Spatial and temporal differences and influencing factors of building eco-efficiency in China

Runrun Dong ¹, Hao Zheng ²,*
¹Henan University of Technology, School of Civil Engineering, Zhengzhou 450000, China
²Henan University of Technology, School of Civil Engineering, Zhengzhou 450000, China

Abstract: This study utilizes the global super-efficiency EBM model to evaluate the eco-efficiency of China's construction industry based on panel data spanning from 2007 to 2021. Furthermore, it examines regional disparities and influential factors using the Dagum Gini coefficient method and panel Tobit model. The findings reveal a sequential decline in efficiency across the eastern, central, and western regions. The overall disparity demonstrates an initial downward fluctuation followed by an upward trend, with the primary contribution shifting from inter-regional variation to hypervariable density. Importantly, the internal discrepancy within the western region surpasses that of other regions. The developmental stage of the construction industry and the composition of energy consumption have a substantial positive impact on its ecological efficiency. In addition, the level of economic development, degree of openness to international markets, and environmental regulations exhibit a positive impact on both the overall construction industry and specifically within the eastern region. Consequently, region-specific measures should be implemented to address disparities in eco-efficiency within the construction industry and promote its high-quality development.

1 Introduction

As a fundamental industry of China's national economy, the construction sector has significantly contributed to advancing economic development. The construction industry's value added as a percentage of GDP has consistently exceeded 5.7% since 2007 and is projected to reach 7.0% by 2021. The construction industry is increasingly assuming the role of a foundational sector. Despite its current boom, challenges persist in substandard development practices, low productivity levels, excessive emissions, and substantial energy consumption. The "14th Five-Year Plan" for developing the construction industry in 2022 proposes expediting the transformation and upgrading of the sector to achieve environmentally friendly and low-carbon growth. In this context, it is of paramount importance to investigate the spatial and temporal disparities as well as the influencing factors of eco-efficiency within the construction industry. This will facilitate the transition towards a green and low-carbon production mode, enhance eco-efficiency in construction, and foster high-quality and high-efficiency development.

2 Literature review

Eco-efficiency, a crucial indicator in evaluating sustainable development, pertains to reducing resource consumption and mitigating environmentally harmful outputs while maximizing economic productivity[1]. The research literature on eco-efficiency in the construction industry is relatively abundant, positioning it as a sub-sector within the broader eco-efficiency study. Xu employed the super-efficient SBM model to assess the eco-economic efficiency of the construction industry and its regional disparities across 30 provinces in China. Additionally, the Tobit model was utilized to examine the key factors influencing the eco-economic efficiency of this sector[2]. Zhou conducted an eco-efficiency analysis of China's construction industry using the radial DEA model, taking into account the entire life cycle of the industry and utilizing carbon footprint as an undesired output indicator that encompasses both direct and indirect carbon emissions[3].

In conclusion, the existing literature has provided crucial groundwork for investigating eco-efficiency in the construction industry; however, certain limitations persist. Firstly, previous studies have primarily focused on comparing regional variations in the efficiency of the construction industry without thoroughly examining the underlying factors contributing to differences in eco-efficiency within this sector. Secondly, most current research on the influencing factors of eco-efficiency in the construction industry has predominantly analyzed large-scale levels, with less emphasis on regional analysis. Exploring influencing factors from a regional perspective can provide more targeted insights into understanding the reasons behind regional disparities in efficiency. Therefore, this study focuses on 30 provinces in China as the research subjects. Firstly, it employs the global super-efficiency model to assess the eco-efficiency of individual provinces. Subsequently, the Dagum Gini coefficient...
decomposition method is utilized to measure inter-regional disparities, intra-regional differences, and super-variance density within three major regions: Eastern, Central and Western. This analysis aims to identify the underlying factors contributing to overall national variations. Finally, a panel Tobit regression model is employed to ascertain influential factors specific to each region.

3 Research Methodology and Data Sources

3.1 Research Methodology

3.1.1 Global super-efficiency EBM model with inclusion of undesired outputs

The eco-efficiency of China’s construction industry is measured using a global super-efficiency EBM model, which incorporates the global reference concept proposed by Pastori[6] and the EBM model proposed by Tone and Tsutsui[5]. This selected model considers non-desired outputs and ensures comparability between decision units while avoiding the no-feasible solution problem. The possibility set (PS) for eco-efficiency in the construction industry is as follows:

\[
PSS = \left\{ (X^i, Y^i, Z^i) : \sum_{i=1}^{J} \sum_{j=1}^{J} \lambda_{j}^i Y_{jm}^i \geq Y_{m}^i, \sum_{i=1}^{J} \sum_{j=1}^{J} \lambda_{j}^i Z_{ji}^i \leq Z_{i}^i; \lambda_{j}^i \geq 0 \right\}
\]

Where \((X^i, Y^i, Z^i)\) is the model optimal solution, \(X_{jm}^i, Y_{jm}^i, Z_{ji}^i\) represent the jth decision unit, the mth input variable, the n desired output variable, and the i undesired output variable in period t, respectively, and \(X_{jm}^i, Y_{jm}^i, Z_{ji}^i\) are all greater than zero. Based on this, with reference to the existing literature[5][6], the global super-efficient EBM model under the assumption of constant returns to scale is constructed to include unwanted outputs, undirected planning equation is as follows:

\[
\gamma^* = \min \frac{\sum_{m=1}^{M} \omega_m s_m^n - s_m^n}{X_{mk}}
\]

\[
\phi + \varepsilon_X \sum_{n=1}^{N} \omega_n s_n^n + \varepsilon_Y \sum_{i=1}^{I} \omega_i s_i^n + \varepsilon_Z \sum_{j=1}^{J} \omega_j s_j^n \leq 0
\]

The \(\gamma^*\) in this equation is a measure of eco-efficiency in the construction sector; \(X_{mk}, Y_{nk}\) and \(Z_{ik}\) represent input vectors, desired outputs and undesired output vectors, respectively. \(j\) represents the number of decision units; \(s_m^n, s_n^n\) and \(s_i^n\) represent slack variables for input variables, desired outputs and undesired outputs, respectively. \(\omega_m, \omega_n, \omega_i\) and \(s_m^n, s_n^n\) are weighting indicators for input, desired output and non-desired output elements, respectively; \(\theta\) is the planning parameter for the radial component. The value of \(\varepsilon\) is in the range of [0,1], which indicates the importance of the proportion of the non-radial part of the model and is a key parameter in the EBM model; Taking 0 corresponds to the traditional BBC radial model; taking 1 corresponds to the non-radial SBM model.

3.1.2 Dagum Gini coefficient method

To further reveal the regional differences in the eco-efficiency of China’s construction industry and their causes, this study used the Dagum Gini coefficient decomposition method to measure the regional differences in the eco-efficiency of China’s construction industry in the three major regions of East, Central and West China. Where and denote the overall variation, inter-regional variation, intra-regional variation, and hypervariable density, respectively, the specific equations are as follows:

\[
G = \frac{\sum_{j=1}^{J} \sum_{h=1}^{H} \sum_{r=1}^{R} \left| W_{ji} - W_{hr} \right|}{2n^2W} (4)
\]

\[
G_{nh} = \frac{\sum_{j=1}^{J} \sum_{h=1}^{H} (p_j s_h + p_h s_j)D_{jh}G_{jh}}{2n^2W} (5)
\]

\[
G_w = \sum_{j=1}^{J} p_j s_j G_{jj} (6)
\]

\[
G_t = \sum_{j=1}^{J} \sum_{h=1}^{H} (p_j s_h + p_h s_j)(1 - D_{jh})G_{jh} (7)
\]

Where \(k\) is the number of divided regions, \(j\) and \(h\) are the region serial numbers, \(n\) is the number of provinces, and \(j\) and \(r\) are the province serial numbers of the measured regions. \(W\) denotes the eco-efficiency of the construction industry in each province within each region, \(\bar{W}\) denotes the mean value of the eco-efficiency of the construction industry in all the provinces, and \(n\) denotes the number of provinces within each region.
3.1.3 Panel Tobit Models

The eco-efficiency values of the construction industry, as measured by the super-efficient EBM model, are all greater than 0, representing a constrained variable. However, biased and inconsistent measurements may arise when employing ordinary least squares (OLS) for regression analysis. To address this issue effectively based on the concept of significant probability, we have opted for the panel Tobit model to examine the factors influencing China's construction industry eco-efficiency. The specific expression is as follows:

\[
Y_i^* = \sigma_0 + \sigma X_i + \mu_i \\
Y_i^* = Y_i' \text{ if } Y_i' > 0 \\
Y_i^* = 0 \text{ if } Y_i' \leq 0
\]  

(8)

3.2 Indicator Selection and Data Sources

3.2.1 Input-output indicators

Building upon the research of previous scholars, we have carefully considered three fundamental principles in selecting indicators: objectivity, accessibility, and avoidance of linear solid correlations among them. Consequently, our chosen input indicators encompass energy consumption, capital stock, labor force, machinery, and equipment. The chosen output indicators comprise the gross output value and the completed area within the construction sector, representing desired outcomes. To assess CO₂ emissions arising from undesired outputs in this field, we employ the IPCC’s established methodology for carbon dioxide emission accounting. Based on research by Feng and others, CO₂ emissions within construction are classified into direct and indirect categories for accurate measurement. For establishing an input-output index system that measures eco-efficiency within this sector, specific indicators can be found in Table 1.

3.2.2 Sample Selection and Data Source


<table>
<thead>
<tr>
<th>Norm</th>
<th>Major indicators</th>
<th>Description of indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Capital investment/10 thousand</td>
<td>Total assets of the construction industry converted to harmonized prices using 2007 as the base period</td>
</tr>
<tr>
<td></td>
<td>Labor inputs /10,000 people</td>
<td>Number of people employed in the construction industry</td>
</tr>
<tr>
<td></td>
<td>Energy consumed /10,000 tons</td>
<td>11 types of major energy consumption in the construction industry, unified conversion &quot;tons of standard coal&quot;</td>
</tr>
<tr>
<td></td>
<td>Mechanical inputs /10,000 kw</td>
<td>Total annual power of construction machinery and equipment owned by construction industry enterprises</td>
</tr>
<tr>
<td>Expected output</td>
<td>Gross value of construction /10 thousand</td>
<td>Harmonized prices converted using 2007 as the base period</td>
</tr>
<tr>
<td></td>
<td>Area of construction completed /10,000 m²</td>
<td>Area of construction completed</td>
</tr>
<tr>
<td>Non-expected output</td>
<td>CO₂Emissions/10,000 tons</td>
<td>CO₂ Total emissions = ΣDirect CO₂ emissions from 11 types of energy consumption + ΣIndirect CO₂ emissions from 5 major building materials used</td>
</tr>
</tbody>
</table>

4 Data analysis

4.1 Eco-efficiency measurement in China's construction industry

This study evaluates the eco-efficiency of China’s construction industry by utilizing provincial-level panel data from 2007 to 2021. The analysis employs MAXDEA software and a global parametric super-efficiency EBM model incorporating non-desired outputs. Figure 1 illustrates the variations in the annual average carbon efficiency of the construction industry at national and regional levels (eastern, central, and western).

In general, the national average green eco-efficiency value from 2007 to 2021 is 0.733, indicating moderate efficiency. From 2007 through 2013, the overall eco-efficiency of the national construction industry exhibited a W-shaped development trend characterized by successive periods of decrease and increase in efficiency levels. Notably, troughs were observed in both 2008 and 2010 with corresponding efficiency values of 0.637 and 0.718, respectively, while reaching its first peak at an efficiency value of 0.723 in 2009. The highest recorded peak was achieved in 2013 with an efficiency value of
0.812. The initial peak value of 0.723 was achieved in 2009, while the highest peak of 0.812 was attained in 2013. Subsequently, from 2013 to 2018, the eco-efficiency of the national construction industry exhibited a consistent downward trajectory, reaching a level of 0.692. From 2018 to 2021, we have observed a sustained upward trend in our eco-efficiency, reaching a value of 0.770 and marking an impressive increase of 11.3%. This outcome highlights the significant impact of the "Opinions of the General Office of the State Council on Promoting the Continuous and Healthy Development of the Construction Industry" issued in 2017, which has effectively stimulated advancements in prefabrication and intelligent buildings, design enhancements, as well as technological research and development efforts aimed at enhancing China's construction industry eco-efficiency.

The distribution of efficiency scores varies across regions, with the eastern region leading in eco-efficiency for the construction sector, exhibiting an average value of 0.784. Throughout the observation period, the trajectory of eco-efficiency development in the construction industry within the eastern region demonstrated a similar and superior trend to that observed nationwide. The eco-efficiency development of the construction industry in the central region exhibited an initial peak value of 0.766 in 2009, followed by a subsequent increase to its highest peak value of 0.873 in 2013, with troughs observed in both 2008 and 2010. However, the overall eco-efficiency of the eastern region remained relatively low from 2013 to 2019, declining to a level of 0.751. Notably, a continuous growth trend has been observed from 2019 to 2021, resulting in an impressive increase to a group of 0.835 by the end of this period, representing a remarkable growth rate of approximately 11.2%. The eco-efficiency of the construction industry in the central region exhibits more pronounced fluctuations, with an annual average value of 0.760, slightly lower than that of the eastern region. From 2007 to 2014, the eco-efficiency of the construction industry in the central region demonstrated an upward fluctuating trend, increasing from 0.690 to 0.865, representing a growth rate of 25.4%. Subsequently, from 2014 to 2021, the construction industry exhibited a "W" development pattern in eco-efficiency, characterized by efficiency troughs in both 2015 and 2018 (with values around 0.771) and peaks observed in both first peak occurring in year 2016 (reaching a maximum weight of approximately 0.696) and second peak achieved in year 2021. Notably, the average annual eco-efficiency value for the construction sector in the western region is significantly lower at 0.662 compared to the eastern and central regions, with an annual average of 0.038, demonstrating relatively consistent fluctuations. Notably, a spike to 0.045 occurred solely in 2010. In terms of regional comparisons, the western region exhibited significantly higher levels of intra-regional variation than both the eastern and central regions, with an annual average of 0.126 and more pronounced fluctuations observed, particularly in 2010 when intra-regional differences surged to as high as 0.193 in the western region; this disparity played a pivotal role in shaping China's construction industry landscape that year. The internal variance in the eastern region exhibits a relatively stable pattern, characterized by fluctuations and a decrease from 0.109 to 0.184 between 2007 and 2013, followed by an increase to 0.119 from 2013 to 2019, resulting in a "rising-declining" trend during the period of 2019-2021.

4.2 Deconstructing regional differences in China's construction eco-efficiency

The temporal evolution of the overall Gini coefficient of eco-efficiency and its differential contributions to China's construction industry are depicted in Figure 2. From 2007 to 2013, a fluctuating downward trend was observed for the overall Gini coefficient across the three major regions, with a notable decline from 0.128 to 0.108, indicating a substantial decrease of 18.5%. However, a significant peak in the overall Gini coefficient of 0.139 was observed in 2010, primarily driven by highly variable density patterns. In terms of variance contribution, the interregional variance exhibited fluctuations over the observation period, decreasing from 45.91% in 2007 to 31.32% in 2021. Conversely, the contribution of highly variable density to the total variance demonstrated a fluctuating increase ranging from 24.86% to 37.77%. Meanwhile, intraregional variation displayed a smoother fluctuation pattern with a consistent contribution rate of approximately 30.9%. Regional overlap issues have led to a shift in the primary driver behind the total variance in the development of the construction industry from interregional contention to highly variable density.

The trend of the coefficient of variation within the three major regions of China's construction industry is depicted in Figure 3. Over the period from 2007 to 2021, the annual average intra-regional variation in China's construction industry was recorded at 0.038, demonstrating relatively consistent fluctuations. Notably, a spike to 0.045 occurred solely in 2010. In terms of regional comparisons, the western region exhibited significantly higher levels of intra-regional variation than both the eastern and central regions, with an annual average of 0.126 and more pronounced fluctuations observed, particularly in 2010 when intra-regional differences surged to as high as 0.193 in the western region; this disparity played a pivotal role in shaping China's construction industry landscape that year. The internal variance in the eastern region exhibits a relatively stable pattern, characterized by fluctuations and a decrease from 0.109 to 0.184 between 2007 and 2013, followed by an increase to 0.119 from 2013 to 2019, resulting in a "rising-declining" trend during the period of 2019-2021.
The temporal variation of the intra-regional variance in the central region resembles that observed in the eastern region, albeit with higher magnitude fluctuations than those witnessed in its eastern counterpart. In terms of the composition of the total intra-regional variance, it is evident that the internal conflict within the western region emerges as the primary contributor to this variance. In contrast, eastern and central regions contribute comparably to the overall intra-regional variance, with an annual average of internal variances at 0.105.

The interregional disparities in eco-efficiency within China’s construction industry are depicted in Figure 4, which shows a fluctuating downward trend from 2007 to 2015, followed by an upward trajectory from 2015 to 2021. The findings reveal a discernible "narrowing-widening" trend in the eco-efficiency disparities among the three major regions of China’s construction industry. Notably, the disparity between the Eastern and Central regions exhibits a significantly smaller magnitude compared to that observed between the Eastern and Western as well as Central and Western regions. This discrepancy can be attributed to the significantly lower levels of eco-efficiency observed in the western region, consequently resulting in more pronounced inter-regional differences between Eastern-Western and Central-Western regions. Enhancing the eco-efficiency of the construction industry in the Western region is crucial for mitigating inter-regional disparities.

4.3 Analysis of factors affecting eco-efficiency in China’s construction industry

To further investigate the influencing factors of eco-efficiency in the construction industry across the three major regions of China from 2007 to 2021, this study builds upon the research conducted by previous scholars and establishes an evaluation index system for influencing factors, as presented in Table 2 below. The panel Tobit regression analysis is sequentially conducted for the entire country and its eastern, central, and western regions. The model is formulated as follows:

$$CIEE_{it} = \sigma_0 + \sigma_1LCD_{it} + \sigma_2ECS_{it} + \sigma_3LED_{it} + \sigma_4Open_{it} + \sigma_5ER_{it} + \mu_{it}$$

Before conducting regression analysis, we initially computed the variance inflation factor (VIF) for all explanatory variables in this study to address the potential bias arising from multicollinearity among variables. The results reveal that the highest VIF value among the explanatory variables is 1.96, and all explanatory variables exhibit a VIF of less than 5, indicating the absence of multicollinearity.

The Tobit regression results for eco-efficiency in China’s construction industry, including its eastern, central, and western regions, are presented in Table 3. Notably, significant variations exist in the impacts and significance levels of different variable factors on the eco-efficiency of the construction industry across these regions, as elaborated below.

(1) The level of development in China’s construction industry, encompassing all three major regions, demonstrates a statistically significant positive trend in eco-efficiency at the 1% significance level. Simultaneously, the progress made by this industry is stimulating both governmental and public demand for high-quality green buildings with ultra-low energy consumption. Consequently, construction companies are compelled to adopt a more efficient and sustainable development model to enhance their competitiveness, thereby elevating the overall quality and efficiency of the construction industry.

(2) The energy consumption structure plays a crucial role in enhancing the overall eco-efficiency of China’s construction industry and its three major regions, thus
pivotal in elevating eco-efficiency. This can be attributed to the fact that electricity, a cleaner energy source, generates fewer carbon dioxide emissions during its consumption than traditional fossil fuel usage. Consequently, increasing the proportion of clean energy utilization and optimizing the energy consumption structure within the production process of the construction industry can significantly improve ecological efficiency levels in this sector.

(3) The level of economic development significantly influences the construction industry in China and the eastern region. At the same time, it does not exhibit a statistically significant impact on the central and western regions. For instance, economically developed provinces in the eastern region demonstrate more significant market potential, a higher caliber of talent, and advanced technological capabilities, thereby attracting more scientific and technical resources to foster innovation within the construction industry. These factors contribute to an enhanced eco-efficiency within the region's construction sector.

(4) The impact of openness to the external world on China's construction industry and the Eastern region is significant, while it lacks statistical significance in the central and western regions. A more robust capacity for innovation-driven development needs to be introduced to enhance foreign investment inflow in the economically advanced eastern region. This will facilitate the infusion of advanced technology and management models by foreign-funded enterprises, thereby enhancing the eco-efficiency of the construction industry in this region. Developing the construction industry in central and western regions necessitates substantial capital, thus requiring a lower threshold for foreign investment to attract enterprises that can contribute to its growth. However, it is essential to note that such enterprises may also introduce elevated energy consumption and pollution levels.

(5) Implementing environmental regulations in China's construction industry, particularly in the eastern region, has significantly improved its eco-efficiency at a 5% significance level. Nevertheless, although evidence suggests a favorable impact in the central and western regions, it does not attain statistical significance. Environmental regulations have effectively mitigated pollution emissions by enhancing the environmental management capacity of construction enterprises, particularly in the economically developed eastern region, where they have facilitated high-quality and low-energy development, thereby bolstering eco-efficiency. However, their influence has been comparatively limited in the central and western regions where developmental efforts primarily focus on improvement.

Table 2. Indicator System for Influencing Factors of Eco-efficiency in China's Construction Industry

<table>
<thead>
<tr>
<th>Type of indicator</th>
<th>Major indicator</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explanatory variable</td>
<td>Eco-efficiency in construction (CIEE)</td>
<td>Solving for the model yields</td>
</tr>
<tr>
<td>Main explanatory variables</td>
<td>Degree of development of the industry (LCD)</td>
<td>Construction GDP/Gross Regional Product</td>
</tr>
<tr>
<td></td>
<td>Energy consumption structure (ECS)</td>
<td>Electricity consumption in construction/energy consumption in construction</td>
</tr>
<tr>
<td>Control variable</td>
<td>Level of economic development (LED)</td>
<td>Per capita GDP</td>
</tr>
<tr>
<td></td>
<td>Degree of openness to the outside world (Open)</td>
<td>(Total FDI x USD-RMB exchange rate)/GDP</td>
</tr>
<tr>
<td></td>
<td>Environmental regulation (ER)</td>
<td>Completed investment in industrial pollution control/industrial added value</td>
</tr>
</tbody>
</table>

Table 3. Analysis of regression results of factors affecting eco-efficiency in the construction industry

<table>
<thead>
<tr>
<th>Variant</th>
<th>Overall</th>
<th>Eastern</th>
<th>Central</th>
<th>Western</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCD</td>
<td>0.0100***</td>
<td>0.0080***</td>
<td>0.0092***</td>
<td>0.0163***</td>
</tr>
<tr>
<td></td>
<td>(0.0012)</td>
<td>(0.0015)</td>
<td>(0.0030)</td>
<td>(0.0022)</td>
</tr>
<tr>
<td>ECS</td>
<td>0.00278***</td>
<td>0.0031***</td>
<td>0.0057***</td>
<td>0.0018***</td>
</tr>
<tr>
<td></td>
<td>(0.0005)</td>
<td>(0.0008)</td>
<td>(0.0017)</td>
<td>(0.0008)</td>
</tr>
<tr>
<td>LED</td>
<td>0.0092***</td>
<td>0.0159***</td>
<td>0.0061</td>
<td>-0.0126</td>
</tr>
<tr>
<td></td>
<td>(0.0035)</td>
<td>(0.0046)</td>
<td>(0.0105)</td>
<td>(0.0083)</td>
</tr>
<tr>
<td>Open</td>
<td>0.0228***</td>
<td>0.0294***</td>
<td>0.0001</td>
<td>-0.0222</td>
</tr>
<tr>
<td></td>
<td>(0.0047)</td>
<td>(0.0057)</td>
<td>(0.0190)</td>
<td>(0.0153)</td>
</tr>
<tr>
<td>ER</td>
<td>0.0461***</td>
<td>0.0107***</td>
<td>0.0260</td>
<td>0.0299</td>
</tr>
<tr>
<td></td>
<td>(0.0173)</td>
<td>(0.0403)</td>
<td>(0.0597)</td>
<td>(0.0194)</td>
</tr>
<tr>
<td>cons</td>
<td>0.328***</td>
<td>0.271***</td>
<td>0.413***</td>
<td>0.319***</td>
</tr>
<tr>
<td></td>
<td>(0.0357)</td>
<td>(0.0571)</td>
<td>(0.0804)</td>
<td>(0.0607)</td>
</tr>
</tbody>
</table>

Number of observations: 450 165 120 165
5 Conclusions and Implications

5.1 Conclusion

In this study, we employ the global super-efficiency EBM model that incorporates non-desired outputs to assess the eco-efficiency of China's construction industry from 2007 to 2021. To analyze the determinants of variations in eco-efficiency within the construction industry, we apply the Dagum Gini coefficient method. Furthermore, we investigate this sector's dynamic development of eco-efficiency and identify its influencing factors using kernel density estimation and a panel Tobit model. The findings are as follows.

(1) The eco-efficiency of China's construction industry and the three major regions (Eastern, Central, and Western) exhibit an overall "N"-shaped temporal trend during the study period. The average efficiency values for the Eastern, Central, and Western regions were 0.784, 0.760, and 0.662, respectively, indicating a consistent long-term relationship where eco-efficiency follows the Eastern > Central > Western pattern. Notably, it is observed that the construction industry in the western region consistently demonstrates lower eco-efficiency compared to the national average over time, thus emphasizing the substantial potential for improvement in this area.

(2) The eco-efficiency of China's construction industry exhibited a fluctuating downward trend from 2007 to 2013, followed by a fluctuating upward trend from 2013 to 2021. Regarding sources of variance, the contribution of intra-regional variance remained relatively stable, while the contribution of inter-regional conflict experienced fluctuations and decreases. Additionally, the contribution of hypervariable density showed changes and increases. Notably, there was a gradual shift in the primary contributor to total variance from inter-regional variance towards hypervariable density.

(3) By analyzing the factors influencing the eco-efficiency of the construction industry, it is demonstrated that both the level of economic development and energy consumption structure exert a significant positive impact on the overall eco-efficiency of not only the national construction industry but also its counterparts in the three major regions. Furthermore, it is found that the level of economic development, foreign direct investment, and environmental regulations significantly positively influence the national construction industry and construction activities, specifically in the eastern region.

This will foster technological progress and innovation within the construction industry and facilitate international exchanges and cooperation. Additionally, it is imperative to introduce cutting-edge environmental protection technologies and management concepts while optimizing the resource allocation efficiency of construction enterprises. The central and western regions should strengthen interregional exchanges, actively cultivate collaborative partnerships with exemplary construction enterprises in the eastern region, capitalize on the technological spillover advantages of the east, harness its propulsive force, incorporate advanced technology and equipment, streamline production processes, refine the industrial structure of the construction industry, and narrow regional disparities.

Secondly, enhancing the eco-efficiency of the construction industry relies on two pivotal factors: improving energy utilization and optimizing energy consumption structure. It is imperative to vigorously develop and deploy clean energy technologies such as wind and solar power in construction, thereby reducing dependence on conventional fossil fuels. Moreover, prioritizing efficient resource recycling while promoting novel environmentally friendly construction methods like intelligent building techniques and green architecture is essential. Encouraging the adoption of green and energy-saving building materials will further contribute to expediting the construction industry's early realization of the "dual-carbon" goal.

Ultimately, it is crucial to facilitate the seamless integration of environmental regulatory policies with the advancement of the construction industry, thereby mitigating any potential eco-efficiency losses resulting from lenient environmental access standards that undermine the effectiveness of environmental regulation. Simultaneously, it is essential to prevent excessively stringent environmental regulations from impeding the growth of the local construction industry and instead harness the "innovation compensation benefits" of environmental law offers for construction enterprises. This can be accomplished through providing tax incentives to incentivize the adoption of energy-saving technologies, active engagement in research and development of green materials and environmentally friendly production processes, and gradual promotion towards eliminating or transforming high-polluting enterprises.

5.2 Suggestions

Given the findings mentioned above, it is crucial to fully acknowledge the regional variability of eco-efficiency within the construction industry and integrate the distinctive characteristics of diverse regions into tailored enhancement strategies. As a region known for its eco-efficient construction practices, the eastern region should capitalize on its regional economy, talent pool, and other advantages to further engage in research and development activities focused on novel materials and technologies.

References


