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Evaluating Building Construction Safety Performance in Different Regions in China

Jiaying Xu [1], Qingfeng Meng [1], Xiaoliang Li [2], Yanrui Bao [1] and Heap-Yih Chong [3,4,*]

[1] School of Management, Jiangsu University, 301 Xuefu Road, Zhenjiang 212013, China; 2212110065@stmail.ujs.edu.cn (J.X.); mqf@ujs.edu.cn (Q.M.); 3220804046@stmail.ujs.edu.cn (Y.B.)
[2] Department of Party Affairs and Publicity (Ideological and Political Education Department), Jiangsu Aviation Technical College, 88 Ruicheng Road, Zhenjiang 212134, China; lixl@jatc.edu.cn
[3] School of Engineering Audit, Nanjing Audit University, Nanjing 211815, China
[4] School of Design and the Built Environment, Curtin University, Perth, WA 6102, Australia
* Correspondence: heap-yih.chong@curtin.edu.au

Abstract: This article employs a three-stage slack-based data envelopment analysis (SBM-DEA) model to evaluate the construction safety performance (CSP) of 30 provinces and cities in China, focusing on enhancing the sustainable development of construction safety in the industry, in line with the concept of sustainable development. The research findings indicate that the supervision environment of each province and city exerts a more substantial influence on the sustainable development of construction safety compared with the level of socio-economic development. Significant changes have been observed in the regional distribution of construction safety management levels within the construction industry by eliminating the impact of economic development, the supervision environment, and random errors. The original pattern of "East > West > Central > Northeast" has shifted to "East > Central > Northeast > West." Moreover, it has been discovered that high-efficiency values of safety performance in certain provinces and cities are partially attributed to external environmental (EE) pressure. In contrast, low-efficiency values cannot be solely attributed to their lack of willingness to implement safety management. Finally, the article proposes strategies, including government policy-led approaches, technology prioritization, and management prioritization, to enhance the sustainable development of construction safety in the construction industry based on the internal safety performance of each province.

Keywords: building construction safety performance; three-stage DEA; slack-based model (SBM); external environmental factors; sustainable

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1. Introduction

The construction industry has become one of the pillars of the world's economic development, but it is also one of the most dangerous industries [1]. Safety issues in the construction industry have gained significant attention worldwide. According to global data statistics, the construction industry employed only about 7% of the world's workforce but was responsible for 30–40% of fatalities (Database | Globalabc). More than 6155 construction workers in the United States died after occupational injuries from 2002 to 2011 (Statistics | U.S. Department of Labor (https://www.dol.gov)). In China, 1222 construction industry accidents and 1303 deaths occurred in the first half of 2022 (https://www.mem.gov.cn). In the face of the difficult situation of construction industry safety, it is essential to improve the level of safety management in the construction industry. The evaluation of safety performance in the construction industry is of great significance for further improving the level of safety management [2]. By assessing the safety performance of the construction industry, we can understand the differences in safety status and weaknesses in various regions of the construction industry, thereby providing essential references for improving

construction safety management practices. Also, provinces that do not show good CSP can learn the successful initiatives the best-performing provinces took.

In construction safety, CSP assessment is an essential aspect. Early researchers focused on accident rates and casualty data on construction sites [3]. However, pure data alone do not allow for a valid and comprehensive assessment [4]. For a more comprehensive assessment, scholars have started to explore various concepts and methods to incorporate multidimensional indicators into CSP evaluation models, such as fuzzy structural equation modeling, integrated evaluation, and rough set theory [5–9]. However, compared to methods such as comprehensive evaluation, which require the determination of indicator weights and a priori assumptions, DEA overcomes the influence of subjective factors and more objectively assesses the efficiency values of decision units [10], becoming the primary method for measuring the efficiency associated with multiple outputs and inputs. It has been widely used in safety management performance problems in various industries, such as mining safety performance [11], energy safety performance [12], road safety performance [7], and CSP in the building industry [13].

Meanwhile, in recent years, the importance of sustainable development in safety management in the construction industry has become increasingly prominent as global environmental issues have intensified and social responsibility awareness has increased. Sustainable development in the construction industry covers various aspects such as environmental protection, resource efficiency, social responsibility, and economic viability, emphasizing the balance and coordination of the economy, environment, and society [14]. More and more scholars have started to conduct research and exploration to achieve the goal of sustainable development in construction safety management. For example, to ensure the sustainable development of construction products in the construction industry, Qi et al. used the DEA method to assess the CSP in Jiangsu, Zhejiang, and Shanghai from 2003–2019 [15]. Zhou analyzed and summarized the spatial and temporal distribution patterns and characteristics of construction safety accidents in China in the past decade and proposed a guide for safe construction management from a sustainable development perspective [16]. Ahmed and Mallick investigated the application of artificial neural networks in promoting the sustainable development of health and safety in the construction industry [17].

However, most of the current studies on safety performance in the construction industry have used traditional DEA models or two-stage DEA models. However, traditional DEA models are susceptible to random errors and interference from external environmental factors (EEF), which may significantly affect the accuracy and rationality of evaluation results [18]. There are differences in building safety performance across regions, which may be influenced by regional characteristics, management practices, and sustainable development practices [17]. Therefore, comparative studies of building safety performance in different regions should consider multiple environmental factors to reveal regional differences, challenges, and directions for improvement. The limited analytical capability of traditional models necessitates introducing a three-stage SBM-DEA model to assess building CSP across regions and consider EEF that may affect safety performance measurement. The three-stage SBM-DEA model is an extended DEA-based model with more refined data analysis capability to eliminate the effects of EEF and random errors on efficiency values and can consider multiple environmental factors for a more scientific setting of model parameters [19,20].

Based on the above, in order to promote the development of the construction industry in a more sustainable direction, this study aims at the sustainable development of the building construction sector, takes each region in China as the target, considers safety inputs from the perspective of "man-machine-environment", and introduces a three-stage SBM-DEA model based on the DEA model for evaluation. The model considers stochastic and specific EEF and evaluates CSP in each province and city from 2009–2019 at a macro level. The three-stage calculation reveals the development differences and limitations in the level of construction safety management across different regions and provinces after

excluding the influence of EEF and random errors. This allows us to understand the differences in the current state of construction safety among different regions and analyze the weak points in each region, providing essential references for improving construction safety management practices.

The remainder of this paper is organized as follows. Section 2 describes the methods used. Section 3 describes the data sources and analyzes and discusses the empirical results. Finally, Section 4 provides the conclusions, recommendations, shortcomings, and future prospects.

2. Methods and Data Sources

2.1. Three-Stage SBM-DEA Model for Non-Desired Outputs

Charnes' DEA model can be used to evaluate multiple-input, multiple-output decision units [21]. The model's foundation is the notion of relative efficiency to measure the relative efficiency between units with the same type of decision. Many experts and scholars have favored the DEA method since its inception due to its unique benefits, and it is now commonly utilized for performance evaluation in numerous fields [22,23]. However, when assessing inefficient decision units, the classic DEA model ignores the issue of slack variables. To solve this problem, Tone presented the SBM model in 2001 to solve the problem of variable slack [24], but this model cannot completely exclude the impact of EEF and random disturbances on the model, which could produce measured efficiency values for each *DMU* at different environmental levels [20]. To overcome this shortcoming, Fried proposed the traditional three-stage DEA model [25], which still suffers from the problems that it can only be used for static analysis, cannot effectively measure non-desired outputs, and ignores technological variability. Although random disturbances and environmental influences can be successfully eliminated using the conventional three-stage DEA approach. We created a three-stage model using non-expected outputs and the stochastic frontier analysis (SFA) method to assess the actual safety performance of construction units in 30 provinces of China between 2009 and 2019. This evaluation excludes the impacts of EEF and random factors (RF) on the CSP value. The specific process is as follows:

Stage 1: Using the non-desired output SBM model proposed by Tone, in the first phase of building CSP values for each province and municipality, the values were measured in terms of inputs and constant payoffs to scale. Each province and municipality is a production decision unit (*DMU*), and each *DMU* has m inputs $X = [x_1, x_2, x_3, \cdots, x_n] \in R^{m \times n}$, s_1 desired output $Y^a = \left[y_1^a, y_2^a, y_3^a, \cdots, y_n^a\right] \in R^{s_1 \times n}$ and s_2 non-desired outputs

$$Y^b = \left[y_1^b, {y_2}^b, {y_3}^b, \cdots, {y_n}^b\right] \in R^{s_2 \times n} \text{ and } X > 0, Y^a > 0, Y^b > 0.$$

Then, the set of production possibilities p is:

$$P = \left\{ \left(x, y^a, y^b\right) \middle| x \geq X\lambda, y^a \leq Y^a\lambda, y^b \geq Y^b\lambda, \sum \lambda = 1 \right\}, \lambda \in R^n.$$

If no vector $\left(x, y^a, y^b\right) \in p$ also satisfies $x^0 \geq x, y_0^a \leq y^a, y_0^b \leq y^b$, then this $DMU_0\left(x_0, y_0^a, y_0^b\right)$ is efficient. This SBM model is specified by the following construction:

$$\rho = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{S_i^-}{X_{i0}}}{1 + \frac{1}{S_1+S_2}\left(\sum_{Y=1}^{s_1} \frac{S_Y{}^2}{y_{r0}{}^s} + \sum_{Y=1}^{s_2} \frac{S_Y{}^b}{y_{Y0}{}^b}\right)} \tag{1}$$

$$\text{s.t.} \begin{cases} x_0 - X\lambda + S^- = 0 \\ y_0^a - y^a\lambda + S^a = 0 \\ y_0^b - y^b\lambda + S^b = 0 \\ S^- \geq 0, S^a \geq 0, S^b \geq 0, \lambda \geq 0 \end{cases} \tag{2}$$

where: $\rho(0 \leq \rho \leq 1)$ is the assessed efficiency value, m is the number of indicators for the input elements, λ is the weight of the efficiency assessment, and X_0, Y_0 is the input and output values for DMU_0, respectively. S^-, S^a, S^b are input slack, desired output slack, and undesired output redundancy, respectively. When $\rho = 1, s^{-^*} = 0, s^{a^*} = 0, s^{b^*} = 0$, the DMU is a valid decision unit; otherwise, the value of CSP can be improved by optimizing the number of inputs and outputs.

Stage 2: The initial efficiency value of the decision unit was calculated using the SBM model in the first stage, but because of the interference of RF and EEF, the efficiency value cannot accurately reflect the actual level of safety management within the construction units in each province and city. In order to identify the environmental factors and RF that have the greatest impact on the outcomes, the SFA model was used to fit the input slack EE variables and errors from the first stage. The stochastic frontier regression expression is shown in Equation (3).

$$S_{ik} = f_i(Z_k; \beta_i) + V_{ik} + U_{ik}(i = 1, 2, \cdots, m; k = 1, 2, \cdots, n) \tag{3}$$

In the above equation, S_{ik} represents the relaxation of the k-th decision unit on the i-th input or output, $Z_k = \left[Z_{1k}, Z_{2k}, \cdots, Z_{pk}\right]$ stands for the p observable EE variables of the kth decision-making unit, β_i is the parameter to be estimated, $f_i(Z_k; \beta_i)$ stands for the impact of the p EE variables of the k-th decision-making unit on S_{ik}; generally let $f_i(Z_k; \beta_i) = \beta_i Z_k$; $V_{ik} \sim N(0, \sigma_{vk}^2)$ stand for the impact of random interference items, and $U_{ik} \sim N(0, \sigma_{vk}^2)$ stand for the impact of internal management and input scale level. The larger the value, the greater the ineffective rate level. It is generally assumed that they are independent and unrelated. $\gamma = \frac{\sigma_u^2}{\sigma_u^2 + \sigma_v^2}$ is defined, when γ tends to 0, RF dominates. The unknown parameters are estimated by maximum likelihood, and then the initial input-output data are adjusted according to Formula (4).

$$x_{ik}^A = x_{ik} + \left[\max\left\{z_k\hat{\beta}_i^-\right\} - z_k\hat{\beta}_i^-\right] + \left[\max\left\{\hat{V}_{ik}^-\right\} - \hat{V}_{ik}^-\right], (i = 1, 2, \cdots, m; k = 1, 2, \cdots, n) \tag{4}$$

In the above formula, x_{ik} is the original input value, and x_{ik}^A is the input value adjusted by Formula (4). The purpose of $\left[\max\left\{z_k\hat{\beta}_i^-\right\} - z_k\hat{\beta}_i^-\right]$ is to set each decision-making unit's EE to the same state, and $\left[\max\left\{\hat{V}_{ik}^-\right\} - \hat{V}_{ik}^-\right]$ is to adjust each decision-making unit's random interference elements to the same state. Following the processing of the above-mentioned algorithm, all decision-making units will be at the same environmental level.

Stage 3: Replace the original data x_{ik}; with the adjusted data x_{ik}^A, and then bring it into the unexpected output SBM model in the first stage for the efficiency calculation. The estimated efficiency value can more objectively and accurately reflect the actual internal safety management level of the building unit because RF and environmental influences are excluded.

2.2. Variables and Data Used for Analysis

Assessing CSP in 30 Chinese provinces and cities requires first identifying the inputs and outputs of CSP. Drawing on Kang and Wu, this paper selects the number of employees, construction machinery and equipment, and completed area of construction enterprises as input indicators from three aspects: people, machines, and environment, which directly reflect the development of the construction industry in each province and city [26]. The selection of input indicators from the three aspects of "human-machine-environment" has

been widely used in various industries, such as passenger car indicator design, computer security warning mechanism design, and mental health research [19,27,28]. In terms of outputs, this paper draws on Qi et al. and selects the number of construction accidents and construction fatalities as non-desired outputs and the value added of the construction industry as desired outputs [15].

In addition, CSP will be affected by various external elements such as the level of social and economic development, supervision environment, relevant policies, and regulations, etc. Based on comprehensive consideration of the availability, scientifically, and operability of indicator data, this paper selects the supervision environment and income level of construction personnel in each province and city as EE influencing factors.

1. Income levels of those employed in the construction industry

On the one hand, the wage level will directly affect the workers' living and working conditions. The good or bad living and working conditions will impact the CSP. Poor working and living conditions will make the workers' attitude negative, mentally disorganized, and physically exhausted, increasing the probability of safety risks and thus leading to safety accidents [29]. On the other hand, the income level of employed workers is closely related to socioeconomic development, which to some extent, reflects the level of socioeconomic development. The level of socioeconomic development plays a vital role in the sustainable development framework, and stable socioeconomic growth is essential for providing employment opportunities, improving the quality of life, and promoting the efficient use of resources. By examining the relationship between the level of socioeconomic development and CSP, we can understand the impact of economic development on safety management and control and thus promote the construction industry in terms of sustainable development. Therefore, in this paper, the average wage of the employed personnel in the construction industry is selected as an indicator to measure the impact of the increase in the income level of the employed personnel in the construction industry on the safety performance of construction.

2. Supervision environment level

Project supervision can not only guarantee the quality of construction projects, but also effectively promote and ensure the construction cost, schedule, and safety. As a key player in the construction market, it not only provides a scientific basis for decision-making during construction preparation, but also plays an active role in construction design, the construction site, and completion, thus providing sustainable safety management for construction industry development [30]. Therefore, the differentiated supervision environment level of each province and city will have different effects on the CSP. Therefore, this paper integrates the supervision environment of each province and city into the external influence factor system and uses the proportion of registered supervision engineers among the number of employees of construction engineering supervision enterprises to measure it.

Based on previous research findings regarding the selection of indicators for assessing the safety performance of building construction, a final set of efficiency evaluation indicators was developed and presented in Table 1.

The raw input and EE data used in this paper are from the China Statistical Yearbooks (http://www.stats.gov.cn) published annually by the National Bureau of Statistics of China (Tibet excluded due to data missing), and output data from the Ministry of Housing and Urban-Rural Development of the People's Republic of China (http://www.mohurd.gov.cn). Due to the unavailability of data, this paper is based on the panel data of 30 provinces and cities in mainland China from 2009 to 2019 after excluding Tibet for real building CSP measurement. And on this basis, in order to facilitate regional comparison, this paper divides the 30 provinces and cities into four regions according to the division method of the National Bureau of Statistics of China according to economic policies, as shown in Table 2.

Table 1. CSP Evaluation Index System.

Type of Indicator	Indicator Name	Calculation Method	Unit
Input indicators	Personnel	Number of employees in construction enterprises	People
	Machines	Construction machinery and equipment for companies in construction industry	Million
	Environment	Building construction completions	hm^2
Ideal output	Value added in the construction industry	—	Billion
Unsatisfactory output	Number of Construction accidents	—	Number
	Total construction fatalities	—	People
External environment variables	Level of socio-economic development	Average wages of people employed in the construction industry	Yuan
	Supervisory environment in each province	Registered supervising engineers in building construction Percentage of supervisory companies in employment	—

Table 2. Breakdown by region.

Region	Eastern Region	Northeast China	Central Region	Western Region
Provincial administrative areas	Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan	Liaoning, Jilin, Heilongjiang	Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan	Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang

3. Results and Discussion

3.1. Stage 1: Basic Information on Safety Performance of Building Construction in China

3.1.1. Analysis of Overall Building CSP in China

The overall safety performance in China, as depicted in Figure 1, did not meet the relative effectiveness of DEA throughout the period from 2009 to 2019 when considering scale efficiency, pure technical efficiency, and technical efficiency of building construction safety. The trend of change remained consistent during this timeframe, but it exhibited instability and followed a cyclical pattern. Thus, the period from 2009 to 2019 is divided into three cycles: the first cycle (2009–2013), the second cycle (2013–2016), and the third cycle (2016–2019). In each cycle, the CSP initially decreased and then increased. Notably, scale efficiency consistently surpassed pure technical efficiency, while pure technical efficiency consistently surpassed technical efficiency. This suggests that the main reason for the relatively inefficient achievement of technical efficiency is the low level of construction safety management in each region.

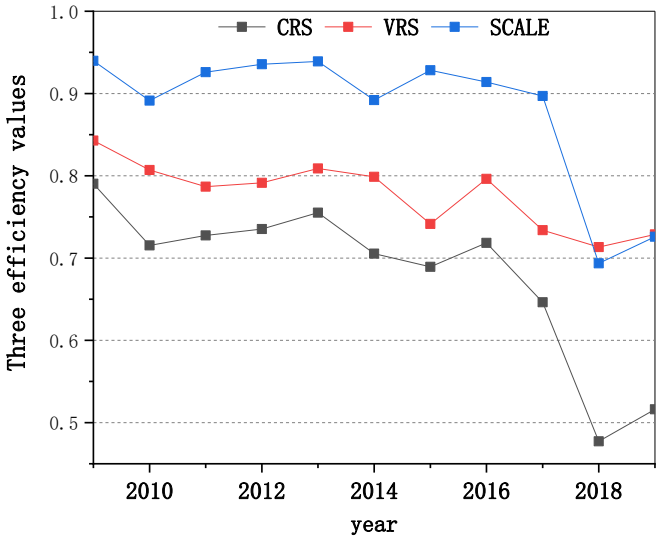


Figure 1. National overall safety performance values.

The study further examines the cyclical nature of building CSP by considering the economic, policy, and natural environments in China during each cycle. In the initial cycle, the value of technical efficiency decreased from 0.9 to 0.71 and then to 0.76, the value of pure technical efficiency decreased from 0.84 to 0.8 and then to 0.81, and the scale efficiency decreased from 0.94 to 0.89 and then to 0.94. Thus, it can be seen that the building construction industry was in the early stages of upgrading its industrial structure. It was adversely affected by the global financial crisis, resulting in a sluggish domestic economic situation and restricted investment demand in the construction sector. Consequently, the overall scale of the building construction industry remained small, technological progress was slow, and unethical practices and safety hazards persisted within the industry. However, the implementation of government stimulus programs and supportive policies, such as the issuance of the "Regulations on Construction Work Safety Management" in 2009, which provided comprehensive regulations and guidelines for ensuring construction work safety, led to a gradual recovery of the industry and improvement in technical capabilities.

During the second phase, the technical efficiency value decreased from 0.76 to 0.68 to 0.72, the pure technical efficiency value decreased from 0.80 to 0.74 to 0.8, and the scale efficiency decreased from 0.94 to 0.89 to 0.91. Thus, it can be seen that China's economy transitioned into a new phase known as the New Normal. In response, the Chinese government introduced a range of policies aimed at stimulating investment. For instance, in 2013, the "mass entrepreneurship and innovation" initiative were implemented, which fostered technological and managerial advancements in the construction industry. As a result, there was a notable enhancement in the industry's overall technical capabilities, production efficiency, and scale. However, between 2013 and 2015, the industry faced temporary setbacks in efficiency and scale due to the lingering effects of the financial crisis and domestic macroeconomic conditions.

In the third phase, the value of technical efficiency decreased from 0.72 to 0.48 and then to 0.52, the value of pure technical efficiency decreased from 0.79 to 0.71 and then to 0.73, and scale efficiency decreased from 0.91 to 0.69 and then to 0.72. Thus, it can be seen that the Chinese government has amplified its backing for the construction sector and expedited the progress of new urbanization, resulting in the swift advancement of the building construction industry. The industry has witnessed an overall improvement in its technical capabilities and scale. Simultaneously, the increased emphasis on safety, strengthened policy regulations and enforcement, and shifts in the competitive landscape have collectively contributed to a decline followed by an upward trajectory in the efficiency and scale of the building construction industry.

These fluctuations in the building construction industry indicate that its overall technical level, production efficiency, and scale will vary over time and in response to changes in national policies. However, there may also be temporary decreases in industry efficiency and scale during certain periods due to external economic factors. This highlights the importance for enterprises to closely monitor the macroeconomic and policy environment, and adjust their business strategies and investment plans accordingly. It is crucial to adapt to market changes and policy adjustments. Emphasizing technological innovation and talent development can enhance technical efficiency and pure technical efficiency. Additionally, in the construction process, it is important to carefully plan the scale of enterprises and leverage the benefits of economies of scale. However, during the process of scale expansion, attention should be given to resource integration and optimizing management to prevent difficulties in management and cost escalation associated with scaling up. Therefore, when assessing the level of internal construction safety management in China, it is important to exclude the influence of EEF in order to accurately evaluate the safety management level in each province and city.

3.1.2. Analysis of Building CSP by Region

This section will further analyze the regional divergence characteristics of building CSP in China. In terms of the four regions of East, Central, West, and Northeast, the more economically developed Eastern region had a much higher CSP than the other three regions from 2009–2017, while the overall technical efficiency and pure technical efficiency of the other regions were almost all lower than the national average. This shows an obvious unbalanced spatial distribution pattern of "East-West-Central", which is similar to the results of Kang et al. [26]. However, after 2017, the building CSP in the western region is greater than the national average, and the pure technical efficiency in the central region is also higher than the national average after 2018, while the other three regions, including the east, are below the national average. The main reasons for this phenomenon are the following:

(i) The Eastern region in China has been accorded preferential development opportunities during the country's reform and development phase. This has led to rapid economic growth and the allocation of ample financial resources and other necessary resources. Consequently, the region has achieved favorable economic outcomes, which can provide better support for construction safety management.

(ii) However, during the period of 2016–2018, China encountered a range of challenges including a slowdown in economic growth, structural adjustments, and environmental management. In response, the government implemented various policy measures such as "deleveraging," supply-side reforms, and initiatives for air pollution prevention and control. These measures have had a certain impact on the CSP across different regions. Additionally, China's construction industry is undergoing a transitional phase, marked by intense market competition, and numerous difficulties and challenges faced by construction enterprises. These challenges include talent attrition, lack of innovation, and low management levels. As a result, the technical efficiency and scale efficiency in the four major regions experienced a downward trend from 2016 to 2018.

(iii) In contrast, the central and western regions experienced an upward trend in pure technical efficiency from 2017 to 2019. This can be attributed to the influence of national policies aimed at promoting development in these regions, such as the policy of Western development and of encouraging the rise of the central region. Over the past few decades, China has undergone significant economic transformation and upgrading as a result of its reform and opening-up policy. This shift has involved a transition from a focus on the eastern coastal cities to the inland regions.

To foster the development of the central and western regions, the government has implemented policies that aim to enhance their overall economic and technological levels. These policies have involved increased investments, promotion of industrial upgrading,

and technological innovation. By comparing Figure 2a,b, we can observe that the comprehensive technical efficiency of the central and western regions primarily relies on scale efficiency during this period. This suggests that the lower CSP in these regions can be attributed to insufficient capital investment and a relatively backward technology level.

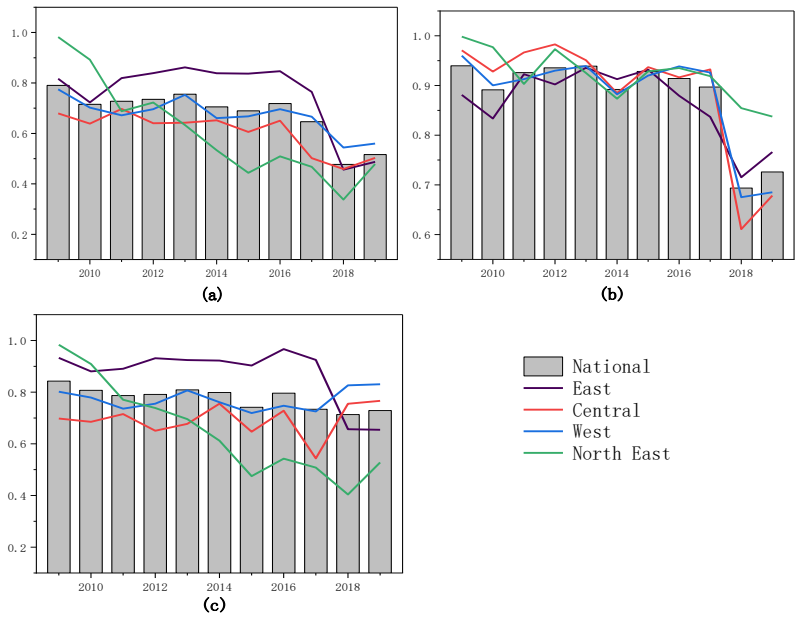


Figure 2. Trend graph of the three performance values by region: (**a**) Mean technical efficiency values, (**b**) Mean scale efficiency values, (**c**) Mean value of pure technical efficiency values.

To address these issues, it is recommended that the central and western regions increase capital investment and improve their technological capabilities while building upon their existing management levels. This would contribute to enhancing the CSP in these regions and narrowing the gap with other regions.

3.1.3. Analysis of Building CSP by Region

Using Maxdea8.0 software, the CSP values of 30 provinces and cities in China, excluding environmental and RF, were obtained. The calculations include total efficiency (TE) and its components (PTE and SE). Figure 3 shows the trend of CSP for each province and city from 2009 to 2019. In terms of the overall performance of construction safety, the top three provinces in terms of average CSP from 2009 to 2019 were Shaanxi Province (0.9925), Fujian Province (0.93359), and Qinghai Province (0.88). Meanwhile, Shaanxi Province has maintained a level of about 1 since 2009, which is consistent with the results of related studies [26,31], but there are many other provinces with safety performance values below 0.6. It can be seen that there are large differences in CSP among regions.

Before accounting for EEF and random influences, it can be observed that seven provinces in China exhibit commendable levels of construction safety with safety performance values exceeding 0.8. Among them, Shaanxi Province consistently holds the top position in terms of construction safety. Shandong, Hainan, and Henan experience varying degrees of fluctuations in safety performance, but their overall rankings remain high. In the case of Fujian, Beijing, and Qinghai, their safety performance ranks among the top in most years, except for certain individual years when their safety performance was lower. This temporary decline can be attributed to significant construction accidents occurring in these provinces and cities during those specific years, directly impacting their safety performance values.

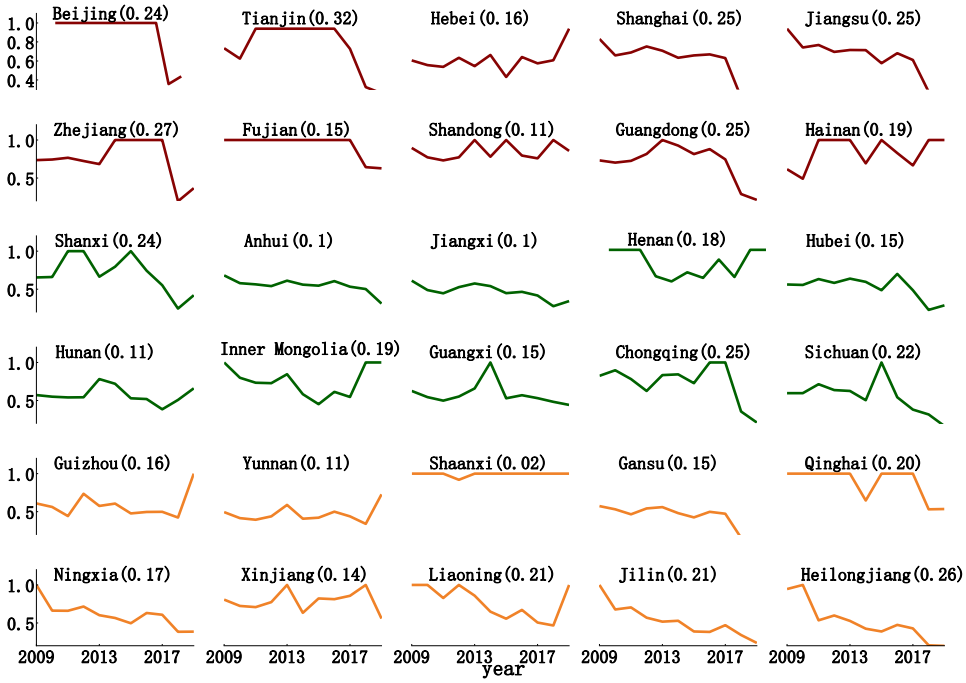


Figure 3. Trend graphs and standard deviations of CSP in Phase 1 by region, 2009–2019. Note: Due to space limitations, this paper does not present the results of the first phase of building CSP for the country as a whole and for 30 provinces and municipalities in tabular form, but the authors can provide the omitted data.

Considering the spatial and temporal variations in CSP across different provinces and cities, significant discrepancies can be observed in the safety standards of Tianjin, Heilongjiang, Zhejiang, Shanghai, Jiangsu, and other provinces. These differences stem from varying levels of investment, regulatory measures, and safety culture associated with construction safety in different regions and periods. Consequently, notable gradients arise in their CSP. On the other hand, Yunnan, Guizhou, Jiangxi, and Gansu exhibit relatively smaller standard differences. However, their persistently low CSP suggests significant challenges and issues in advancing safety practices within these regions. It implies that substantial difficulties remain in promoting the development of construction safety in these areas.

3.2. Stage 2: SFA Regression Analysis

In the second stage of the SFA regression analysis, the dependent variables will be the slack variables of each input factor that was measured in the first stage. These slack variables include the slack in the number of employees, slack in the net value of construction machinery and equipment at the end of the year, and slack in the completed area. As independent variables, the selected environmental variables (level of income of employed workers in the construction industry, level of socioeconomic development, level of supervisory environment in each province) will be used. Using Frontier 4.1 software, the SFA model was built and regression analysis was performed. The results of the analysis are shown in Table 3.

The SFA analysis results indicate that the values are all near 1 and greater than 0, demonstrating the appropriateness of the constructed SFA model. Additionally, the LR one-sided error test values are all significant at the 1% confidence level, indicating a strong influence relationship between each slack variable generated by the input elements and the selected environmental variables. Thus, it is feasible to apply the three-stage SBM-DEA model to eliminate the environmental effects.

Table 3. Regression results of the second stage SFA model for 30 provinces in China, 2009–2019.

Variables	Slack in the Number of Employees		Construction Plant and Equipment Year End Net Slack Value		Slack in Completed Area	
	Coefficient Values	T-Test Value	Coefficient Values	T-Test Value	Coefficient Values	T-Test Value
Constant values	−1,124,333	−5886.44 ***	−1,190,999.4	−1,190,983.1 ***	−7384.48	−10.05 ***
Income level of employees in the construction industry	14.59	23.27 ***	12.99	8.79 ***	−0.03	−1.11
Supervisory environment in each province	33,634.42	14.94 ***	35,698.23	35,681.3 ***	503.97	9.02 ***
σ^2	1,330,392,100,000	1,330,392,100,000 ***	1,358,871,000,000	1,358,871,000,000 ***	117,715,480 ***	117,679,490 ***
γ	0.75	38.27 ***	0.64	22.83 ***	0.83	62.56 ***
log value	−4887.01		−4938.63		−3297.31	
LR one-sided error test	212.69407 ***		119.87157 ***		276.04025 ***	

Note: *** represents passing the 1% significance level test.

The regression findings demonstrate that the regression coefficients of the provincial supervision environment and all slack variables are positive and pass the *t*-test at a 90% confidence level, showing that this variable has a substantial influence on each input slack variable, i.e., higher levels of supervision environment will increase the redundancy of inputs, with the greatest effect on the redundancy of construction machinery and equipment inputs. The level of socio-economic development has a smaller impact on the input redundancy values compared to the supervision environment variables in each province.

3.3. Stage 3: Efficiency Evaluation Results after Removing Environmental and RF

Table 3 shows that, despite the fact that the regression coefficient of the relaxation of EEF and individual input variables is not significant, the LR unilateral error test passes at the 1% significance level. As a result, while modifying the input variables, the above two environment variables must still be considered. In the first stage, the modified input data acquired by the formula will replace the original data to remeasure the efficiency, and the CSP value may then be established after eliminating the impact of EEF and RF.

First, when analyzed from a national overall perspective, there is a significant change in the mean value of China's building CSP after excluding the influence of EEF and RF. In terms of the average, there is a significant decrease in the adjusted efficiency mean, from 0.68 to 0.55, indicating that the presence of EEF and RF significantly overestimates the overall building CSP in China. In terms of the development trend, the efficiency value in the third stage has greater oscillation and fluctuation compared to the first stage, indicating the unstable level of construction safety management within the country.

Secondly, comparing the four major regions of East, Central, West and Northeast, there is a spatial dispersion characteristic of CSP. That is, the gap between the regions with lower safety performance and the higher regions is widening in terms of pure internal management efficiency. As can be seen in Figure 4, the highest average level of CSP in the four major regions is still the eastern region. However, the central region has replaced the original western region in second place and exceeded the national average. Among them, the average efficiency values of the four regions also have different degrees of change, the east from 0.75 to 0.7, down 7%; the west from 0.67 to 0.4, down 39%; the northeast from 0.61 to 0.44, down 44%; while the central from 0.61 to 0.63, up 4%. It can be seen that the external environment has a more significant impact on the measurement of CSP. The high safety performance shown in the northeastern and western regions in the first stage is

more from the influence of EEF, while the internal construction safety management level is facing a more significant challenge. The efficiency values in the eastern and central regions are more stable, indicating that some improvements have been made in purely internal safety management.

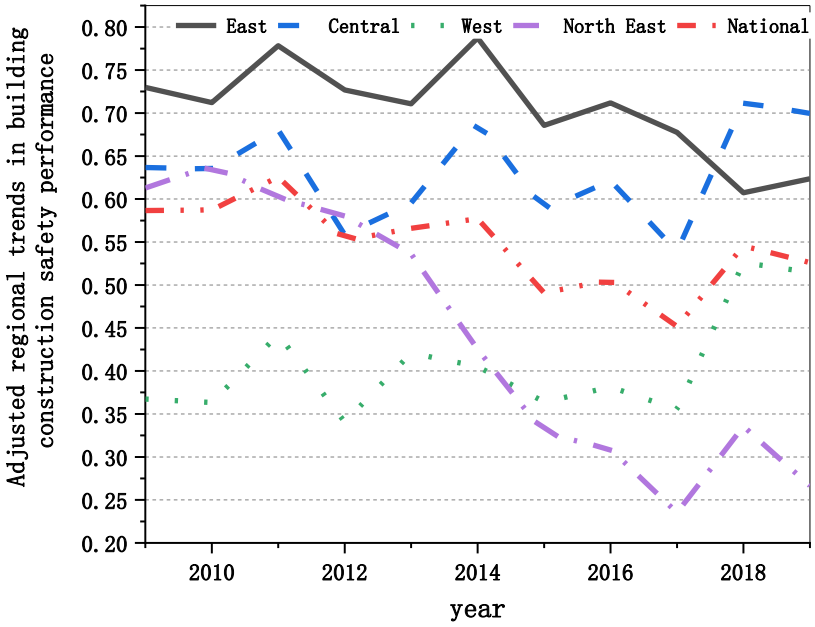


Figure 4. Trends in adjusted regional CSP.

Finally, from the perspective of various provinces and cities, combined with the spatial distribution map in Figure 5 and the trend chart of CSP in Figure 6, it can be seen that there have been significant changes in the distribution of CSP among provinces and cities before and after the adjustment. Among them, 13 provinces and cities, including Beijing, Tianjin, Hainan, Shanxi, Inner Mongolia, Guangxi, Guizhou, Gansu, Qinghai, Ningxia, Xinjiang, Jilin, and Heilongjiang, showed a characteristic of decline in comparison to before and after the adjustment. Hainan, Qinghai, Ningxia, Gansu, and Guizhou had low levels of construction safety production, especially Hainan and Qinghai, whose CSP values dropped from the top of the national rankings to the bottom. This indicates that the real internal construction safety management level of these provinces and cities lags behind, and the safety production situation is relatively severe. These regions may have difficulties attracting and retaining talent due to factors such as geographical location, resulting in a relatively backward level of construction safety management and technical expertise. For such areas, measures led by government policies can be adopted. First, taking the opportunity to promote urbanization and comprehensive and balanced regional economic development as a prerequisite, strong support can be provided to the local construction industry, and corresponding policies in terms of technology, economy, culture, and other aspects can be formulated. In addition, it is possible to attract experienced and financially strong construction companies to exchange and cooperate with local small and medium-sized enterprises, thereby improving the safety production level of the local construction industry. Through these measures, the gap between regions with better construction safety production levels can be narrowed, and the sustainable development of the construction industry can be achieved.

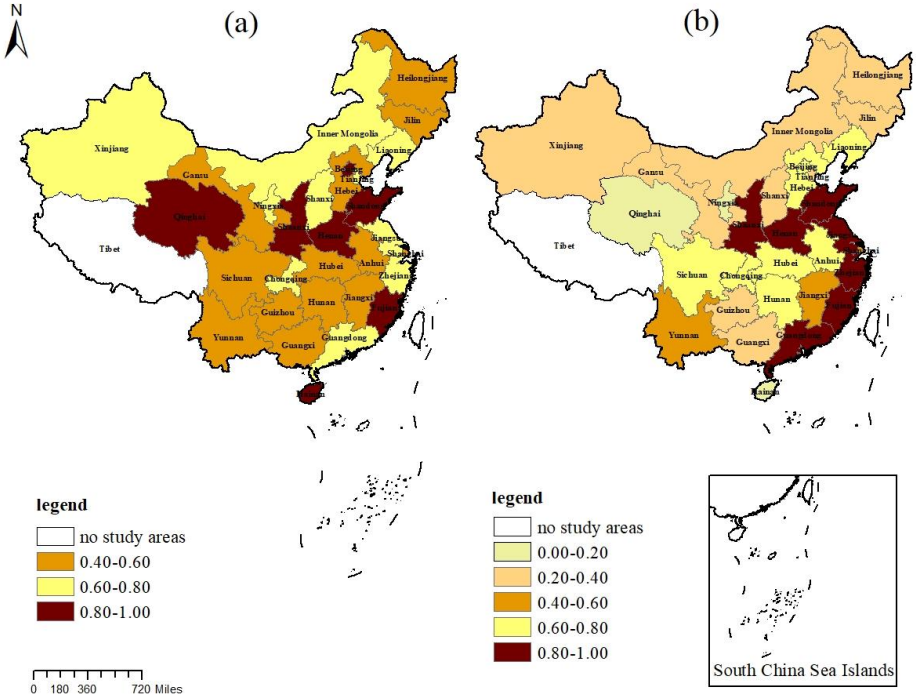


Figure 5. Spatial distribution of building construction safety levels in China's provinces: (**a**) phase I, (**b**) phase III. Note: The modified map is based on the standard map GS (2019) No. 1822 downloaded from the standard map service website of the National Administration of Surveying, Mapping and Geographic Information of China, without any modification.

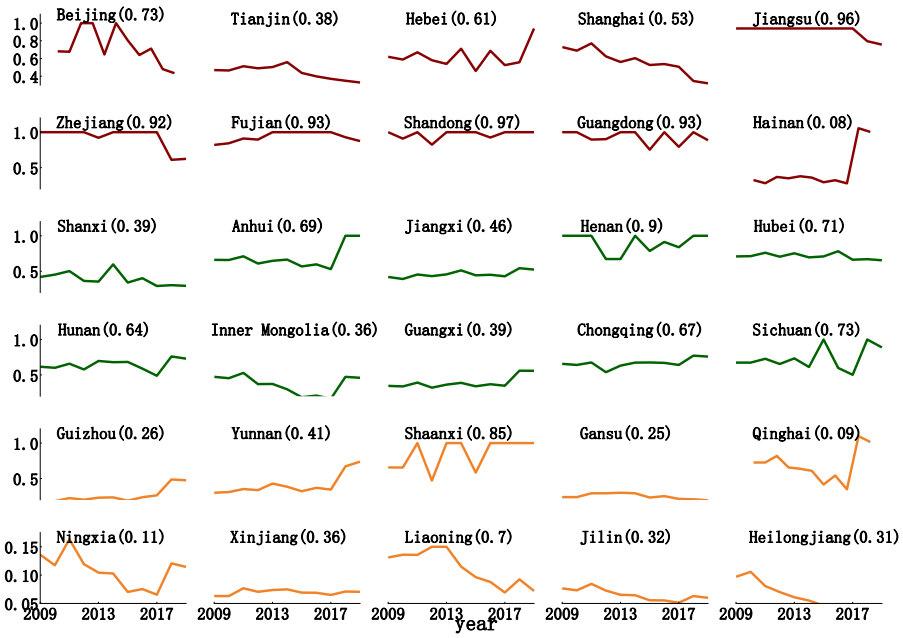


Figure 6. Trends and averages of CSP in Phase III by region, 2009–2019.

On the other hand, provinces that show upward trends in performance include Jiangsu, Zhejiang, Shandong, Guangdong, Anhui, Hubei, Hunan, and Sichuan. This indicates that the relatively low levels of CSP in these provinces are not solely due to their internal management capabilities but are more influenced by external EEF. Among them, Shaanxi, Fujian, Shandong, and Henan have changed in terms of safety performance values and rankings, but they still maintain a leading position nationwide. In addition, Jiangsu, Zhejiang, and Guangdong are also among the top provinces in terms of safety level in the third stage. For

these provinces, a strategy prioritizing technology can be adopted to stabilize the current state of construction safety production and avoid significant fluctuations. At the same time, continuous improvement and exploration of higher levels of production, development, and management models can be pursued based on the existing levels of construction production and safety management. These provinces can also play a demonstrative role in construction safety production and supervision, providing references and assistance to the construction industry in other provinces and cities.

In addition, the remaining provinces and cities have slightly lower safety performance compared to provinces with good levels of safety production, most of which are in a stage of inadequate safety production. Provinces and cities such as Jiangxi, Yunnan, and Chongqing, although economically relatively underdeveloped, have relatively high levels of construction safety production. This indicates that these regions attach great importance to the safety production of the construction industry and can adopt a prioritized management strategy by strengthening safety supervision and management to improve the safety production situation in the construction industry. At the same time, they can learn from regions with good levels of safety production and introduce their advanced production, development, and management models.

4. Conclusions and Recommendations for Future Research

This study selects 30 provinces and cities in China as the research objects, introduces EE variables into the evaluation of CSP, and uses an input-oriented three-stage SBM-DEA model to evaluate and analyze CSP from the perspective of the sustainable development of the construction industry. The actual CSP and distribution in each province, city, and region are calculated. This study introduces a new perspective and research methodology to the field of construction safety management, providing targeted recommendations for various stakeholders such as construction companies, governments, and regulatory agencies in different provinces and cities. The main findings of this study are as follows:

(1) RF and EE conditions have a significant effect on China's CSP, and the existence of both significantly overestimates China's CSP. Specifically, the supervisory environment in each province and city, i.e., the proportion of registered construction supervision engineers among the number of employees in construction supervision enterprises has a greater impact on the value of CSP relative to the improvement in the level of socio-economic development. In terms of regional differences, building CSP in the west and northeast regions is more influenced by EEF than in the east and central regions, and the performance values in the central region are more stable and realistic. The spatial distribution basically shows East > Central > Northeast > West, and in general, the primary segments of East, Central, Northeast, and West have greater room for improvement.

(2) After adjusting for EE influences and RF, China's national average CSP falls from 0.68 to 0.55, and its overall level shows a decreasing trend. This indicates that the presence of EEF and RF significantly overestimates the overall CSP in China. It is indisputable that the national average level of CSP is low and there is still much room for improvement in the internal safety management of Chinese construction-related units.

(3) The difference between the real CSP after excluding the influence of EEF and RF and the pre-adjustment level of CSP is obvious; the high efficiency value of CSP in some areas is to some extent the result of the EEF in which it is forced, but there are also some provinces where the low CSP is not entirely due to their lack of willingness to carry out safety management.

(4) In view of the differentiated performance of the eastern, central, western and north-eastern regions in terms of CSP, the provinces and cities should take into account the disparity between the regions in terms of internal management in the process of promoting construction safety and formulating measures to prevent construction accidents, and focus on enhancing the internal management efficiency of the north-

eastern and western regions, especially to strengthen the exchange of talents and management techniques between the eastern and western and northeastern regions, and make use of the excellent talents and more effective management methods in the east to effectively enhance their own CSP.

Based on the results and conclusions, the following recommendations are made:

(1) For regions with relatively lower levels of construction safety management and technological development, such as Hainan and Qinghai, measures led by government policies can be implemented. For example, strong support can be provided to the local construction industry, and corresponding incentives can be formulated regarding technology, economy, culture, and other aspects.
(2) A strategy focusing on technological advancements can be adopted for provinces and cities that rank high in construction safety management, such as Jiangsu and Zhejiang. The current safety production situation should be stabilized, and the exploration of higher-level production models should be pursued.
(3) A strategy emphasizing management can be implemented for provinces and cities with good levels of construction safety production but still have room for improvement, such as Jiangxi and Yunnan. Strengthening safety supervision and management should be prioritized, and learning from regions with good safety production levels should be encouraged, including the introduction of their advanced production, development, and management models.

One limitation of this research is that it only considered China's social and economic development level, supervisory environment level, and RF as EEF in the DEA system. It is important to include as many environmental factors that influence the sustainable development of construction safety as possible, such as resource utilization efficiency, energy consumption during the construction process, and waste management level. This is an area that needs further improvement in the future, and researchers should collect more data. Another point to note is that when adopting this method in other countries or regions, indicator selection and data collection should be tailored to their specific circumstances.

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