.[31]

A reduction in the amount of carbon emissions produced by the urban construction industry cannot be achieved without the support of technological innovation.[9] The input-output structure effect (IOS) can be regarded as a measure of the intermediate level of technological investment in the construction industry in each city. The IOS resulted in an increase in the CBEC of Beijing's construction industry (6.31 Mt) and that of Chongqing (35.48 Mt) during the period 2010-2015. Conversely, the IOS had a significantly negative effect on Tianjin's (-9.57 Mt) and Shanghai's (-22.79 Mt)

construction industry. From 2015 to 2019, the IOS resulted in a decrease in the CBEC of the construction industry for all four cities, by the following amounts: 50.95 Mt for Beijing, 13.68 Mt for Tianjin, 19.52 Mt for Shanghai, and 77.35 Mt for Chongqing. This shows that all four cities have greatly reduced the levels of CBEC in the construction industry by adjusting the industry's production structure, introducing technological innovations, and actively developing low-carbon methods of construction.[8]

In order to evaluate how the final demand of a city can drive the increase in CO₂ emissions within the construction industry, we analysed its effects from 2010 to 2015.

FDS rises in the CBEC of the construction industry of 17.19 Mt, 8.87 Mt, 25.39 Mt, and 4.44 Mt for Beijing, Tianjin, Shanghai, and Chongqing, respectively, were recorded.

Due to the rapid economic and population growth in Beijing and Shanghai, the proportion of capital formation in the construction industry to total final demand has continued to rise, leading to a significant expansion in production capacity and output in high energy-consuming and carbon emission generating industries, such as steel and building materials.[32] From 2015 to 2019, FDS had a negative effect on the CBEC of

the construction industry in Beijing (-4.70 Mt) and Tianjin (-4.28 Mt). By contrast, a positive effect was observed for Shanghai (5.44 Mt) and Chongqing (50.23 Mt) with respect to the FDS. The capital formation of the construction industry mainly involves real estate and infrastructure investment, both of which have a high demand for fuel, which produces carbon emissions. Thus, in order to reduce the amount of carbon emissions generated by the construction industry, there is a need to transform the

demand structure.[33]

The per capita final demand level effect (PFD) reflects the level of demand from urban residents for products of the construction industry. From 2010 to 2015, the PFD played a role in increasing the levels of CBEC in the construction industry, which resulted in a corresponding rise in the CBEC of the construction industry in Beijing, Tianjin, Shanghai, and Chongqing of 30.58 Mt, 21.69 Mt, 12.32 Mt, and 107.46 Mt, respectively. However, from 2015 to 2019, the PFD made a smaller contribution to increasing CBEC levels in the construction industry in Beijing, Tianjin, and Shanghai, with growth values of 9.83 Mt, 1.22 Mt, and 6.48 Mt, respectively. Conversely, the PFD had the effect of reducing the CBEC of Chongqing's construction industry (-22.02 Mt). Overall, compared to the period 2010-2015, the four cities all recorded a reduction in the amount of CBEC in the construction industry caused by the PFD from 2015 to 2019.

Population scale plays an important role in relation to carbon emissions by increasing the final demand.[34] The PSE made a significant contribution to the growth in the CBEC of the construction industry in the four cities from 2010 to 2019, but the magnitude of growth decreased over time. From 2010 to 2015, the PSE resulted in an increase in the CBEC growth of the construction industry of 6.58 Mt in Beijing, 10.30 Mt in Tianjin, 2.99 Mt in Shanghai and 5.83 Mt in Chongqing. However, these values subsequently decreased to 0.13 Mt, 0.73 Mt, 0.74 Mt, and 5.80 Mt, respectively from 2015 to 2019. Therefore, the PSE resulted an increase in the CBEC of the construction industry in the four cities, but its impact has been gradually decreasing in recent years.

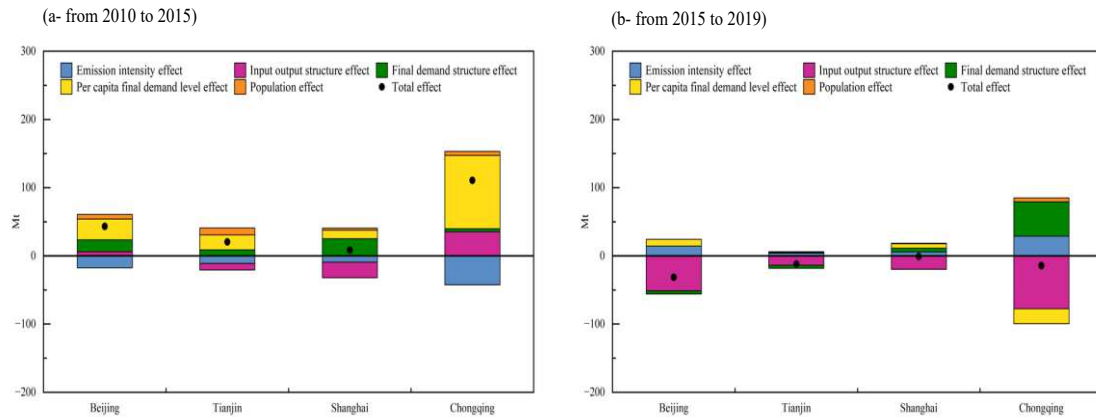


Fig10 The proportion of CBEC of the construction industry contributed by each influencing factor in the four cities during the period 2010-2015 (a), and 2015-2019 (b).

To sum up, during the period 2010-2015, the PFD had a positive effect on increasing the CBEC of the construction industry in the four cities, whereas the CEI had a negative effect. From 2015 to 2019, the CEI increased the CBEC of the construction industry in Beijing, Tianjin, Shanghai and Chongqing, while the IOS caused the CBEC to decrease. In addition, the effects of the IOS could not be determined with any certainty. However, the PFD and PSE were found to be positively related to the CBEC of the construction industry in the four cities.

5 Discussion and Policy Implications

The aim of the research is to explore the characteristics, changes, and mechanisms of the consumption-based embodied carbon emissions (CBEC) of the construction industry from the perspective of Chinese municipalities. And it provides reference and suggestions for other cities in China and other regions around the world to be studied for the green and sustainable development of the construction industry. Firstly, the variations in CBEC were studied from the perspective of provinces and cities in China and the types of final demand they drive. Secondly, an industry linkages and transfer

models were established from the perspective of the CBEC in industry and the driving role and correlation effects between the construction industry and its industry were analyzed. In addition, based on this model, further analysis was conducted on the reasons why the spatial transfer of CBEC is driven by the construction industry in the four major cities. Finally, the generation mechanism of CBEC in the construction industry of four cities at different periods was investigated from a dynamic structural perspective.

5.1 Comparison with relevant studies

Reducing the CBEC of cities is of great significance for achieving green and low-carbon socio-economic development. Research shows that the growth of CBEC in the four municipalities directly under the central government is mainly driven by the total amount of fixed capital formation. This is due to the high level of urbanization development in these municipalities, which requires a large amount of resources and energy investment in infrastructure construction, inevitably accompanied by a large amount of carbon dioxide emissions. Therefore, reducing the proportion of total fixed capital formation in urban final demand is crucial for governing urban CBEC. This discovery is consistent with Kobayakawa's proposal that the main reason for rapid economic growth in developing countries is the investment in carbon intensive capital formation.[35] From the perspective of industrial linkages analysis, the construction industry has a strong CBEC backward correlation effect with many upstream industries (such as electricity and hot water production and supply, metal smelting and stamping, non-metallic mineral products), all of which are high energy consuming industries,

indicating that the construction industry is a key industry for cities to reduce CBEC.[36]
From the perspective of spatial transfer in CBEC, the urban construction industry is
gradually shifting the embodied carbon emissions produced locally to other provinces
and cities in the surrounding area. This is supported by Sun's viewpoint that developed
regions transfer the pressure of carbon reduction to less developed surrounding
regions.[37] In addition, from the analysis of the underlying mechanism of CBEC in
urban construction industry, cities need to take measures to reduce the carbon emission
intensity of the construction industry to achieve the goal of reducing CBEC.[38]

5.2 Policy Implications

The following are policy recommendations for other cities to reduce construction
CBECs in response to the study.

First, with regard to urban development, in view of the fact that both the total amount
and the intensity of CBEC were high in the four cities, municipal governments could
reduce the demand for high carbon emission-related industries by subsidising low-
carbon products and increasing consumption taxes on carbon intensive products.[31]

Secondly, in terms of the construction industry, policymakers need to consider the
embodied carbon emissions of related industries driven by the consumption side of the
construction industry, and encourage them to take responsibility for reducing carbon
emissions. On the one hand, the construction industry needs to make adjustments of its
demand for upstream industries with low carbon emissions; on the other hand, the
upstream enterprises of the construction industry with outdated production capacity
should be eliminated, and the efficiency of energy utilisation of them need be

improved.[39]

Thirdly, although four cities have reduced their total embodied carbon emissions through spatial transfer, but this process exacerbates regional inequalities which is unsustainable. Thus, developed regions are encouraged to provide more fundings to help less developed regions to improve their technology and reduce their carbon emissions, as well as to work together to address the environmental issues of carbon emissions leakage in the construction process.[28]

Finally, the structural decomposition analysis indicated that reducing carbon emission intensity can alleviate the growth of embedded carbon emissions in the construction industry. By examining the energy consumption structure of the construction industry, reducing the proportion of fossil fuels used in the production process, and replacing them with more clean energy sources such as wind and solar energy.[40] In addition, the production technology of the construction could be further improved. For example, the utilisation and recovery rate of intermediate products can be improved by using low-carbon intermediate products.[33]

5.3 Limitations and prospects

This study investigated the characteristic changes and decision-making mechanisms of CBEC in the construction industry of Chinese municipalities directly under the central government. This study strengthened the theoretical analysis of reducing CBEC in the construction industry from an urban perspective and provides insightful conclusions. However, there were limitations to the conclusion. On the one hand, this study calculated CBEC using the latest input-output table data and carbon emission inventory

from multiple regions in China, but these data were only updated until 2019. In the future, this study will always pay attention to the release of the latest data, calculate more accurate model data in a timely manner, and update the latest research conclusions. On the other hand, this study only focused on the economic and carbon emission linkages between municipalities and provinces. Further research work could focus on multi-city models, linking major cities and other cities together. A further possibility for future research could involve carrying out a more detailed linkage analysis using multi-scale MRIO models to focus on specific aspects of urban transformation that are necessary to achieve a low carbon economy, such as buildings and materials, or waste.

6 Conclusions

This study used the MRIO model to examine the overall levels of CBEC and CBEC levels within different industries in Beijing, Tianjin, Shanghai, and Chongqing in 2010, 2015, and 2019. The industrial linkages of the construction industry in these four municipalities with other sectors were analysed in order to identify key industries with close linkages between the upstream and downstream ends of the construction industry in relation to carbon emissions. We also examined how the spatial transfer of CBEC was pulled by the construction industry in the four cities. In addition, structural decomposition analysis was used to explore the determinants of the CBEC of the construction industry in the four cities during the periods 2010-2015 and 2015-2019. The key findings of this study are as follows.

At first, during the period 2010-2019, there were few changes in the CBEC in Beijing and Tianjin, while the total amount of CBEC pulled by Shanghai decreased and that of

Chongqing increased. However, the intensity of the CBEC in the four cities gradually decreased. In terms of the types of final demand, more than 50% of the CBEC in the four cities was caused by gross fixed capital formation.

Second, from an industrial sector perspective, the Construction (S24) industry was responsible for the highest amount of CBEC in the four cities during the period 2010-2019. More than 95% of the CBEC from the construction industry was caused by gross fixed capital formation. According to the industry linkage analysis, from 2010 to 2019, the upstream industries with the largest backward carbon emission linkages with the construction industry in the four cities were: the Production and Supply of Electric Power and Hot Water (S22), Smelting and Pressing of Metals (S14), and Nonmetal Mineral Products (S13). Construction (S24) itself was the downstream industry with the largest forward carbon emissions linkage with the construction industry in the four cities.

Third, with regard to the spatial transfer of embodied carbon emissions, the amount of carbon emissions generated locally by the consumption side of the construction industry ultimately followed a downward trend in the four cities, while the carbon emissions generated by other provinces gradually increased. From 2010 to 2015, the regions that witnessed the most significant changes in terms of embodied carbon emissions driven by the consumption side of the construction industry were Hebei, Tianjin, Inner Mongolia, and Jilin. However, between 2015 and 2019, a shift occurred and the regions that underwent the greatest changes were the central and southeastern coastal regions, such as Guangdong, Henan, and Shandong.

At last, in terms of the mechanisms behind the CBEC of the construction industry, the PFD resulted in a huge increase in the CBEC of the construction industry, whereas the CEI led to a significant decrease in the CBEC in the four cities from 2010 to 2015. By contrast, the CEI made a major contribution to the CBEC of the construction industry from 2015 to 2019. The IOS was negative during this period, while the PFD and PSE had positive effects. Meanwhile, there was uncertainty about the effect of the FDS.

Declarations

Not applicable

Availability of data and materials

The data can be made on request.

Competing interests

The authors declare they have no competing interests.

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Authors' contributions

Jinkai Li and Wen Wen provided the conceptualization and methodological framework, and conducted the core analysis. Yang Su and Xing Gao processed the data curation,

formal analysis, and visualization. Liu Ouyang and Sitian Li contributed to the manuscript writing, content review, and textual and graphical refinement. All authors read and approved the final manuscript.

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933 of Cleaner Production. 2020;243:118534.

934 **Table 1: Top Upstream Industries of Construction's Backward Carbon Linkages**

	Beijing			Tianjin			Shanghai			Chongqing		
	2010	2015	2019	2010	2015	2019	2010	2015	2019	2010	2015	2019
S1	0.0280	0.0253	0.0095	0.0251	0.0205	0.0155	0.0171	0.0138	0.0061	0.0684	0.0221	0.0150
S2	0.2110	0.1663	0.0944	0.1900	0.0927	0.0768	0.2858	0.1243	0.0638	1.1227	0.2862	0.1858
S3	0.0267	0.0246	0.0159	0.0190	0.0150	0.0166	0.0233	0.0256	0.0153	0.0281	0.0368	0.0226
S4	0.0159	0.0167	0.0047	0.0102	0.0058	0.0135	0.0124	0.0057	0.0013	0.0195	0.0207	0.0098
S5	0.0066	0.0136	0.0042	0.0123	0.0326	0.0095	0.0135	0.0092	0.0056	0.0534	0.0172	0.0179
S6	0.0092	0.0057	0.0031	0.0076	0.0040	0.0039	0.0072	0.0037	0.0019	0.0055	0.0052	0.0038
S7	0.0043	0.0026	0.0008	0.0044	0.0023	0.0009	0.0053	0.0018	0.0011	0.0065	0.0025	0.0011
S8	0.0016	0.0008	0.0001	0.0013	0.0004	0.0002	0.0023	0.0004	0.0012	0.0006	0.0009	0.0003
S9	0.0048	0.0073	0.0030	0.0076	0.0049	0.0034	0.0052	0.0066	0.0018	0.0016	0.0026	0.0011
S10	0.0091	0.0095	0.0044	0.0080	0.0067	0.0034	0.0134	0.0086	0.0029	0.0142	0.0129	0.0059
S11	0.1648	0.1612	0.0698	0.1582	0.1015	0.1154	0.1617	0.1255	0.0705	0.1724	0.2984	0.1100
S12	0.0920	0.0644	0.0257	0.0615	0.0528	0.0282	0.0648	0.0395	0.0129	0.1181	0.0969	0.0499
S13	1.5456	1.1225	0.6000	0.8010	1.2357	0.7351	1.5952	1.0802	1.2990	3.2178	1.9171	1.1020
S14	1.9903	1.4329	0.8697	2.1232	1.1946	1.0612	1.3011	0.8171	0.2142	0.9830	1.3427	1.7108
S15	0.0059	0.0057	0.0080	0.0101	0.0065	0.0091	0.0084	0.0066	0.0058	0.0072	0.0098	0.0070

S16	0.0105	0.0088	0.0036	0.0107	0.0078	0.0053	0.0146	0.0048	0.0029	0.0202	0.0081	0.0059
S17	0.0049	0.0013	0.0007	0.0044	0.0013	0.0014	0.0040	0.0009	0.0011	0.0093	0.0016	0.0008
S18	0.0052	0.0033	0.0028	0.0064	0.0031	0.0037	0.0036	0.0023	0.0029	0.0039	0.0020	0.0033
S19	0.0007	0.0006	0.0005	0.0005	0.0003	0.0004	0.0006	0.0003	0.0002	0.0004	0.0003	0.0003
S20	0.0002	0.0003	0.0002	0.0002	0.0002	0.0001	0.0003	0.0001	0.0000	0.0011	0.0006	0.0001
S21	0.0064	0.0037	0.0009	0.0045	0.0023	0.0010	0.0038	0.0049	0.0009	0.0042	0.0065	0.0012
S22	2.2361	2.5470	1.7045	3.1523	2.2428	2.0935	2.9701	1.7922	1.4026	2.8640	4.1924	3.2516
S23	0.0046	0.0054	0.0111	0.0044	0.0037	0.0180	0.0196	0.0157	0.0186	0.0023	0.0088	0.0116
S24	0.2117	0.0714	0.0568	0.4224	0.2963	0.2822	0.2403	0.1175	0.1015	0.1547	0.0843	0.0759
S25	0.3604	0.2870	0.2429	0.5567	0.1781	0.2848	0.3509	0.2262	0.4339	0.4402	0.4667	0.2077
S26	0.0773	0.0591	0.0360	0.0794	0.0468	0.0346	0.0530	0.0408	0.0287	0.0373	0.0449	0.0456
S27	0.0420	0.0435	0.0240	0.0431	0.0436	0.0280	0.0443	0.0488	0.0211	0.0344	0.0383	0.0179

935 Note: The colours vary from lighter to darker, meaning the values increase from small to large.

936 **Table 2: Top Downstream Industries of Construction's Forward Carbon Linkages**

	Beijing			Tianjin			Shanghai			Chongqing		
	2010	2015	2019	2010	2015	2019	2010	2015	2019	2010	2015	2019
S1	0.0394	0.0069	0.0091	0.0403	0.0285	0.0378	0.0512	0.0068	0.0154	0.0153	0.0020	0.0043
S2	0.0845	0.0091	0.0125	0.0466	0.0326	0.0239	0.0319	0.0113	0.0085	0.0367	0.0101	0.0171
S3	0.0346	0.0048	0.0241	0.0421	0.0430	0.0397	0.0754	0.0121	0.0128	0.0721	0.0116	0.0162
S4	0.0673	0.0254	0.0080	0.0752	0.0258	0.0174	0.0328	0.0114	0.0059	0.0319	0.0069	0.0065
S5	0.0658	0.0110	0.0098	0.0494	0.0236	0.0324	0.0381	0.0109	0.0086	0.0475	0.0097	0.0145
S6	0.0483	0.0098	0.0068	0.0331	0.0176	0.0249	0.0502	0.0121	0.0105	0.0191	0.0046	0.0052

S7	0.0405	0.0082	0.0075	0.0323	0.0196	0.0365	0.0763	0.0110	0.0119	0.0242	0.0049	0.0069
S8	0.0411	0.0083	0.0073	0.0289	0.0147	0.0288	0.1415	0.0125	0.0157	0.0196	0.0053	0.0059
S9	0.0568	0.0174	0.0115	0.0395	0.0174	0.0457	0.1064	0.0204	0.0164	0.0548	0.0051	0.0077
S10	0.0619	0.0126	0.0086	0.0491	0.0259	0.0377	0.0950	0.0142	0.0164	0.0369	0.0067	0.0065
S11	0.0288	0.0088	0.0044	0.0622	0.0506	0.0470	0.0765	0.0114	0.0069	0.0372	0.0066	0.0055
S12	0.0596	0.0131	0.0073	0.0527	0.0432	0.0390	0.0915	0.0183	0.0146	0.0352	0.0098	0.0078
S13	0.0611	0.0442	0.0081	0.0534	0.0612	0.0356	0.1061	0.0176	0.0135	0.0910	0.0108	0.0087
S14	0.0443	0.0138	0.0057	0.0441	0.0383	0.0292	0.0707	0.0152	0.0123	0.0259	0.0073	0.0062
S15	0.0519	0.0599	0.0067	0.0519	0.0389	0.0361	0.1017	0.0191	0.0152	0.0355	0.0058	0.0061
S16	0.0603	0.0161	0.0077	0.0467	0.0375	0.0369	0.0991	0.0194	0.0155	0.0291	0.0067	0.0075
S17	0.0470	0.0130	0.0074	0.0487	0.0287	0.0331	0.1167	0.0191	0.0186	0.0239	0.0088	0.0095
S18	0.0567	0.0167	0.0077	0.0452	0.0360	0.0347	0.1019	0.0167	0.0148	0.0289	0.0059	0.0064
S19	0.0392	0.0125	0.0082	0.0346	0.0424	0.0373	0.0528	0.0134	0.0115	0.0145	0.0082	0.0087
S20	0.0583	0.0116	0.0077	0.0579	0.0237	0.0390	0.0767	0.0160	0.0145	0.0282	0.0074	0.0082
S21	0.0449	0.0160	0.0095	0.0289	0.0267	0.0343	0.1221	0.0172	0.0228	0.0331	0.0101	0.0044
S22	0.0879	0.0357	0.0165	0.0858	0.0345	0.0569	0.1340	0.0217	0.0262	0.0315	0.0194	0.0126
S23	0.1463	0.0200	0.0081	0.0739	0.0512	0.0491	0.0924	0.0294	0.0149	0.0946	0.0143	0.0141
S24	6.3412	2.1481	1.7161	12.6745	8.8772	8.4878	7.2305	3.5472	3.0653	4.6529	2.5198	2.2850
S25	0.0861	0.0250	0.0150	0.1537	0.0824	0.0496	0.1949	0.0252	0.0234	0.1014	0.0101	0.0124
S26	0.1516	0.0156	0.0120	0.1131	0.0387	0.0471	0.1484	0.0201	0.0195	0.0869	0.0066	0.0108
S27	0.2192	0.0287	0.0182	0.1462	0.0941	0.0637	0.2951	0.0304	0.0286	0.0844	0.0145	0.0211

937 Note: The colours vary from lighter to darker, meaning the values increase from small to large.

938 **Table 3: Construction CBEC by Final Demand, 2015–2019**

	Beijing		Tianjin		Shanghai		Chongqing	
	2015	2019	2015	2019	2015	2019	2015	2019
Consumption by rural residents	12.8	4.8	2.8	2.1	8.8	24.6	19.8	9.3
Consumption by urban residents	168.1	11.5	55.4	5.0	115.2	189.1	91.5	22.3
Government consumption	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gross fixed capital formation	9190.4	6228.0	7090.8	5960.2	6819.6	6633.0	18891.7	17536.0
Increase in inventory	-5.0	0.0	-0.5	0.0	-4.8	0.0	-6.0	0.0
Total	9366.2	6244.3	7148.5	5967.2	6938.9	6846.7	18996.9	17567.6

939 **Table 4 Structural factors on the reduction of CBEC from the construction industry**

Structural indicator	Abbr.	Definition
Carbon emissions intensity effect	CEI	The ratio of carbon emissions produced by a sector to its total output
Input-output structure effect	IOS	The input-output economic linkages of sectors
Final demand structure effect	FDS	The ratio of the final demand of a sector to the total
Per capita final demand level effect	PFD	The ratio of the final demand of a region to its population scale
Population scale effect	PSE	The population scale of a region
Total effect	TLS	All effects of embodied carbon emissions

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