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Study on Regional Differences of Carbon Emission Efficiency: Evidence from Chinese Construction Industry

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Abstract: The escalating issue of global climate change necessitates urgent measures to reduce carbon emissions globally. Within this context, the construction industry emerges as a critical sector to address given its high energy consumption, substantial CO_2 emissions, and low utilization rate. Therefore, it is pivotal to foster energy conservation and reduce emissions in this sector. To this end, this paper delineates two primary objectives: (1) identifying optimal research methodologies and index parameters for evaluating carbon emission efficiency in the construction industry, and (2) assessing the variance in carbon emission efficiency at disparate stages and regions. Leveraging the Malmquist index, we scrutinize the carbon emission data from 30 Chinese provinces spanning from 2010 to 2019. Our findings indicate a geographical dichotomy in China's construction industry's carbon emission efficiency—lower in the west and higher in the east. Additionally, this study delves into the distinguishing features of emission efficiency alterations across regions, the main influencing factors, and avenues for enhancement. Subsequently, it proposes policy recommendations tailored to the unique attributes of various regions and the overarching framework.

Keywords: carbon emission efficiency; the field of construction; dynamic and static efficiency models

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1. Introduction

In recent years, with the acceleration of the process of world industrialization, the massive consumption of fossil energy has promoted the rapid growth of global carbon emissions, the problem of global climate change has become increasingly prominent, and the destruction of ecological environment has gradually threatened the sustainable development of human society. As a pillar industry sector of the national economy, the construction industry is closely related to building materials, manufacturing, electrical and mechanical engineering, metallurgy, light industry and other sectors. At the same time, due to the characteristics of long building operation and service cycle, high energy consumption of traditional buildings and low resource utilization rate, the construction industry has a large carbon emission reduction potential [1], so it is very important to conduct targeted measurement and exploration. However, the current measurement of the carbon emission efficiency of the construction industry is not uniform, mainly including single factor measurement and full factor measurement. Relevant studies usually analyze the overall situation of the region, and there are few studies on regional differences in the carbon emission efficiency of the construction industry.

"Carbon peak" "carbon neutrality" is China's strategic policy, but also China's solemn commitment to the world. Improving carbon emission efficiency plays an important role in reducing carbon emission. As one of the important sectors of carbon emission, in-depth analysis of the trend and regional differences of carbon emission efficiency in the construction industry is of great significance for understanding the key factors of regional carbon emission efficiency change. According to recent statistics, the carbon emission of the construction industry is second only to that of coal power, industrial production and transportation, and the overall emission is high [2]. If the carbon emissions of the construction industry are further subdivided, the production and construction of building materials account for 55%, and the construction operation and maintenance account for about 45%. Therefore, it is necessary to study the regional development of carbon emission efficiency in the construction field and pay attention to the improvement of carbon emission efficiency in the construction industry from the production and manufacturing of building materials, building construction to the operation and maintenance of the whole life cycle of buildings. However, at present, there is no effective method to calculate the carbon emission efficiency of the building sector, which is very backward compared with other fields. Without effective measurement of carbon emission efficiency in the building sector, it will be impossible to understand its characteristics and formulate relevant emission reduction strategies.

Therefore, this paper has two core objectives: firstly, to explore appropriate research methods and index parameters to measure carbon emission efficiency in the building sector; Secondly, summarize the characteristics of carbon emission efficiency in different stages and regions in the construction field.

The primary innovative contributions and focal points of this study can be summarized as follows: (1) Implementation of the super-efficiency Slacks-Based Measure (SBM) model to scrutinize the comprehensive carbon emission efficiency within the construction sector across 30 provinces in mainland China, barring Tibet. (2) Employment of the Malmquist index to delineate the overarching trends in the carbon emission efficiency in China's construction industry. (3) Segmenting the analysis based on China's geographical demarcations to elucidate the divergent characteristics of carbon emission efficiency, pinpoint the principal driving forces, and highlight prospective avenues for improvement. Subsequently, this study proposes strategies to augment carbon emission efficiency in the construction sector, accommodating both national and regional dimensions.

The subsequent sections of this paper are structured as follows: Section two offers a synthesis of pertinent literature in the domain of carbon emission efficiency. Section three details the analytical model and the origin of the data employed in this study. Section four presents a meticulous analysis of the data acquired. Section five explores regional disparities in carbon emission efficiency. Section six furnishes a comprehensive summary of the discussion undertaken throughout the paper.

2. Literature Review

Scholars have proposed indicators to measure carbon emission efficiency from different angles. For example: CO_2 emissions per unit GDP (CO_2 emission intensity) [3], CO_2 emissions per unit energy consumption [4], CO_2 emissions per capita in regions [5], etc., The above indicators measure the relationship between the two in the form of ratio, which is called a single-factor indicator, which can only reflect the CO_2 emission efficiency from a certain aspect, and cannot judge the regional carbon emission efficiency by combining multiple factors such as energy consumption, capital, labor force and economic output value [6,7].

In order to analyze carbon emission efficiency from the perspective of total factor production, DEA (Data Envelopment Analysis) is usually used to calculate decision-making unit efficiency of multiple input variables and output variables. Traditional DEA models mainly include CCR and BCC. CCR, proposed by A. Charnes et al., is the earliest DEA model. Its basic assumption is CRS (Constant Return Scale), and the resulting efficiency is A comprehensive efficiency that includes scale efficiency and pure technical efficiency [8,9]. BCC was improved on the basis of CCR by R. D. Banker et al., whose assumption was VRS (Variable Return Scale), and the pure technical efficiency of DMU (Decision Making Unit) could be obtained [10]. But CCR and BCC are unable to handle undesired outputs. In addition, both CCR and BCC belong to radial distance functions, ignoring the problem of variable relaxation [11]. Based on this, Tone proposed the SBM (Slacks-based Measure) model on the basis of the traditional DEA model, which effectively solved the problem of relaxation of input-output and the efficiency evaluation problem of non-expected output [12]. SBM synthesizes traditional input-oriented and output-oriented models and considers the possible improvement space of all input and output variables [13].

DEA has been widely used in industry, transportation, energy and other fields, and has derived a variety of improved DEA models such as Super-SBM, DDF, EBM, DEA-Malmquist productivity index. A large number of scholars have used various DEA models to measure carbon emission efficiency. For example, in the transportation industry, Chang et al. and Zhou et al. analyzed the carbon emission efficiency of the transportation industry in various provinces in China through the non-radial DEA model, and the empirical results showed that the provinces with effective carbon emission efficiency of the transportation industry in China were decreasing from 2004 to 2006. It reached its lowest point in 2006 and has since recovered slightly [14,15]. Zhang et al. used the Luenberger index to analyze the dynamic change of total factor carbon emission efficiency of China's transportation industry, and the study showed that the increase of carbon emission efficiency was mainly driven by technological innovation [16]. In the energy industry, Duan et al. analyzed the energy utilization efficiency and carbon emission efficiency of thermal power industry in various provinces of China from the static and dynamic aspects from 2005 to 2012, and the results showed that technological progress was the main driving factor for both [17]. Zhang et al. analyzed the dynamic change of carbon emission efficiency of fossil fuel power plants in China from 2005 to 2010, and the results showed that there was a U-shaped change during the sample period, with the overall efficiency increasing by 0.38%. In the field of industry and manufacturing [18], Wang et al. analyzed the energy use efficiency and carbon emission efficiency of the industrial sector in major Chinese cities from the regional level, and the empirical results showed that economically developed cities had high industrial carbon emission efficiency, and there were significant differences in industrial carbon emission efficiency between regions [19]. Pérez et al. analyzed the energy efficiency and carbon emissions of the intellectual manufacturing industry, and the results showed that the industrial sectors with the highest efficiency included communications, metals and clothing [20].

In general, in the industry research, most of the carbon emission efficiency studies are in the fields of transportation, industrial manufacturing and agricultural production, while the carbon emission efficiency studies in the construction industry started relatively late, and there are few related research literatures, which mainly include static research and dynamic research.

2.1. Static Study on Carbon Emission Efficiency in Building Field

As shown in Table 1, through literature analysis, it can be seen that scholars usually take provinces and regions of China as the decision-making unit (DMU) for the carbon emission efficiency of the construction industry, make use of panel data for analysis, take energy consumption, labor, capital, machinery and other input factors, take the total output value of the construction industry as the desirable output, and take the carbon emission of the construction industry as the undesirable output.

For example, Huang et al. (2018) used the input-output table to analyze the changes in carbon emissions of the construction industry in 40 countries around the world, and found that the direct and indirect carbon emission intensity of developing countries was higher than that of developed countries [27]. Zhang et al. (2021) analyzed the carbon emission efficiency of China's construction industry from 2006 to 2017 based on the three-stage DEA model excluding random interference factors, and used Tobit regression model to analyze the influencing factors of carbon emission efficiency [28]. Based on the analysis of provincial panel data in China, Liao et al. (2022) found that the development of green buildings helped promote carbon neutrality in the construction industry [29]. Li et al. (2020) evaluated the total factor carbon emission Performance Index (NMTCPI) of China's provincial construction industry from 2004 to 2017, and the results showed that the carbon emission efficiency of the construction industry was at a low level, but the growth rate was fast [30].

Table 1. Statistics of literature related to carbon emission efficiency of the construction industry.

Source	Research Object	Method	Inputs	Outputs	
				Desirable Outputs	Undesirable Outputs
Du et al. (2022) [21]	Carbon Emission Efficiency (CEE) of the Construction Industry in 30 Provinces of China from 2005 to 2016	SBM	Capital, labor, energy consumption, machines	GDP	Carbon emission
Zhou et al. (2019) [22]	Total factor carbon emission efficiency (CEE) of China's construction industry from 2003 to 2016	SBM	Labor, capital, energy consumption	GDP	Carbon emission
Zhang et al. (2018) [23]	Energy Efficiency (EE) of China's Construction Industry from 2007 to 2016	BBC	Capital stock, labor force, mechanical equipment, building energy consumption	GDP and environmental impact	
Zhou and Yu (2021) [24]	Carbon Emission Efficiency (CEE) of China's Construction Industry from 2003 to 2016	Three-stage DEA	Labor, capital, technical equipment	Floor space under construction	Carbon emission
Xue et al. (2015) [25]	Energy Efficiency (EE) of China's Construction Industry from 2004 to 2009	DEA-Malmquist	Coal consumption, electricity consumption	Construction value added	
Huo et al. (2020) [26]	Total Factor Energy Efficiency (TFEE) of China's Construction Industry from 2006 to 2015	DEA	Labor, capital, technological level	GDP and floor space under construction	

In addition, some scholars have constructed the input-output index system of the carbon emission efficiency of the construction industry from other aspects. Wang et al. combined with social network analysis, studied the spatial correlation network structure characteristics of China's construction industry carbon emission intensity, and the results showed that China's carbon emission had significant regional differences [31]. Erdogan studied the interaction between carbon emission efficiency and technological innovation in the construction industry of BRICS countries, and analyzed the internal mechanism of technological innovation in reducing carbon emission [32]. Du et al. used the log-average Divisia index (LMDI) model to analyze the carbon emission and carbon emission intensity of the construction industry, and obtained the relationship among the influencing factors such as energy consumption per unit value, indirect carbon emission intensity and output scale effect [33].

Building upon existing research, it is evident that the Data Envelopment Analysis (DEA) model has become a prevalent tool in the static analysis of the carbon emission efficiency in the construction industry, chiefly due to its capabilities to handle multiple inputs and outputs without pre-assumptions on the production relationships of decision-making units (DMUs). However, this traditional model encounters several pitfalls when applied to this context, including: (1) The obligatory proportional escalation or reduction of input and output indicators, coupled with the neglect of slack variables in efficiency evaluation, a scenario that potentially yields underestimations of efficiency. (2) The cumbersome necessity to integrate expected output costs, such as carbon emissions, as input parameters, or alternatively, to apply distinct assessment techniques like the distance function method and linear data transformation method, in cases where unexpected outputs are to be gauged. (3) The occurrence of multiple efficient DMUs, necessitating the integration of a super-efficiency DEA model to facilitate a comprehensive efficiency comparison amongst all DMUs. (4) The potential overlooking of environmental contingencies and stochastic errors, which can inadvertently amplify the efficiency measurement outcomes. Given these constraints, the

Slacks-Based Measure (SBM) model emerges as a robust alternative, offering computational prowess in evaluating carbon emission efficiency in the construction sector.

2.2. Dynamic Study on Carbon Emission Efficiency in Building Field

Since the DEA model is based on the annual cross-section data to construct the front plane, it does not have the characteristics of comprehensive comparison, so it needs to introduce Malmquist or Malmquist-Luenberger index to realize the dynamic analysis of efficiency changes. Malmquist index model can effectively measure the dynamic efficiency of time series data, and can be decomposed into comprehensive technical efficiency change index (which can also be decomposed into pure technical efficiency change index and scale efficiency change index) and technological progress index, therefore, it has good analytical characteristics, so it is widely used in the field of time comparison of carbon emission efficiency in various industries and sectors. Zhou et al. proposed the Malmquist Carbon emission Efficiency Index (MCPI) under the framework of total factor productivity, and conducted a comparative study on the dynamic changes of carbon emission efficiency in 18 major carbon emitting countries in the world [34]. Zhang et al. used the Luenberger Index to construct the frontier non-radial Luenberger Carbon Emission Performance Index (MNLCPI), which is used to evaluate the dynamic change of total factor carbon emission performance of the transportation industry [16]. The results show that, driven by technological innovation, the overall carbon emission efficiency of China's transport sector increased by 6.2% from 2000 to 2012. In general, there are relatively few studies on the application of Malmquist index in the field of carbon emission efficiency in buildings.

Based on the above discussion, on the basis of existing studies, this paper adopts the non-radial SBM model to study the carbon emission efficiency of the construction industry, applies the Malmquist index to analyze the development of carbon emission efficiency of the construction industry in each year, and analyzes the main contributing factors of carbon emission efficiency by combining technological progress, pure technical efficiency and scale efficiency. The SBM model can effectively solve the problem that the traditional DEA model cannot take into account the undesired output, and can measure the input-output relaxation better. Combined with Malmquist index, dynamic changes in carbon emission efficiency can be analyzed, and changes in carbon emission efficiency of various provinces in China can be intuitively evaluated from the perspective of time.

3. Methods

3.1. Models

3.1.1. SBM Model of Carbon Emission in Construction Industry

Since the carbon emission efficiency of the construction industry has a number of input and output indicators, if the ineffective decision-making unit is improved by reducing the input or increasing the output in an equal proportion, it may only achieve weak efficiency in the end, and there are still some parts that need to be relaxed and improved. In this paper, based on the non-radial SBM model, a model suitable for the measurement of carbon emission efficiency in the construction industry is constructed, so as to make up for the defect of relaxation improvement and take the calculation requirements of carbon dioxide emission into account as non-expected output. The specific model is as follows: In this study, a total of n decision units (n = 30) are set, and each decision unit has 3 vectors, namely, input indicator vector x, expected output vector y, and non-expected output vector b. x_{io} represents the amount of input i of decision unit o. y_{ro} represents the expected output of type r of the o decision unit. b_{ko} represents the quantity of the KTH undesirable output of the o decision unit.

$$\theta^* = \min_{\lambda, s^+, s^-} \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{S_i^-}{x_{io}}}{1 + \frac{1}{q+h}\left(\sum_{r=1}^{q} \frac{S_r^+}{y_{ro}} + \sum_{k=1}^{h} \frac{S_k^-}{b_{ko}}\right)} \tag{1}$$

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$$x_{io} = \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- \quad i = 1,\ 2,\ 3 \ldots\ldots m$$

$$y_{ro} = \sum_{j=1}^{n} \lambda_j x_{ij} - s_r^+ \quad r = 1,\ 2,\ 3 \ldots\ldots q$$

$$b_{ko} = \sum_{j=1}^{n} \lambda_j b_{kj} + s_k^- \quad k = 1,\ 2,\ 3 \ldots\ldots h$$

In Formula (1), for any j there is $\lambda_j \geq 0$, for any i there is $s_i^- \geq 0$, for any r there is $s_r^+ \geq 0$, and for any k there is $s_k^- \geq 0$. θ^* is the carbon emission efficiency value and $0 \leq \theta^*$, λ_j represents the weight vector, s_i^- is the relaxation variable of the input, s_r^+ is the relaxation variable of the expected output, and s_k^- is the relaxation variable of the non-expected output. In this study, m is 5, q is 1, and h is 1. When $\theta^* < 1$, and the DMU is not effective, there is room for improvement in carbon emission efficiency. When θ^* gradually approaches 1, it indicates that the carbon emission efficiency of the DMU is gradually improved. When $\theta^* = 1$ and s_i^-, s_r^+, and s_k^- are all 0, the carbon emission efficiency of the DMU is the best, and the DMU reaches strong efficiency. If $\theta^* = 1$ but any variable in s_i^-, s_r^+, and s_k^- is not 0, it is weakly efficient, and there is still room for improvement of the relaxation variable.

3.1.2. Malmquist Index Model

Based on the static efficiency measured by SBM, the dynamic change of carbon emission efficiency from t period to $t + 1$ period was measured by Malmquist index. In this study, the panel data of 5 time points of 30 DMU were mainly analyzed to obtain the change of carbon emission efficiency. The Malmquist index is measured by:

$$TFPCH = \sqrt{\frac{D^t(x_{t+1}, y_{t+1})}{D^t(x_t, y_t)} \times \frac{D^{t+1}(x_{t+1}, y_{t+1})}{D^{t+1}(x_t, y_t)}} \tag{2}$$

$$\begin{aligned} &= \frac{D^{t+1}(x_{t+1}, y_{t+1})}{D^t(x_t, y_t)} \times \sqrt{\frac{D^t(x_{t+1}, y_{t+1})}{D^{t+1}(x_{t+1}, y_{t+1})} \times \frac{D^t(x_t, y_t)}{D^{t+1}(x_t, y_t)}} \\ &= EFFCH \times TCHCH \\ &= PECH \times SECH \times TCHCH \end{aligned}$$

In formula (2), $D^t(x_t, y_t)$ and $D^t(x_{t+1}, y_{t+1})$ indicate that according to the technological front of period t, the relative efficiency of input and output corresponding to period t and period $t + 1$ is taken by DMU respectively. $D^{t+1}(x_t, y_t)$, $D^{t+1}(x_{t+1}, y_{t+1})$ indicate that according to the technological frontier of the $t + 1$ period, the relative efficiency corresponding to the input and output of the DMU in the $t + 1$ period is taken respectively. TFPCH is the change index of total factor productivity of each decision-making unit, which reflects the change of carbon emission efficiency of the province from t period to $t + 1$ period. When the value of TCPCH is greater than 1, the total factor productivity of the province increases from t period to $t + 1$ period. When the value of this coefficient is equal to 1, it indicates that the total factor productivity has not changed in the two adjacent periods. When the coefficient is less than 1, it indicates that the total factor productivity shows a downward trend. Meanwhile, TFP can be decomposed into technical efficiency (EFFCH) and technical progress (TCHCH), and technical efficiency synchronization can be decomposed into pure technical efficiency (PECH) and scale efficiency (SECH). Technical efficiency indicates the speed at which DMU moves to the front, also known as "catch-up effect". The movement of the technological frontier from the t period to the $t + 1$ period of technological progress is also known as the "technological transformation effect". If the index is greater than 1, the technological frontier moves forward and technological progress occurs; if the index is less than 1, the technological regression occurs.

3.2. Data Resources

The data utilized in this study is sourced from the China Statistical Yearbook, China Construction Industry Statistical Yearbook, China Energy Statistical Yearbook, along with pertinent statistics from the National Bureau and Local Bureau of Statistics, as presented in Table 2. Due to the unavailability of data for Tibet Autonomous Region, Hong Kong, Macao Special Administrative Region, and Taiwan Province, these regions have been excluded from the analysis. To streamline the narrative within this paper, provincial abbreviations are employed in the ensuing empirical analysis section. Employing the most recent statistical yearbook, this study examines the carbon emission efficiency across 30 provinces in China over the decade spanning 2010 to 2019.

Table 2. Carbon emission efficiency input and output variable names, index selection and related data sources.

Elements	Variable	Indicators	Data Sources
Inputs	Capital stock	Total asset value of construction enterprises	China Construction Industry Statistical Yearbook
	Labor force	Number of employees in construction enterprises	China Statistical Yearbook
	Energy consumption	11 types of energy converted into standard coal quantity	China Energy Statistical Yearbook
	Mechanical equipment	Total power of self-owned construction machinery and equipment at the end of the year	China Construction Industry Statistical Yearbook
	Building materials	Total value of materials used in the construction industry	China Construction Industry Statistical Yearbook
Desirable output	Gross output of building industry	Gross Domestic Product of the Construction Industry	China Construction Industry Statistical Yearbook
Undesirable output	Carbon emissions from the construction industry	Carbon emissions from the construction industry	China Construction Industry Statistical Yearbook

3.3. Variables

Data envelopment analysis (DEA) mainly evaluates efficiency from two aspects: input and output. Summarizing the existing research and combining with the input-output practice of the construction industry, in terms of input index, the total assets of construction enterprises in each province are selected as the capital stock index, and the number of employees in construction enterprises in the current year is selected as the labor input index (considering the strong mobility of labor force in the construction industry, the annual number of employees in construction enterprises is selected as the measurement). The amount of standard coal converted from 11 main energy sources (raw coal, briquette, coke, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, natural gas, electricity and heat) is selected as the energy consumption index, and the total power of construction machinery and equipment in the construction industry is selected as the mechanical equipment index. The total value of construction materials used in the current year (including steel, wood, cement, glass and aluminum) is selected as the index of construction materials. In terms of output indicators, the expected output is the total output value of the construction industry, and the measurement variable of the total output value of the construction industry in the current year is selected. The undesired output is the carbon emission of the construction industry, and the weight coefficient method is adopted to calculate the direct carbon emission.

4. Results

4.1. Static Analysis of Carbon Emission Efficiency in the Construction Industry

Matlab software is used to measure the carbon emission efficiency values of 30 provinces in China from 2010 to 2019 according to Formula (1), and the results are shown in Table 3.

Table 3. Carbon emission efficiency values of construction industry in 30 provinces of China from 2010 to 2019.

Province	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Mean
Beijing	1.5616	2.8992	2.7116	3.6822	2.2562	2.6618	2.0714	2.1188	2.5970	2.5661	2.5126
Tianjin	1.4050	1.6534	1.5222	1.7582	1.5345	1.3607	1.5214	1.2760	0.7369	1.3929	1.4161
Hebei	0.4950	0.5904	0.5345	0.7915	1.2308	0.6090	0.6734	0.5049	0.8684	0.7270	0.7025
Shanxi	0.4530	0.8966	0.8068	0.7346	0.6367	0.5883	0.6476	0.6388	0.6401	0.6967	0.6739
Inner Mongolia	0.5516	0.6884	0.5791	0.7069	0.6295	0.5099	0.4490	0.5301	0.5065	0.9362	0.6087
Liaoning	1.4521	1.1319	1.5214	1.1799	1.4839	0.7671	0.8203	1.0859	2.4391	1.3950	1.3277
Jilin	1.2729	1.2568	0.4327	0.5275	1.1418	0.6803	0.7940	0.7036	0.8611	0.9718	0.8643
Heilongjiang	1.5394	1.7223	1.6556	1.2997	1.4894	1.4252	1.3932	1.3444	1.1285	1.1965	1.4194
Shanghai	1.7041	1.6881	1.7153	1.5936	1.8674	1.8431	1.8091	1.6641	1.9988	1.8307	1.7714
Jiangsu	1.6426	1.6316	1.6208	1.7981	1.6479	2.0725	1.8009	1.9725	2.1272	2.2030	1.8517
Zhejiang	1.4382	1.4114	1.3933	1.4396	1.4176	1.2424	1.2120	1.1882	1.6031	1.4423	1.3788
Anhui	0.8841	0.9254	0.6822	0.7490	0.6659	0.6865	0.6408	0.5815	0.5968	0.6116	0.7024
Fujian	0.7467	0.7840	0.9055	0.7026	0.8222	0.8511	0.8714	0.7264	0.7828	1.3066	0.8499
Jiangxi	1.1039	1.1317	1.1405	1.2749	1.6490	1.1804	1.5542	1.7000	1.7679	1.7439	1.4246
Shandong	0.7157	0.6985	0.5496	0.8689	1.2530	0.8774	0.6684	0.7764	0.8184	0.7836	0.8010
Henan	0.7533	1.5598	1.1900	0.7393	0.7977	0.6217	0.6344	0.6768	0.6102	0.7484	0.8332
Hubei	0.6731	0.7174	0.5881	1.1593	1.1998	1.3806	1.3800	1.3651	1.3601	1.3658	1.1189
Hunan	0.6143	1.0789	1.0360	1.1160	1.1921	0.6817	0.7606	0.6276	0.6555	1.2035	0.8966
Guangdong	0.8449	0.8519	0.6713	1.2321	0.9701	0.9654	0.7960	0.7151	0.8796	1.0718	0.8998
Guangxi	1.0871	1.1585	1.1388	2.1106	2.0726	1.5667	2.2134	2.1448	1.8713	1.6406	1.7004
Hainan	2.1446	2.9386	2.4240	3.4699	3.2902	1.9139	1.9746	2.0403	1.6971	2.1277	2.4021
Chongqing	0.9286	0.9179	0.9867	1.0577	1.3274	1.3229	1.2686	1.2107	1.2692	1.2888	1.1578
Sichuan	0.5485	0.7527	0.6980	0.8306	1.0471	1.0686	0.8612	0.7795	0.7601	1.3008	0.8647
Guizhou	0.7076	0.6188	0.7156	0.6836	0.6840	0.6188	0.5293	0.5849	0.6909	0.7216	0.6555
Yunnan	0.7405	0.9739	0.6941	0.5721	0.5108	0.6853	0.7014	0.5893	0.5781	0.7449	0.6790
Shaanxi	1.1327	1.0657	0.7262	0.8086	1.1870	1.1181	1.1389	1.1058	1.1447	1.0636	1.0491
Gansu	0.6444	0.8119	0.6650	1.0460	0.9736	0.9863	0.8624	0.8631	0.9171	0.7453	0.8515
Qinghai	1.1087	1.1055	1.1154	1.2378	1.2529	1.1114	0.7711	0.7051	1.0800	1.1222	1.0610
Ningxia	1.1615	0.9086	0.6712	0.7430	0.8718	0.7283	0.8797	0.8002	0.8643	0.7198	0.8348
Xinjiang	1.1217	1.0679	1.0984	1.2402	1.2379	1.2233	1.1124	1.2246	1.1478	0.7656	1.1240

According to the geographical region division of China, the evolution of carbon emission efficiency of each region is drawn in Figure 1 (according to the natural geographical location and climatic conditions of China and the textbook Physical Geography of China, mainland China is usually divided into seven regions: North China, Northeast China, East China, Central China, South China, Southwest China and Northwest China). It can be seen from Figure 1 that the carbon emission efficiency of China's construction sector is about 1.14, which remains stable in the 10-year period from 2010 to 2019, indicating that the overall carbon emission efficiency is effective and changes are small in the whole country.

From the perspective of China's regions, the carbon emission efficiency of South China is the highest, followed by East China, followed by Northeast China, North China, Central China, Northwest China and Southwest China, respectively. The efficiency values in South and East China remain stable and significantly higher than the national average, indicating that the construction industry in South and East China has a high carbon emission efficiency, which is above the production frontier and reaches an efficient state. Compared with the eastern region, the carbon emission efficiency of the construction industry in the western region, with the northwest and southwest as the main body, is lower than the national average level and has not reached the effective state. Considering that the technology level in the western region of China is relatively backward and it is rich in various energy resources, the western region has a great potential to improve the carbon emission efficiency. At the same time, the carbon emission efficiency in Southwest China is steadily improving year by year from 2017 to 2019, indicating that the situation of extensive production in the construction field is gradually improving under the drive of energy conservation and emission reduction policies in this region in recent years.

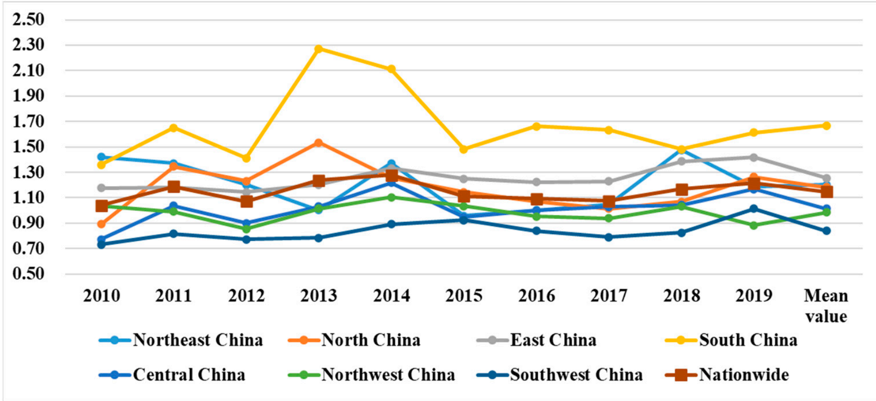


Figure 1. Changes in carbon emission efficiency in different regions of China.

From the perspective of national provinces, the carbon emission efficiency of the 30 provinces generally shows a trend of "low in the west and high in the east" (see Figure 2 for the distribution of carbon emission efficiency of all provinces nationwide), with significant differences between regions and provinces. In 2010, 15 provinces reached the efficient state and were located on the production frontier. By 2019, the carbon emission efficiency value of 18 provinces has been greater than 1, indicating that the provinces with effective carbon emission efficiency have steadily increased in the past 10 years of development. By comparison, it is found that six provinces, including Fujian, Hubei, Hunan, Guangdong, Chongqing and Sichuan, have moved from the ineffective state to the effective state, while three provinces, including Jilin, Ningxia and Xinjiang, have moved from the effective state to the ineffective state during the 10-year development. It can be seen that under the influence of technological progress and technology diffusion effect, the central region has achieved good results, and the carbon emission efficiency of the construction industry has been significantly improved, developing towards the direction of refinement. On the contrary, due to the large amount of resources and extensive production, the carbon emission efficiency of the western region and some provinces in northeast China has not caught up with the national improvement in time, resulting in the carbon emission efficiency from effective backward to ineffective.

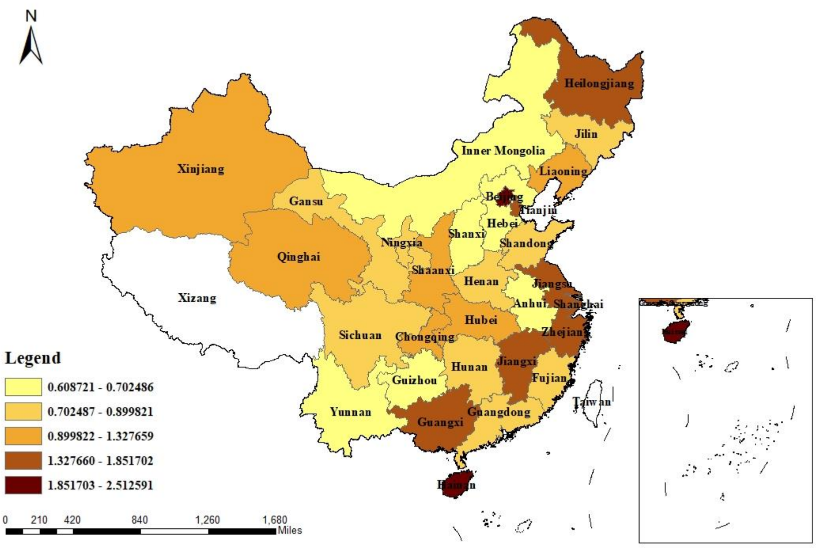


Figure 2. Distribution of carbon emission efficiency in various provinces in China.

4.2. Dynamic Analysis of Carbon Emission Efficiency in the Construction Industry

According to Formula (2), the carbon emission efficiency of the construction industry in 30 provinces in China from 2010 to 2019 is dynamically analyzed by using Matlab software, and the Malmquist index is calculated and shown in Tables 4 and 5.

Table 4. Malmquist index of carbon emission efficiency of construction industry in 30 provinces of China.

Province	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017	2017–2018	2018–2019	Mean	Rank
Beijing	1.7074	1.5484	1.0632	1.0855	1.3365	0.8540	1.1867	0.7336	0.6064	1.1246	13
Tianjin	1.2300	1.0070	1.2548	1.0102	0.6483	1.4077	1.0309	0.4836	2.4721	1.1716	8
Hebei	1.6006	1.0643	1.1667	1.7787	0.4780	1.3641	0.7923	1.7967	0.9376	1.2199	5
Shanxi	1.2466	0.9997	1.0887	1.0044	0.9176	0.8588	0.9890	1.1041	1.0263	1.0261	25
Inner Mongolia	1.1971	0.9583	1.0304	0.8816	0.9903	0.8452	0.9514	0.9132	1.0958	0.9848	28
Liaoning	1.4205	1.1628	1.6759	0.6663	0.6760	0.7308	1.5406	8.2256	0.1675	1.8073	1
Jilin	1.0061	0.4866	1.6456	1.1320	0.6778	1.1170	1.0628	1.1902	0.7995	1.0131	26
Heilongjiang	0.7923	1.3290	0.8085	0.8750	0.7095	1.2889	0.8651	0.5364	0.8203	0.8917	30
Shanghai	0.9938	1.0818	1.2596	0.9849	1.2276	1.0235	0.9978	1.6907	0.9847	1.1383	10
Jiangsu	1.0244	1.4886	1.4702	0.9625	1.5341	0.7089	1.2224	1.0672	1.0706	1.1721	7
Zhejiang	1.2088	1.1467	1.1173	1.1878	1.0152	1.0239	1.3262	1.0766	0.5109	1.0682	19
Anhui	1.2498	1.1239	1.0827	0.9868	1.2233	1.0101	1.0558	1.1930	0.9854	1.1012	14
Fujian	1.2913	1.1717	0.9705	1.0624	1.1587	1.0368	1.0769	1.0042	0.9555	1.0809	17
Jiangxi	1.0016	1.1004	1.0021	1.3680	0.7900	1.2682	1.5467	1.3234	1.6289	1.2255	4
Shandong	1.0955	0.8512	1.2245	1.0494	1.3770	0.6178	1.8297	1.2298	1.0061	1.1423	9
Henan	0.9385	0.9955	1.0206	1.0297	0.8851	1.0181	1.3848	0.9180	1.2214	1.0458	22
Hubei	1.0947	0.8756	1.1767	1.4869	0.7911	1.7274	1.1536	1.4861	1.3245	1.2352	3
Hunan	1.7811	0.9033	1.2532	1.2225	0.6487	1.0552	0.8135	1.0829	1.0400	1.0889	15
Guangdong	1.1285	0.8751	1.4902	0.8956	1.1449	0.8406	0.8299	1.5980	1.3578	1.1290	11
Guangxi	1.2791	1.1623	1.8974	0.9850	0.6985	1.6778	1.4151	0.4813	1.1955	1.1991	6
Hainan	1.1903	1.0380	0.7577	0.7797	0.7913	1.4632	1.3276	0.9642	1.0121	1.0360	23
Chongqing	1.0717	1.5515	1.3001	1.5135	1.2267	1.2008	1.2322	1.0996	1.1923	1.2654	2
Sichuan	1.2783	1.0733	1.3776	1.0538	1.3541	0.8781	0.9892	0.9873	1.1573	1.1277	12
Guizhou	1.1950	1.0141	0.9737	1.0340	1.0304	0.9684	1.0444	1.0456	1.1251	1.0479	21
Yunnan	1.1240	1.0844	0.8342	0.7086	1.2512	0.9676	1.0798	0.9912	1.2031	1.0271	24
Shaanxi	0.9618	0.9929	1.0057	0.9412	1.2034	1.2434	1.0982	1.0175	0.9761	1.0489	20
Gansu	0.9411	0.5594	0.8410	0.9440	1.1557	1.0428	0.9797	0.9823	0.9928	0.9377	29
Qinghai	1.0777	0.9484	0.9431	1.1044	1.0249	0.9738	0.9311	0.9245	1.0267	0.9949	27
Ningxia	1.1813	1.2804	1.2522	0.9598	0.9944	1.0568	1.1213	0.9288	0.8843	1.0733	18
Xinjiang	1.0726	1.4280	1.6281	1.0278	1.0543	0.8765	1.0740	0.4812	1.1462	1.0877	16
Mean	1.1794	1.0767	1.1871	1.0574	1.0005	1.0715	1.1316	1.2852	1.0641	1.1171	-

Table 5. Malmquist index of carbon emission efficiency of China's regional construction industry.

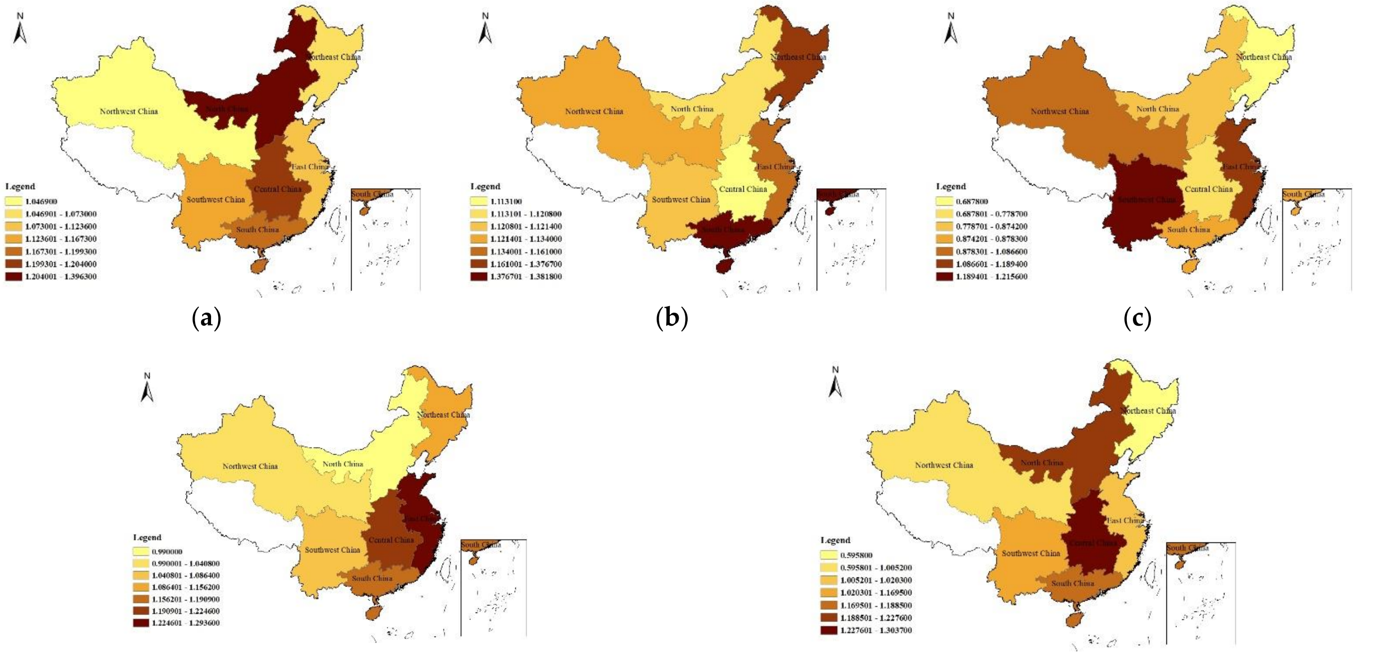
Region	Northeast	North	East	South	Central	Northwest	Southwest
2010–2011	1.073	1.3963	1.1236	1.1993	1.204	1.0469	1.1673
2011–2012	0.9928	1.1155	1.1378	1.0251	0.9687	1.0418	1.1808
2012–2013	1.3767	1.1208	1.161	1.3818	1.1131	1.134	1.1214
2013–2014	0.8911	1.1521	1.086	0.8868	1.2768	0.9954	1.0775
2014–2015	0.6878	0.8742	1.1894	0.8783	0.7787	1.0866	1.2156
2015–2016	1.0455	1.0659	0.9556	1.3272	1.2672	1.0387	1.0037
2016–2017	1.1562	0.99	1.2936	1.1909	1.2246	1.0408	1.0864
2017–2018	3.3174	1.0062	1.2264	1.0145	1.2026	0.8669	1.0309
2018–2019	0.5958	1.2276	1.0203	1.1885	1.3037	1.0052	1.1695
Mean	1.2374	1.1054	1.1326	1.1214	1.1488	1.0285	1.117

It can be seen from Table 4 that the mean value of Malmquist index in China from 2010 to 2019 is 1.1171, higher than the reference value of 1. The annual ML index is higher than 1, indicating that the national average carbon emission efficiency has shown an increasing trend year by year in the 10 years from 2010 to 2019, and the carbon emission efficiency has developed steadily from low efficiency to high efficiency, which is inseparable from the great importance China attaches to the construction of ecological civilization and the continuous elimination of backward production capacity in recent years.

From the ML index of provincial carbon emission efficiency, the mean value of 26 provinces is greater than 1, indicating that the carbon emission efficiency of most provinces in China has been steadily improved from 2010 to 2019. First of all, Liaoning, Chongqing, Hubei and Jiangxi rank top in the ML index, which indicates that these four provinces have made great progress in improving the carbon emission efficiency. Secondly, it should also be noted that the mean value of the ML index of Heilongjiang, Gansu, Inner Mongolia and Qinghai provinces is not greater than 1, indicating that their carbon emission efficiency shows an average negative change in the past 10 years. The average value of carbon emission efficiency in Inner Mongolia and Gansu is less than 1, indicating that they have a long way to go to improve the carbon emission efficiency of the construction industry. Thirdly, the ML index of Beijing, Ningxia and Jilin provinces has been gradually declining in recent years, indicating that the growth rate of their carbon emission efficiency is slowing down. According to the actual situation of carbon emission efficiency in each province, it can be inferred that the carbon emission efficiency of Beijing is relatively high, and the space for improving the carbon emission efficiency in the whole country is limited. The carbon emission efficiency of Jilin and Ningxia has not reached the effective state, and although the carbon emission efficiency has been improved in recent years, the rate of improvement has slowed down, which requires attention.

As shown in Table 5, from the perspective of China's regions, the mean values of the ML index in the seven geographical regions are all greater than 1, indicating that the carbon emission efficiency in the seven regions shows an upward trend, which is consistent with the trend of the national average, and there are no regions with negative growth. As can be seen in Figure 3, the ML index in northeast China and central China is relatively high and has shown an increasing trend in recent years, indicating that the carbon emission efficiency in northeast China and central China is gradually and steadily improving, and the improvement speed is gradually increasing. In particular, the growth rate of carbon emission efficiency during the 13th Five-Year Plan period is significantly stronger than that during the 12th Five-Year Plan period, indicating that the measures of ecological civilization construction in relevant areas have achieved good results. In contrast, the ML index of carbon emission efficiency in northwest China is low, which does not reach the national average, indicating that the growth rate of carbon emission efficiency of the construction industry in northwest China is slower than that in other regions of the country, so more attention should be paid to improving the carbon efficiency of the construction industry in the northwest China in the future.

According to Formula (2), the ML index can be further decomposed into the comprehensive technical efficiency index (EFFCH) and the technological progress index (TECH). Meanwhile, the comprehensive technical efficiency index can be decomposed into pure technical efficiency index (PECH) and scale change index (SECH), and the decomposition results are shown in Table 6. The results show that at the national level, the improvement of carbon emission efficiency in the past 10 years is mainly due to the improvement of pure technical efficiency and technological progress. PECH is greater than 1 and the median value of index decomposition is the largest, indicating that the improvement of pure technical efficiency makes the greatest contribution to the improvement of national carbon emission efficiency. DMUs are constantly moving to the production frontier, the overall level of the industry is improving, and the ability to use technology is constantly improving. TECH is greater than 1, indicating that through 10 years of development, the carbon emission technology of the construction industry has made continuous progress, the overall production frontier of the country has been constantly improved, and the technology, method and means of the construction industry have been constantly innovated, bringing new opportunities for energy conservation and emission reduction. SECH is less than 1, indicating that China's construction industry has not effectively played the economies of scale, and the decision-making unit is farther and farther away from the optimal scale.



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 3. Malmquist Index of Carbon Emission Efficiency in China's Construction Industry, 2010–2019. (**a**) Malmquist Index in 2010–2011. (**b**) Malmquist Index in 2012–2013. (**c**) Malmquist Index in 2014–2015. (**d**) Malmquist Index in 2016–2017. (**e**) Malmquist Index in 2018–2019.

The ML index decomposition of 30 provinces in four periods, 2010–2011, 2013–2014, 2016–2017 and 2018–2019, is selected for summary statistics, as shown in Table 7. It can be seen from the table that the improvement of carbon emission efficiency in each province mainly benefits from the impact of technological progress and pure technical efficiency improvement. From 2013 to 2014, the scale efficiency in North China increased to some extent, while in other periods, the scale efficiency had a negative impact on the carbon emission efficiency, which was consistent with the national average. On the contrary, in the northwest region, the scale efficiency is greater than 1 in the above four periods, while the pure technical efficiency is less than 1 in the three periods of 2010–2011, 2016–2017 and 2018–2019, indicating that the improvement of carbon emission efficiency in the northwest region is mainly due to the increase of scale efficiency.

Table 6. Malmquist index decomposition of carbon emission efficiency of China's construction industry.

Year	ML Index	PECH	SECH	TECH	EFFCH
2010–2011	1.179388	1.174051	1.117697	0.963686	1.256037
2011–2012	1.076745	0.904084	0.876089	1.422637	0.782884
2012–2013	1.187079	1.180415	1.055724	1.016976	1.181975
2013–2014	1.057396	1.104164	1.172917	0.880673	1.242662
2014–2015	1.000498	0.891075	1.172436	1.016697	1.033574
2015–2016	1.071529	0.993712	1.066827	1.06636	1.072021
2016–2017	1.131616	0.980947	1.017284	1.159947	0.997372
2017–2018	1.285228	1.110863	0.966665	1.119239	1.172201
2018–2019	1.064101	1.121977	0.966917	1.016341	1.056899

Table 7. Malmquist index decomposition of carbon emission efficiency of the construction industry in 30 provinces of China in some years.

Region	Province	2010–2011			2013–2014			2016–2017			2018–2019		
		PECH	SECH	TECH	PECH	SECH	TECH	PECH	SECH	TECH	PECH	SECH	TECH
North	Beijing	1.8566	0.6761	1.3602	0.6127	2.1352	0.8297	1.0229	0.9335	1.2427	0.9881	0.9087	0.6753
	Tianjin	1.1768	1.1158	0.9367	0.8728	1.1628	0.9955	0.8387	1.1442	1.0744	1.8903	1.0567	1.2376
	Hebei	1.1927	0.9869	1.3599	1.5551	1.2648	0.9043	0.7499	0.8993	1.1749	0.8371	0.8804	1.2723
	Shanxi	1.9793	0.7554	0.8338	0.8668	1.3153	0.8809	0.9864	0.9391	1.0677	1.0886	0.9566	0.9856
	Inner Mongolia	1.2478	1.0053	0.9543	0.8905	0.8784	1.1270	1.1806	0.8938	0.9016	1.8485	0.5857	1.0122
	Mean	1.4906	0.9079	1.0890	0.9596	1.3513	0.9475	0.9557	0.9620	1.0923	1.3305	0.8776	1.0366
Northeast	Liaoning	0.7795	1.9736	0.9234	1.2576	0.5999	0.8832	1.3237	1.0889	1.0688	0.5719	0.3586	0.8169
	Jilin	0.9874	1.0432	0.9768	2.1644	0.6035	0.8665	0.8862	1.3551	0.8850	1.1286	0.6086	1.1641
	Heilongjiang	1.1188	0.7662	0.9243	1.1459	0.8608	0.8870	0.9649	0.7226	1.2407	1.0602	0.9726	0.7955
	Mean	0.9619	1.2610	0.9415	1.5226	0.6881	0.8789	1.0583	1.0555	1.0648	0.9202	0.6466	0.9255
East	Shanghai	0.9906	1.1261	0.8910	1.1718	0.9476	0.8870	0.9199	0.9718	1.1161	0.9159	1.0000	1.0751
	Jiangsu	0.9933	1.2421	0.8303	0.9165	0.8371	1.2546	1.0953	0.9875	1.1302	1.0356	1.0001	1.0336
	Zhejiang	0.9813	1.0578	1.1645	0.9847	1.1448	1.0536	0.9804	0.9686	1.3965	0.8997	0.5669	1.0016
	Anhui	1.0466	1.6350	0.7303	0.8890	1.2938	0.8579	0.9074	0.9840	1.1825	1.0249	1.0178	0.9446
	Fujian	1.0501	1.1966	1.0277	1.1702	0.9399	0.9659	0.8336	1.1655	1.1085	1.6693	1.1208	0.5107
	Shandong	0.9761	1.4285	0.7857	1.4420	0.8807	0.8263	1.1616	1.4881	1.0585	0.9576	0.9442	1.1128
	Mean	1.0063	1.2810	0.9049	1.0957	1.0073	0.9742	0.9830	1.0943	1.1654	1.0838	0.9416	0.9464
Central	Jiangxi	1.0251	1.0051	0.9721	1.2935	1.1266	0.9388	1.0938	1.1220	1.2603	0.9864	1.1376	1.4516
	Henan	2.0707	0.8307	0.5456	1.0790	1.2103	0.7885	1.0669	1.1448	1.1339	1.2265	1.0501	0.9483
	Hubei	1.0657	1.1785	0.8717	1.0350	1.3821	1.0395	0.9892	0.9575	1.2179	1.0042	1.0285	1.2824
	Hunan	1.7562	0.9859	1.0287	1.0681	0.9660	1.1848	0.8251	0.9804	1.0056	1.8361	0.5564	1.0179
	Mean	1.4794	1.0001	0.8545	1.1189	1.1713	0.9879	0.9938	1.0512	1.1544	1.2633	0.9432	1.1751
South	Guangdong	1.0083	1.2862	0.8702	0.7873	1.3391	0.8495	0.8983	0.8652	1.0679	1.2186	0.9926	1.1225
	Guangxi	1.0657	1.3360	0.8984	0.9820	1.3443	0.7462	0.9690	0.6202	2.3546	0.8767	1.1449	1.1910
	Hainan	1.3702	0.8691	0.9995	0.9482	1.0539	0.7803	1.0332	0.8840	1.4535	1.2537	0.9163	0.8810
	Mean	1.1481	1.1638	0.9227	0.9058	1.2458	0.7920	0.9668	0.7898	1.6253	1.1163	1.0179	1.0648
Southwest	Chongqing	0.9885	0.9807	1.1055	1.2550	1.3668	0.8823	0.9544	0.9829	1.3136	1.0154	0.9450	1.2425
	Sichuan	1.3723	0.9949	0.9363	1.2608	1.2202	0.6850	0.9050	0.9686	1.1284	1.7115	0.6563	1.0303
	Guizhou	0.8744	1.4104	0.9689	1.0006	1.9350	0.5341	1.1051	0.8303	1.1382	1.0444	1.2376	0.8705
	Yunnan	1.3152	0.8607	0.9929	0.8929	1.1778	0.6738	0.8402	1.1863	1.0833	1.2886	1.0798	0.8647
	Mean	1.1376	1.0617	1.0009	1.1023	1.4250	0.6938	0.9512	0.9920	1.1659	1.2650	0.9797	1.0020
Northeast	Shaanxi	0.9408	1.0726	0.9531	1.4681	0.7572	0.8467	0.9709	1.0026	1.1281	0.9291	0.9660	1.0876
	Gansu	1.2600	1.0744	0.6952	0.9308	1.1979	0.8466	1.0008	0.9179	1.0665	0.8126	1.3399	0.9118
	Qinghai	0.9971	1.5469	0.6987	1.0122	2.3467	0.4649	0.9144	1.2345	0.8248	1.0391	0.9208	1.0730
	Ningxia	0.7822	1.3762	1.0973	1.1734	0.8988	0.9100	0.9096	1.3726	0.8980	0.8329	1.0320	1.0288
	Xinjiang	0.9521	0.7140	1.5778	0.9981	1.0001	1.0297	1.1009	0.9068	1.0759	0.6670	2.0259	0.8482
	Mean	0.9864	1.1568	1.0044	1.1165	1.2401	0.8196	0.9793	1.0869	0.9987	0.8561	1.2569	0.9899

Pure technical efficiency plays a negative role in the improvement of carbon emissions, which also indirectly confirms the analysis of the reasons why the carbon emission efficiency in Northwest China is generally lower than the national average level in the static efficiency analysis. The pure technical efficiency of carbon emissions in the construction industry in Northwest China needs to be improved, and the technical utilization rate should be improved mainly through the management reform and technological innovation within the construction industry.

In addition, in the four observed periods, all kinds of efficiency indexes in Southwest China are generally greater than 1 (only four indexes are less than 1), indicating that the improvement of carbon emission efficiency depends on the coordinated promotion of all aspects, showing a good trend.

5. Discussion

1. North China: Technology-Driven Developments, but Room for Growth in Economies of Scale.

As shown in Figure 4, over the past decade, North China has demonstrated a TECH value consistently greater than 1, underlining the pivotal role of technological advancements in augmenting carbon emission efficiency in the region. This nucleus of China has fostered remarkable urban development centered around Beijing, capitalizing on a rich pool of talent and intellectual resources derived from a dense network of universities and research institutes. Furthermore, technology firms have flourished, introducing sophisticated emission and carbon reduction technologies that have heightened clean energy usage and improved carbon emission efficiency.

In the construction sector, it is imperative to maintain a holistic view of the projects, fostering a people-centric approach that leverages digital technology to minimize manpower and resource input, while mitigating waste generation. This aligns with the strategic objective of creating constructions that are resource-efficient, environmentally friendly, and safe, without compromising on quality. Despite these developments, there remains a discernible gap in industrial agglomeration, as indicated by a SECH value generally below 1, underscoring the need for further intensification in this arena.

2. Northeast China: Fluctuating Indices with a Call for a Stable Developmental Directive.

The Northeast has sustained a carbon emission efficiency roughly on par with the national average. Despite its historical status as a foundational industrial hub in China, the region has witnessed a contracting trend in the construction industry over recent years. An illustrative case is Liaoning Province, where the output value of the construction industry experienced successive annual declines, dropping to 325.84 billion yuan by 2018.

Historically a frontrunner in urbanization, the Northeast has seen a recent dip in its permanent population owing to industrial relocation and urban decay, consequently reducing the overall carbon emissions from the construction sector. Nevertheless, extensive coal consumption for heating purposes during winter has been a detriment to carbon emission efficiency. Looking forward, it is crucial to emphasize the incorporation of clean energy solutions and thermal insulation materials in building operations, aiming to cut down energy consumption and foster a more sustainable pathway.

3. East China: High Technical Efficiency with Scope for Technological Enhancement.

East China demonstrates a commitment to incorporating low-carbon technology in its construction sector, underpinned by existing industrial clusters. Notably, the Yangtze River Delta urban agglomeration is advancing the deployment of prefabricated and modular construction technologies, a move characterized by factory production and site assembly of building modules. This strategy not only abbreviates the construction timeline by over half but also diminishes waste emissions by a significant 80%, curtailing both dust and noise pollution prevalent in conventional construction processes. As a result, there is a marked reduction in carbon emissions throughout the construction phase, enhancing overall emission efficiency.

Despite these strides, there remains an imperative for East China to bolster scientific and technological advancements in carbon reduction within the building sector, steering towards the realization of green and zero-carbon buildings. This endeavor may include fostering innovations in civil engineering materials informed by the properties of established building materials like steel bars and cement. By developing materials with heightened resistance to erosion and rust, the durability and lifespan of civil engineering structures can be augmented, setting a benchmark for technological innovation in the national construction landscape.

4. Central China: Reliant on Technical Efficiency with a Necessity for Scale and Technological Advancement.

Central China's pathway to augmenting carbon emission efficiency is predominantly hinged on proficient technology application, albeit with substantial room for growth in technological innovation and scaling efficiency. To propel this growth, central urban hubs such as Wuhan and Zhengzhou must assume a pivotal role, fostering urban conglomerates in the Central Plains and nurturing strategic new industrial clusters within the construction sphere, thereby facilitating the emergence of industrial scale merits.

A focused approach towards regional industrial specialization guided by urban agglomerations should be complemented by a vigorous pursuit of scientific and technological R&D. The objectives should span fostering fossil energy efficiency, advancing the uptake of clean energy solutions, and orchestrating a harmonized progression towards carbon reduction through the instrumentality of green technology.

(**a**) North China (**b**) Northeast China (**c**) East China (**d**) Central China (**e**) South China (**f**) Southwest China (**g**) Northwest China

Figure 4. Malmquist index decomposition of carbon emission efficiency in various regions of China from 2010 to 2019.

5. South China: Predicated on Technological Advancements with Room for Enhanced Technical Efficiency.

Leveraging the geographical boons of the Pearl River Delta and the Guangdong-Hong Kong-Macao Greater Bay Area, South China has ardently fostered high-tech sectors, positioning itself at the forefront of innovative building materials and sustainable low-carbon building technology in China. This endeavor has elevated the regional carbon emission efficiency in the construction industry above the national benchmark. Looking ahead, it is pivotal to hone the utilization of emerging technologies, expedite the translation of R&D breakthroughs into practical applications, and foster the swift integration of carbon-saving technologies into engineering protocols. To illustrate, efforts should be intensified to fast-track the factory production and digitization of prefabricated buildings. In this context, a smart manufacturing platform could streamline the production of precast concrete components of varied dimensions, incorporating automated technologies for steel bar processing, product demolding, and concrete pouring, thereby augmenting efficiency across production lines.

6. Southwest China: Technical Efficiency-Centric with a Need for Technological Upgrades.

Southwest China primarily hinges on technological application and industry scaling to ameliorate its carbon emission efficiency, albeit its current efficiency remains below the national average. A strategy poised for success involves bolstering industrial synergy with South China, assimilating advanced technology transfers, and elevating the indigenous technological prowess. To substantially curtail carbon emissions in the construction sector, it is imperative to marshal the region's geographic attributes, harnessing an energy portfolio enriched with local clean energy sources such as photovoltaic, hydropower, and wind energy. This approach necessitates a paradigm shift in the energy consumption pattern across various stages of construction, from material production to building operation and maintenance, reducing reliance on fossil fuels. Concurrently, urban revitalization initiatives and architectural ventures should be grounded in principles of low-carbon and carbon-reduction methodologies, steering towards zero-carbon or carbon-sink outcomes to foster a sustainable future.

7. Northwest China: Scale-Efficiency-Driven with Imperative Technological and Managerial Advancements.

Currently falling below the national average, the carbon emission efficiency in Northwest China has primarily been propelled by enhancements in scale efficiency over the past decade. However, a pressing need remains to foster technological advancement and apply sophisticated technology more rigorously.

Construction firms in the region generally grapple with limited financial resources and suboptimal financing capabilities, placing them at a disadvantage in the competitive market landscape. This predicament is further exacerbated by the region's geographical location deep inland, characterized by a lagging economy, outdated infrastructure, and restrictive transportation avenues. Consequently, while the region's population and, by extension, the total carbon emissions from the construction sector remain relatively low, the efficiency of these emissions is unfortunately diminished.

Addressing this necessitates leveraging Northwest China's resource endowments to amplify the adoption of clean energy solutions within the construction domain. It is prudent to accentuate the optimal exploitation of solar energy, given the region's cold winters. This involves a meticulous approach in building design and construction, opting for materials boasting high thermal insulation properties and implementing energy-efficient heating systems to curtail energy expenditure during the operational phase of buildings.

6. Conclusions

6.1. Reflection on Methodology

(1) Leveraging the existing body of research, this paper employs the SBM (Slacks-Based Measure) model method. This approach effectively addresses the limitations of the traditional DEA (Data Envelopment Analysis) model, which fails to accommodate

unexpected outputs, offering a more robust mechanism for gauging input-output slack. Coupled with the Malmquist index, it facilitates a nuanced analysis of the temporal dynamics of carbon emission efficiency, rendering a lucid appraisal of efficiency shifts across Chinese provinces over time.

(2) This research analyzes carbon emission data spanning 2010 to 2019 from 30 Chinese provinces. Drawing upon established research and integrating insights from the input-output practices prevalent in the construction industry, we devised a cogent model index system. This encompasses input factors, desired outputs, and undesirable outputs, paving the way for a comprehensive examination of regional variances in carbon emission efficiency over time, pivotal driving factors, and avenues for enhancement.

6.2. Limitations and Future Research Directions

(1) Given the lack of comprehensive national data on cumulative carbon emissions in the construction sector, this study narrows its examination to direct carbon emissions, excluding indirect emissions from auxiliary sectors such as electricity, heat, and gas. It is advocated that future research extend the geographical scope of the analysis to provide a more encompassing insight into the industry's carbon emission efficiency.

(2) Going forward, a profound investigation into the factors affecting carbon emission efficiency is imperative. This initiative seeks to illuminate regional disparities, thereby aiding in the crafting of nuanced policy measures to enhance efficiency across the construction sector.

(3) This study sheds light on the regional subtleties of carbon emission efficiency within China's construction sector. It suggests that ensuing research employ case studies of leading construction firms as a tactic to extrapolate findings to a micro-level, thus deepening the understanding from a corporate standpoint.

(4) During the COVID-19 era, China's containment policies contributed to the subdued development of the construction industry, which may, in turn, have led to a reduction in carbon dioxide emissions to some extent. Incorporating data from 2020 to 2022 in subsequent studies could reveal the impact of COVID-19 on the carbon emissions of the construction industry.

6.3. Implications

At the national level:

(1) Championing Technological Advancements in the Construction Sector

Through a comprehensive decomposition of the Malmquist index, this research identifies that technological progression plays a significant role in enhancing carbon emission efficiency within the construction industry. Currently, the contribution of technological advancements to carbon emission efficiency remains limited, highlighting the need for elevating the technological standard to augment this efficiency.

To curtail carbon emissions, the construction sector must intensify its commitment to adopting clean energy solutions. This demands the formulation and adoption of rigorous low-carbon construction standards, optimization of architectural designs for superior energy efficiency—especially in heating, cooling, and illumination systems—and the strategic integration of centralized heating and cooling systems, essential for energy conservation and emission mitigation.

Furthermore, the sector should prioritize retrofitting pre-existing infrastructures, balancing both cost-effectiveness and functional efficiency to lower the carbon energy consumption per unit. Such approaches can include adding insulative layers to walls and roofs, leveraging rooftop solar panels, and tapping into wind and geothermal energy sources to establish self-reliant energy systems. Drawing from global best practices can result in edifices distinguished by their low energy consumption and intelligent, livable design. The ultimate objective is a consistent reduction in the construction sector's total energy consumption.

(2) Refining the Framework of Energy Supply and Consumption

In assessing carbon emission efficiency, energy input emerges as a crucial variable, necessitating the optimization of the energy supply and consumption structure within the construction sector. In tandem with evolving economic landscapes, strategic realignment of the energy supply framework is imperative, with a marked emphasis on elevating the utilization of clean energy sources such as hydro, wind, solar, and nuclear energies, whilst diminishing reliance on traditional fossil fuels.

To expedite this transition, it is incumbent upon government authorities to champion the diversification of the power grid. This entails a sustained advancement of both onshore and offshore wind farms, solar thermal and photovoltaic resources, alongside fostering research in bioenergy and nuclear technology. Concurrently, harnessing the regulatory capacity of hydroelectric resources is vital to ensure grid stability.

(3) Enhancing Carbon Emission Efficiency during Building Operations

During carbon emission computations, this study identified the predominant source of energy consumption within the construction sector to be the operation and maintenance of buildings. Thus, there is a pressing need to enhance carbon emission efficiency throughout construction and operational phases. By positioning communities, villages, and industrial parks as fundamental units, the aim is to cultivate low-carbon societies, thereby fostering an active engagement between corporations and individuals:

Community Integration: The proposed blueprint entails the establishment of "low-carbon communities" and "green industrial parks," purposed to streamline public service allocation while promoting resident involvement. This involves the precise development of a green public service infrastructure, which encompasses clean energy distribution, regional waste segregation, and resource recycling strategies. Such an infrastructure is further enriched by green transit systems and an encompassing carbon platform.

Action Plan: Building upon the sustainable community frameworks observed in developed nations, proposed initiatives encompass the endorsement of eco-friendly construction materials and centralized heating/cooling systems. Simultaneously, the augmentation of vital public amenities such as kindergartens, activity centers, and parks is advocated, paired with the provision of charging infrastructure for electric vehicles.

From the regional perspective:

(1) Tailoring Carbon Emission Strategies to Local Contexts

Drawing from the preceding analysis, it is evident that carbon emission efficiency exhibits regional variances, necessitating the formulation of differentiated policies attuned to local developmental conditions. Local governments should articulate detailed roadmaps towards carbon neutrality, marked with clear milestones aligned with the national timeline. Given the disparities in resource availability, industrial foundations, and economic statuses across different regions, forging transformation trajectories that harmonize state directives with regional distinctiveness is imperative. This tailored approach fosters a nuanced management of resources and propels industry development, aligning with the overarching aim of enhanced carbon emission efficiency.

(2) Incentivizing High-Efficiency Regions to Pioneer Pilot Projects

In the preceding analysis, it was observed that China's carbon emission efficiency exhibits a geographical characteristic of being "higher in the east and lower in the west." The technological transformation efficiency index is notably higher in the eastern region, thereby enhancing the efficacy of innovation pilot projects. It is advocated that regions with advanced economic development take the lead in initiating endeavors aimed at achieving carbon neutrality peaks, intertwining these goals with technological advancements and cross-regional collaborations to promote harmonized developmental pathways. To fortify this strategy, it is recommended that regional governments establish distinct carbon neutrality policy test zones, employing a "first trial" approach to nurture innovative routes toward achieving nationwide carbon peak and neutrality milestones.

(3) Fostering Cross-Regional Collaboration Leveraging Urban Cluster Linkages

Research findings indicate a pronounced agglomeration effect in carbon emission efficiency across regions. Cities within the same region tend to have similar carbon emission efficiency indices. Thus, fostering cross-regional collaboration is recommended. Regions exhibiting higher efficiency in the construction sector should disseminate their effective practices to enhance collective efficiency. Local authorities are urged to explore strategies targeting carbon peak and neutrality. Such strategies may include cooperative initiatives within urban clusters, setting carbon emission limits, and establishing technical standards for industrial emissions. Additionally, refining the regulatory processes for high carbon-emitting enterprises, complemented by rigorous carbon emission evaluations, is crucial to align economic growth with environmental conservation.

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